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Study on weak link of energy utilization in oil transfer station system: Insights from energy level analysis method



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ABSTRACT

In this paper, an energy level analysis model of oil transfer station system is established, which is divided into oil transfer station subsystem and pipeline network subsystem. From the perspective of the level of energy, the system is evaluated and optimized by virtue of using energy level analysis method and combining with the “three box” analysis model. Moreover, the energy level evaluation indexes of import and export, energy level difference and energy level balance coefficient, are calculated in terms of the calculation results. Then the energy utilization diagrams (EUD) are drawn, it can be seen that more than 95% of the supply energy in the oil transfer station subsystem is provided by gas. The energy level difference of the heating furnace is the largest, which can be seen intuitively that the heating furnace is the weak link of energy utilization in the whole system. Based on the influencing factors, the corresponding energy saving and consumption reduction measures are preliminarily proposed.

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1. Introduction

Oil and gas gathering and transportation systems are large energy dissipation systems (Liu et al., 2019b,a). Based on statistics, the energy consumption of oil and gas gathering and transportation generally accounts for 30%~40% of the total energy consumption in crude oil production. The consumed heat energy and electric energy are the main energy consumption objects in oilfields and have great potential for energy conservation. Consequently, it is of great significance to analyze the energy utilization of the system to save energy and reduce consumption in the oilfields.

Currently, the research on gathering and transportation systems only considers the energy analysis and exergy analysis stages (Gholam and Davood, 2016; Gholam et al., 2017b,a, 2018). Gholam R. A. et al. selected efficiencies of energy and exergy as objective functions and used Cycle-tempo software for simulations. The best plan in terms of efficiency and cycle power

promotion is provided (Gholam and Davood, 2015). Davood T. et al. analyzed an existing combined heat and power (CHP) system in a Petrochemical Plant in terms of energy, exergy and environmental (3E) aspects. The simulation revealed that the energy, exergy, heat and total efficiencies are 8.22%, 7.87%, 48.92% and 56.8%, respectively (Gholam et al., 2019). Ma Y. et al. analyzed the natural convection energy recovery loop system experimentally in different airflow rates from the view of energy and exergy analysis and extracted their values (Yulin et al., 2020).

The second law of thermodynamics points out that energy not only has quantity but also has quality (Wu et al., 2019; Ahmadi et al., 2018; Singh and Kaushik, 2013). Yang Donghua proposed a new energy equilibrium method, energy level equilibrium, on the basis of the principle of “energy utilization by level” and “energy supply by level”, and the energy level equilibrium coefficient was taken as the quality index of the rationality of energy utilization (Lin, 2009). Energy savings and reasonable energy level matching are advocated. Energy and exergy are utilized. In essence, the energy level supplied is exactly equal to the energy level required for the users. By means of an exergy analysis, only the thermodynamic perfection or utilization of exergy can be explored (Cheng et al., 2018; Soltani et al., 2013). However, by analyzing the energy level of the gathering and transportation system, the rationality of energy utilization can be comprehensively evaluated and analyzed with the help of the theoretical

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energy level equilibrium and the corresponding evaluation indexes. Feng Xiao introduced the energy level-enthalpy diagram with the advantages of the exergy analysis and pinch method combined together in order to solve the limitation of the pinch method, which fails to address the process involving pressure or component changes. The diagram can be utilized to assess the performance of the system and set the modified target (Chen, 2008). Zhou Jicheng discussed the reasonable matching issue between the energy supply and energy utilization in the waste heat recycling system of iron and steel enterprises from the energy “quality” aspect, and this work provided a reference for the recovery and rational utilization of waste heat resources of iron and steel enterprises (Wang, 2008). The energy level analysis theory is initiated by Prof. Yang Donghua in China; however, foreign scholars have produced few in-depth studies. Rahul Anantharaman developed an energy integration method to define the interaction relationship between subsystems in the plant, and the simulation results were explained from the physical point of view; moreover, energy efficiency was improved by exploring possible integration schemes. Through the energy integration of methanol plants, the effectiveness of this method was verified (Zhu and Chen, 2014). The energy level analysis method is the continuation of the exergy analysis method. An energy level analysis can be used to estimate the reasonability of energy matching in the system, and this may avoid high-quality energy with low-quality utilization, resulting in wasted energy; in addition, energy is utilized in a hierarchical way (Dong, 2017; Jiang, 2008; Mao et al., 2015).

Based on the above research background (Cheng et al., 2019a; Nishida et al., 2002; Morosuk and Tsatsaronis, 2009; Han et al., 2007), distinguishing from the traditional energy analysis and exergy analysis and aiming at the level of energy, the energy level analysis models of oil transfer station subsystem and pipeline network subsystem are established from the perspective of reasonable energy utilization in this paper. The energy level analysis method and the “three box” analysis model are combined together to optimize the analysis and evaluation process of each subsystem. According to the calculated results of energy level difference and energy level balance coefficient, it is concluded that the oil transfer station subsystem is the weak link of energy consumption, which verifies the results of the exergy analysis model. By drawing the EUD, the weak energy consumption equipment of the heating furnace as the subsystem of the oil transfer station is determined intuitively, and the corresponding improvement measures are put forward.

2. Establishment of the energy level analysis model for an oil transfer station system

2.1. Present situation of an oil transfer station

An oil transfer station in East China is taken as an example, and it has an annual output of 575 000 tons of liquid, a comprehensive water content of 90.6%, an average wellhead oil temperature of 29.8 °C, a total gas consumption of 1.499 million cubic meters, and a total power consumption of 982 000 kWh with more than 70% of the mixing pump consumption. The oil transfer station system is divided into an oil transfer station subsystem and a pipe network subsystem, which is shown in Fig. 1 (Zhang et al., 2019; Cheng et al., 2019b; Sun et al., 2019).

The physical parameters of the oil products in the oil transfer station system are shown in Table 1.

2.2. Energy level equilibrium model

The quality of energy can be measured by the size of the energy level Ω , which is defined as the exergy value of the unit energy. The transfer energy can be expressed as follows:

$$\Omega = \frac{E}{Q} \quad (1)$$

Therefore, the mechanical energy, electrical energy and useful work values are all equal to 1, and the energy level of heat depends on the temperature of the system T and the ambient temperature T_0 , which can be expressed as follows:

$$\Omega = 1 - \frac{T_0}{T} \quad (2)$$

Based on the principle of energy equilibrium and exergy equilibrium, the energy level, energy level difference and energy level equilibrium system are combined together. Moreover, energy level matching and energy consumption reduction are regarded as guiding ideologies of energy utilization, and the energy level difference and energy level equilibrium coefficient are taken as two evaluation criteria of the rationality of energy utilization. The abovementioned work is the framework of the energy level analysis, of which the model is shown in Fig. 2.

As shown in Fig. 2, Q represents the energy exchanged to each other from each unit, while E stands for mutual exergy.

According to the model, the relevant energy and exergy equilibrium formulas are established as follows:

$$Q_{res}^+ + Q_u^+ + Q_{en}^+ = Q_{res}^- + Q_u^- + Q_{en}^- \quad (3)$$

$$\text{Or } E_{res}^+ + E_u^+ + E_{en}^+ = E_{res}^- + E_u^- + E_{en}^- \quad (4)$$

Exergy efficiency of equipment:

$$\eta_{ex} = \frac{E_u^- - E_u^+}{E_{res}^+ - E_{res}^-} = 1 - \frac{E_{in} + E_{ex}}{E_{res}^+ - E_{res}^-} \quad (5)$$

When $Q_{en}^+ = 0$, the energy efficiency of equipment is:

$$\eta_t = \frac{Q_u^- - Q_u^+}{[(Q_{res}^+ - Q_{res}^-) + Q_{en}^+]} \quad (6)$$

The energy level of input energy of equipment is:

$$\Omega_{im} = \frac{E_{res}^+ - E_{res}^-}{Q_{res}^+ - Q_{res}^-} \quad (7)$$

The level of energy required for users:

$$\Omega_u = \frac{E_u^- - E_u^+}{Q_u^- - Q_u^+} \quad (8)$$

The energy input from the environment to equipment is taken into account and is totally made up of energy, namely, $E_{en}^+ = 0$, and the above formula can be simplified as:

$$\Delta\Omega = (\Omega_{im} - \Omega_u) = \left[1 - \left(\frac{\eta_{ex}}{\eta_t} \right) \right] \Omega_{im} \quad (9)$$

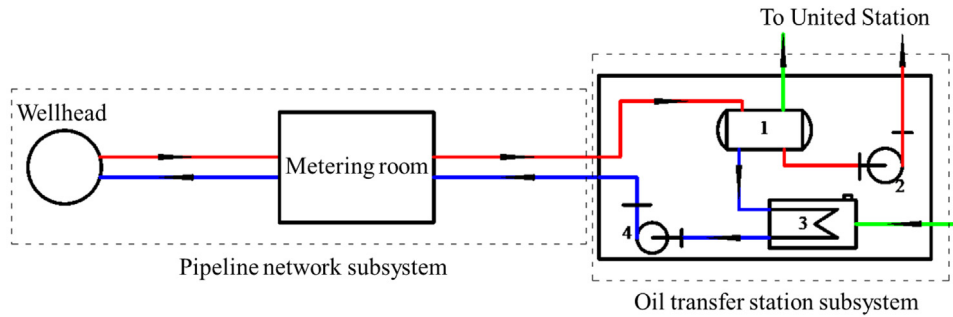
The relevant difference value is determined as a new index, the energy level equilibrium coefficient ξ_{Ω} , which is presented as the relative change between the energy level of the energy input and output of the system:

$$\xi_{\Omega} = \left[1 - \left(\frac{\eta_{ex}}{\eta_t} \right) \right] \quad (10)$$

It is more reasonable to take the energy level difference $\Delta\Omega$ (or energy level equilibrium coefficient ξ_{Ω}) as the quality index of the rationality on energy utilization than the exergy efficiency η_{ex} .

Table 1
Physical parameters of oil products in the oil transfer station.

Density of crude oil (kg/m ³)	Viscosity of crude oil (mPa s)		Freezing point (°C)	Production GOR (m ³ /m ³)	Density of natural gas (kg/m ³)	Wax content (%)	Wax precipitation temperature (°C)
	50 °C	30 °C					
851.7	13.86	26.0	27.8	75.35	0.7476	25.32	39



1- “Three-in-one” device, 2- Efflux pump, 3- “Two-in-one” device, 4- “Water mixing pump”

Fig. 1. Subsystem division of the gathering and transportation system of the oil transfer station.

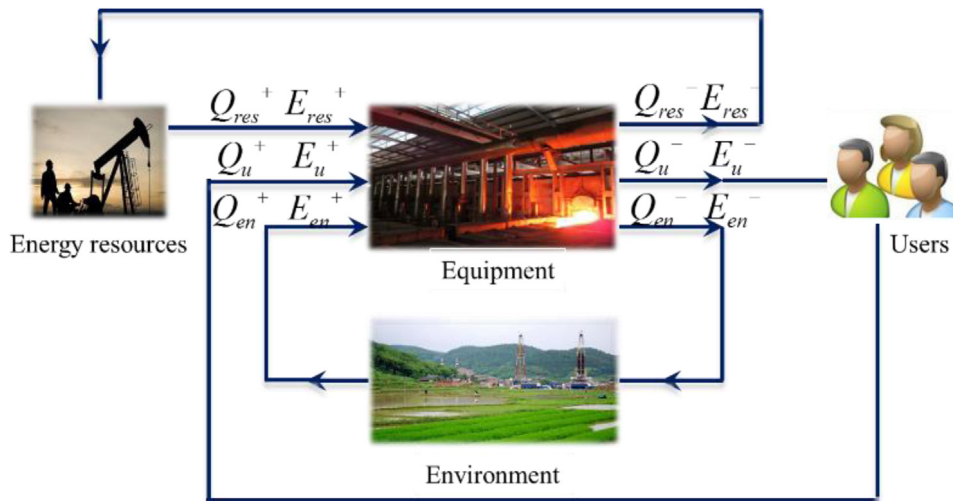


Fig. 2. Energy level analysis model of the system.

2.3. Establishment of the energy level analysis model for each subsystem in the oil transfer station

Due to the evaluation index, energy equilibrium coefficient and energy level difference during the energy level analysis, the energy level analysis needs to be calculated with these parameters during the process of the exergy analysis and energy analysis, such as input and output flow and efficiency of exergy and energy; moreover, the corresponding energy level equilibrium model is established considering the exergy and energy equilibrium model.

(1) Black box model on the basis of the energy level equilibrium in the oil transfer station subsystem

In the equilibrium model of the oil transfer station subsystem, the energy level at the inlet consists of the energy supply flow (heating furnace, water mixing pump, efflux pump) and the energy flow of the in-station mixture. The energy level at the outlet is composed of the energy flow of the out-station gas, mixing water and efflux mixture. In terms of the energy equilibrium and exergy equilibrium model, the energy level equilibrium model is constructed. The black box model is based on the energy level



Fig. 3. Black box energy level analysis model of the oil transfer station subsystem.

equilibrium in the oil transfer station subsystem as follows (Wei et al., 2014; Xia, 2011; Wang and Feng, 2000) (see Fig. 3):

The energy level of logistics input to the oil transfer station subsystem is:

$$\Omega_{in} = \frac{E_{m1} + E_f + E_{e1} + E_{e2}}{E_{xm1} + E_{xf} + E_{xe1} + E_{xe2}} \quad (11)$$

where E_{m1} is the energy input by the production fluid on the wellhead; E_f is the fuel energy supplied to the heating furnace;

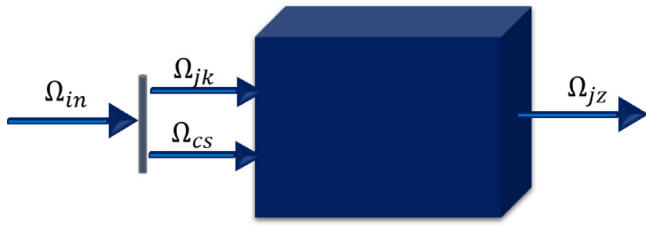


Fig. 4. Black box model on the basis of the energy level equilibrium in the pipeline network subsystem.

E_{e1} is the electrical energy supplied to the efflux pump; E_{e2} is the electrical energy supplied to the water mixing pump; E_{xm1} is the logistical exergy of the mixture including the oil, gas and water input oil transfer station; and E_{xf} , E_{xe1} , and E_{xe2} are the fuel exergy consumed by the heating furnace, electrical energy supplied to the efflux pump and the water mixing pump, respectively.

The logistical exergy is caused by the potential field between the theoretical states 1 and 2, which contains the temperature field, pressure field, velocity field and gravity field. In general, the dynamic exergy and position exergy can be ignored, and the logistical exergy is calculated by:

$$E_{xm} = H - H_0 - T_0(S - S_0) \quad (12)$$

where, H is the enthalpy value of logistics, kJ/kg; H_0 is the enthalpy value of the environment; S is the entropy value of logistics, kJ/(kg K); and S_0 is the entropy value of the environment, kJ/(kg K).

The logistical energy level output from the oil transfer station subsystem is:

$$\Omega_{out} = \frac{E_g + E_w + E_{m2}}{E_{xg} + E_{xw} + E_{xm2}} \quad (13)$$

where E_{m2} is the energy output by the efflux fluid; E_w is the energy output by the circulating water; E_g is the energy output by the separating gas; and E_{xm2} , E_{xw} , and E_{xg} are the exergy of the water cut crude oil output of the oil transfer station, exergy of the water mixing after heating and pressurizing, and exergy of the natural gas separated from the station, respectively.

The energy level difference between the input and output of the oil transfer station subsystem is as follows:

$$\Delta\Omega = \Omega_{in} - \Omega_{out} = \left[1 - \left(\frac{\eta_{ex}}{\eta_t} \right) \right] \frac{E_{m1} + E_f + E_{e1} + E_{e2}}{E_{xm1} + E_{xf} + E_{xe1} + E_{xe2}} \quad (14)$$

The energy level equilibrium coefficient of the oil transfer station subsystem is as follows:

$$\xi_{\Omega_{sub}} = \left[\frac{\Omega_{in} - \Omega_{out}}{\Omega_{in}} \right] = 1 - \frac{\eta_{exsub}}{\eta_{tsub}} \quad (15)$$

(2) Black box model on the basis of the energy level equilibrium in the pipeline network subsystem

In the equilibrium model of the pipeline network subsystem, the energy level at the inlet consists of the physical energy flows of the input logistics and water mixing. The energy level at the outlet is composed of the physical energy flow of the output logistics. The black box model is based on the energy level equilibrium in the pipeline network subsystem as shown in Fig. 4.

The energy level input pipeline network subsystem is:

$$\Omega_{in} = \frac{Q_{jk} + Q_{cs}}{E_{xjk} + E_{xcs}} \quad (16)$$

The energy level output pipeline network subsystem is:

$$\Omega_{out} = \frac{Q_{jz}}{E_{xjz}} \quad (17)$$



Fig. 5. Black box model based on the energy level equilibrium in the heating furnace.

The energy level difference between the input and output of the pipeline network subsystem is as follows:

$$\Delta\Omega = \Omega_{in} - \Omega_{out} = \left[1 - \left(\frac{\eta_{ex}}{\eta_t} \right) \right] \frac{Q_{jk} + Q_{cs}}{E_{xjk} + E_{xcs}} \quad (18)$$

The energy level equilibrium coefficient of the pipeline network subsystem is as follows:

$$\xi_{\Omega_p} = \left[\frac{\Omega_{in} - \Omega_{out}}{\Omega_{in}} \right] = 1 - \frac{\eta_{exp}}{\eta_{tp}} \quad (19)$$

(3) Black box model on the basis of energy level equilibrium in the heating furnace

In the equilibrium model of the heating furnace, the energy level at the inlet is made up of the physical energy flows of the heated media input to the heating furnace and combustion of gas. The energy level at the outlet consists of the physical energy flow of the heated media output to the heating furnace. The black box model based on the energy level equilibrium in the heating furnace is shown in Fig. 5.

The energy level input to the heating furnace is:

$$\Omega_{in} = \frac{Q_{in} + Q_r}{E_{xin} + E_{xr}} \quad (20)$$

The energy level output from the heating furnace is:

$$\Omega_{out} = \frac{Q_{out}}{E_{xout}} \quad (21)$$

The energy level difference between the input and output of the heating furnace is:

$$\Delta\Omega = \Omega_{in} - \Omega_{out} = \left[1 - \left(\frac{\eta_{ex}}{\eta_t} \right) \right] \frac{Q_{in} + Q_r}{E_{xin} + E_{xr}} \quad (22)$$

The energy level equilibrium coefficient of the heating furnace is:

$$\xi_{\Omega_h} = \left[\frac{\Omega_{in} - \Omega_{out}}{\Omega_{in}} \right] = 1 - \frac{\eta_{exh}}{\eta_{th}} \quad (23)$$

3. Solution of the energy level analysis model of the oil transfer station system

3.1. Energy level analysis of the black box in the oil transfer station subsystem

The energy level analysis model is used to solve the relevant evaluation indexes. The results of the energy level analysis of the black box in the oil transfer station subsystem can be seen in Table 2 (Anantharaman et al., 2006; Zhou et al., 2013).

Based on the data in the table, the change in the energy level evaluation index in the oil transfer station subsystem is as follows (see Fig. 6):

From the definition of the energy level evaluation index, the smaller the energy level difference and energy level equilibrium

Table 2
Energy level analysis output and input results to the oil transfer station subsystem.

Months	Energy level converted by input energy	Energy level converted by output energy	Energy level difference	Energy efficiency	Exergy efficiency	Energy level equilibrium coefficient
January	0.547	0.12	0.429	79.88	14.54	0.818
February	0.538	0.11	0.429	77.84	13.44	0.827
March	0.535	0.11	0.427	76.23	13.05	0.829
April	0.531	0.11	0.422	68.60	12.23	0.822
May	0.538	0.10	0.44	68.06	11.29	0.834
June	0.567	0.06	0.508	68.35	7.98	0.883
July	0.425	0.04	0.385	41.06	40.17	0.022
August	0.429	0.04	0.391	40.12	38.95	0.029
September	0.419	0.04	0.379	39.95	39.29	0.016
October	0.563	0.07	0.493	68.56	9.25	0.865
November	0.564	0.08	0.480	75.69	10.67	0.859
December	0.561	0.11	0.453	74.39	12.56	0.831

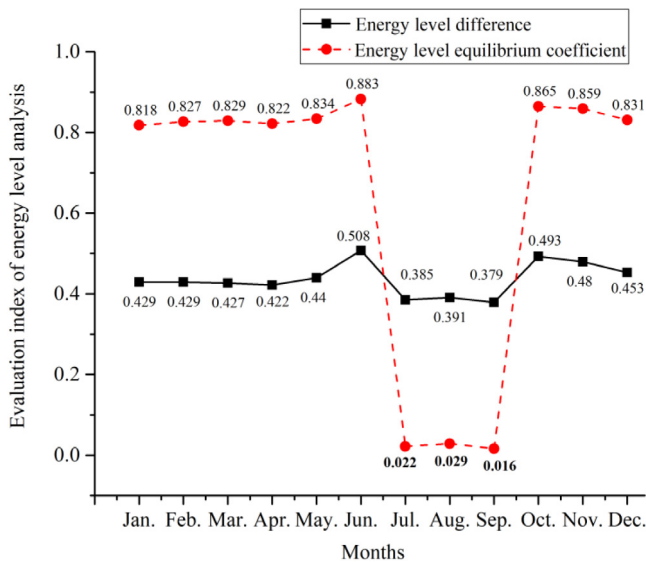


Fig. 6. The change in the energy level evaluation index in the oil transfer station subsystem.

coefficient are, the more energy level matching of the system, and the more reasonable the energy utilization. In general, the rationality of energy utilization in the oil transfer station subsystem is relatively low. In July, August and September, there is no heating furnace working in the water mixing process, and there is only a pump in operation with an energy level that is close to 1; thus, the energy level equilibrium coefficient of the oil transfer station subsystem is close to 0. In contrast, during the operation process of the heating furnace, the oil transfer station subsystem has a large energy level difference, which illustrates that the energy of the heating furnace is the weak link of energy utilization in the oil transfer station subsystem.

3.2. Energy level analysis of the black box in the pipeline network subsystem

The results of the energy level analysis of the black box in the pipeline network subsystem can be seen in Table 3 (Chen et al., 2014; Ameri and Askari, 2013).

Considering the data in the table, the change in the energy level evaluation index in the pipeline network subsystem is shown in Fig. 7:

From Fig. 7, it can be seen that the energy level coefficient and energy level difference of the pipe network subsystem are both at a low level, which indicates that the energy level or exergy

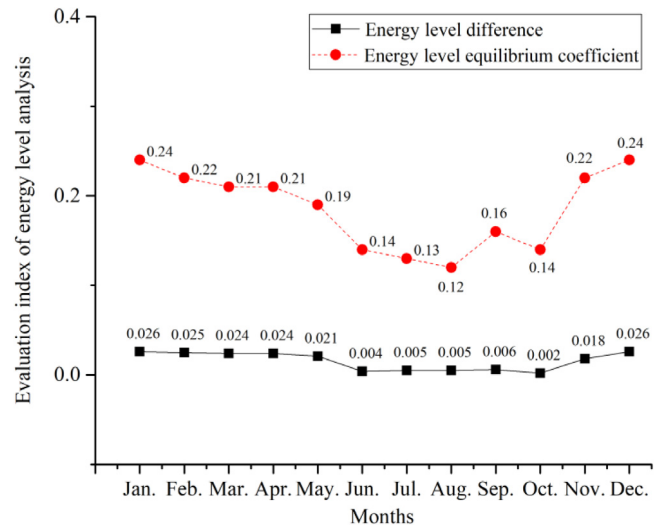


Fig. 7. The change in the energy level evaluation index in the pipeline network subsystem.

value consumed at the inlet and outlet of the pipeline network subsystem is small and the energy utilization condition is fine. When the ambient temperature is low, the temperature of mixing water is higher, which increases the potential difference between the medium in the pipeline and the ambient temperature, and this makes the assessment index larger during the months with low ground temperature; in addition, the energy level matching degree of the pipeline network subsystem is higher. In July, August and September, due to the shutdown operation of the heating furnace, the effective exergy in the pipe network subsystem is only pressure exergy, which accounts for a relatively small proportion of the total exergy loss; thus, the energy level difference and energy level equilibrium coefficient are at a low level all year round. The logistical input and output energy levels are both less than 0.1; therefore, the energy level of the pipeline network subsystem and the energy consumption are lower.

3.3. Energy level analysis of the black box in the heating furnace

In terms of the basic energy level analysis model of the heating furnace, relevant evaluation indexes are calculated, of which the results are shown in Table 4 (Cheng et al., 2017; Ahmadi et al., 2012).

The change in the energy level evaluation index in the heating furnace is as follows (see Fig. 8):

Because of the shutdown operation of the heating furnace in July, August and September, the corresponding analysis of the

Table 3
Energy level analysis results of the pipeline network subsystem.

Months	Conversion energy level	Output energy level	Energy level difference	Energy efficiency	Exergy efficiency	Energy level equilibrium coefficient
January	0.10	0.07	0.026	14.50	34.83	0.24
February	0.10	0.08	0.025	15.44	33.99	0.22
March	0.10	0.07	0.024	13.86	32.08	0.21
April	0.09	0.07	0.024	10.94	29.52	0.21
May	0.08	0.06	0.021	7.81	25.76	0.19
June	0.04	0.03	0.004	2.33	16.19	0.14
July	0.03	0.03	0.005	1.68	14.68	0.13
August	0.03	0.03	0.005	0.49	12.30	0.12
September	0.04	0.03	0.006	2.58	16.53	0.14
October	0.04	0.03	0.002	8.67	23.55	0.16
November	0.06	0.04	0.018	10.87	30.24	0.22
December	0.08	0.05	0.026	12.96	33.80	0.24

Table 4
Energy level analysis results of the heating furnace.

Months	Conversion energy level	Output energy level	Energy level difference	Energy efficiency	Exergy efficiency	Energy level equilibrium coefficient
January	0.44	0.16	0.277	79.38	15.50	0.80
February	0.42	0.13	0.299	76.48	14.32	0.81
March	0.42	0.12	0.295	72.15	12.97	0.82
April	0.41	0.10	0.310	70.32	11.24	0.84
May	0.41	0.10	0.311	63.85	9.83	0.85
June	0.46	0.06	0.406	62.33	6.36	0.90
October	0.46	0.05	0.406	65.01	7.91	0.88
November	0.47	0.07	0.397	80.48	11.21	0.86
December	0.47	0.09	0.384	81.67	13.69	0.83

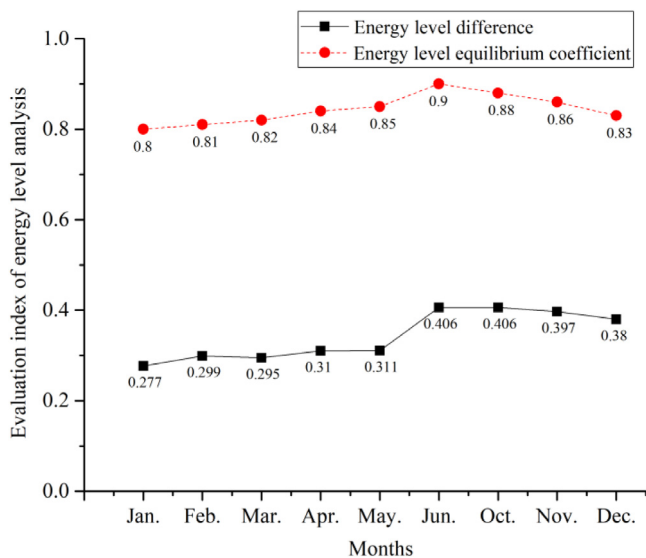


Fig. 8. The change in the energy level evaluation index in the heating furnace.

heating furnace is not conducted. During the months with normal operation of the heating furnace, the energy level difference fluctuates within the range of 0.25–0.4, with a variation amplitude of 8%. The energy level equilibrium coefficient ranges from 0.8 to 0.9, which varies by only 1%. The input energy level is depend on the inlet logistics and the supplied natural gas of the oil transfer station, in which the energy level of the natural gas is higher, is approximately 0.6, and the comprehensive conversion energy level is approximately 0.4. Concurrently, the output energy level is the water mixing logistics, which is approximately 0.1, and the energy level difference is mainly caused by the heat exchange loss and the cooling loss of combustion products in the internal heat loss. By comparing the energy level analysis of the oil transfer

station subsystem, the heating furnace is confirmed as the weak link of energy utilization in the oil transfer station system.

4. EUD in the energy level analysis method

The energy level analysis method and EUD analysis method can both provide guidance for rational energy utilization, but the energy level analysis is still based on the black box model, which can reflect neither the change in energy transmission and transformation in the system nor the amount of energy conversion during the process. The EUD method divides an energy utilization process into several subprocesses and shows the grades of the energy on both the release side and the reception side in the form of diagrams; this method demonstrates all details of energy transmission during the process, which can reveal the production reason for exergy loss and provide guidance for the improvement process.

The procedure of the EUD analysis method is as follows (see Fig. 9):

In the oil transfer station gathering and transportation system, the supply energy flow at the inlet is divided into several strands, and then the weighted average is taken on the basis of total quantity. The exergy flows obtained are considered as the corresponding input and output energy levels. The energy level analysis only involves the input and output logistics, and it has little significance to calculate the average of the energy level coefficients; hence, the middle month of each season is taken as the average month. Among these months, April, May and June are spring; July, August and September are summer; October, November, and December are autumn; and January, February, and March are winter (see Figs. 10–13).

It can be seen from the figures that the red line is the supplied energy, of which the first half is consumed by the pump. Because the energy consumed by the pump is relatively small, it is very short, and the second half is consumed by the heating furnace. The first half of the black line is the oil transfer station subsystem, and the second half is the pipeline network subsystem.

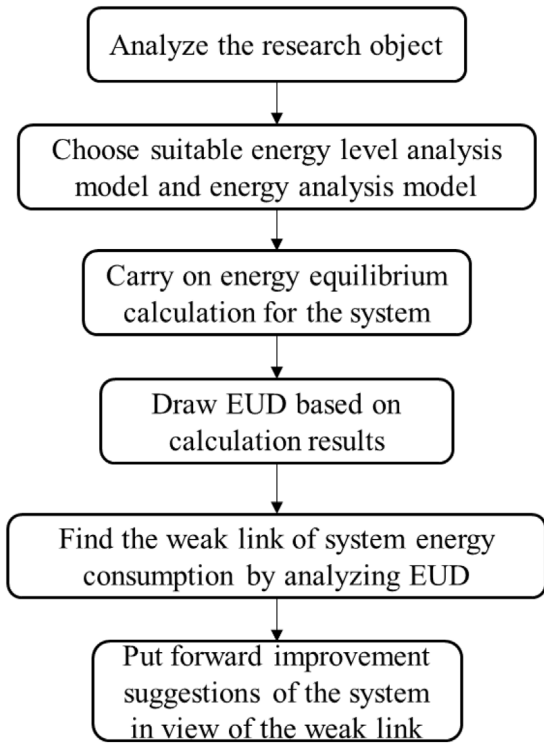


Fig. 9. The procedure of the EUD analysis method.

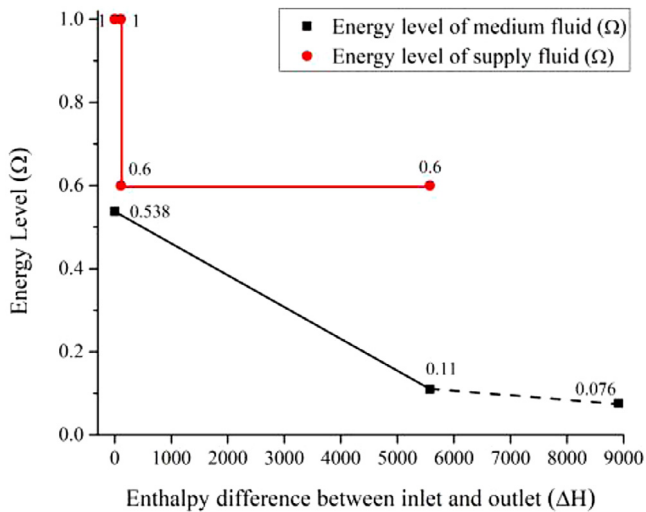


Fig. 10. EUD in winter.

During the whole year, because of the heating furnace and pump in the oil transfer station subsystem, there is an energy exchange between the energy level of energy flow provided by gas and electricity and the fluid medium with a low energy level of energy flow, while there only exists the dissipation of the energy level to the environment, without energy applied. Only in summer does the heating furnace shut down with no chemical energy applied; however, during the other seasons, energy is all provided from the chemical and electrical energy of fuel gas, among which electrical energy merely accounts for approximately 2% of the total applied energy and the rest of the energy is furnished by fuel gas. However, only the pump supplies a small amount of energy during summer with less effect on the energy level reduction in the pipeline. When it is closer to the cold season,

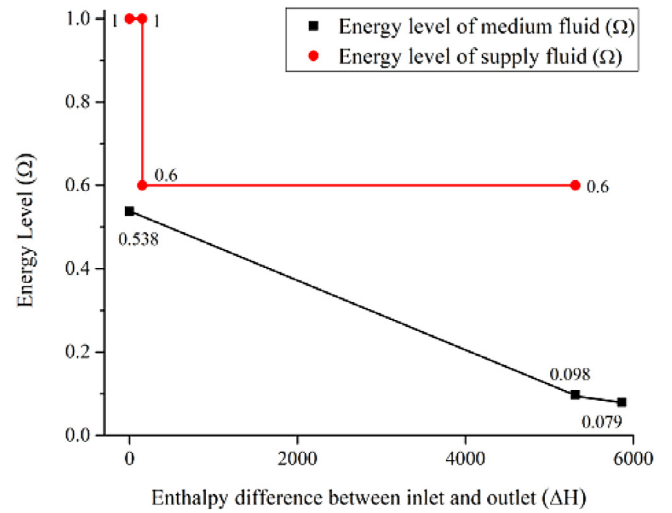


Fig. 11. EUD in spring.

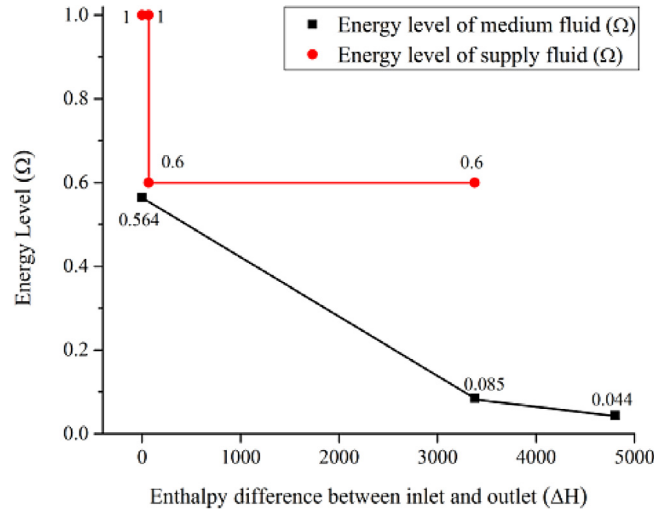


Fig. 12. EUD in autumn.

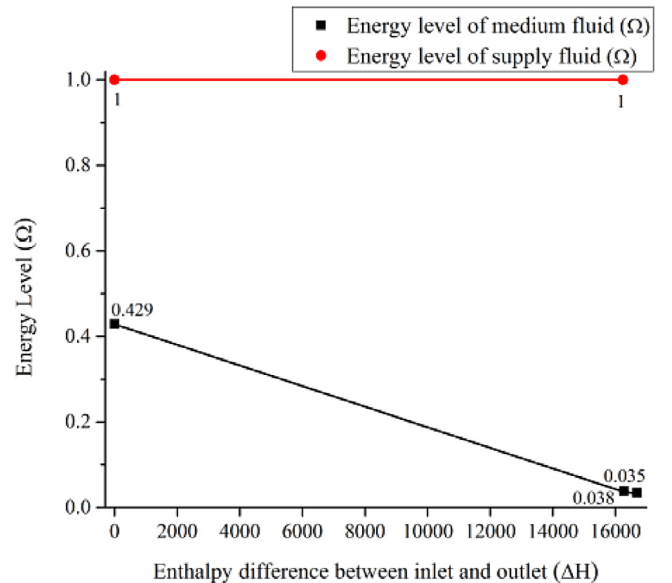


Fig. 13. EUD in summer.

with the increase in the water mixing volume and temperature, the heat dissipation capacity of the pipeline network subsystem to the environment becomes larger, while it shows an opposite change in the oil transfer station subsystem. Since the energy level difference and enthalpy difference in the oil transfer station subsystem account for a larger proportion of the whole system than that in the pipeline network subsystem, the descending speed of the energy level in the oil transfer station subsystem is faster than that in the pipe network subsystem, which indicates that the oil transfer station subsystem is the weak link of the system. Simultaneously, by virtue of the nonheated gathering and transportation during summer, the descending speed of the energy level in the oil transfer station subsystem is the same as that in the pipe network subsystem. The magnitude is so small for the electrical energy of the supply pump that the effect on the descending speed of the energy level in the oil transfer station subsystem fails to appear in the diagram, the red line in the EUD is almost a straight line, different from other seasons, which means the EUD can intuitively prove that the heating furnace is the weak link of energy utilization in the whole gathering and transportation system. The heating furnace has a high potential of energy saving and consumption reduction.

The following improvement measures are proposed on the basis of analyzing the influencing factors of the heating furnace exergy efficiency:

(1) In months with higher ambient temperature and lower water mixing temperature, the number of heating furnaces in operation can be reduced to increase the load rate of a single heating furnace.

(2) By optimizing the mixing water volume and temperature and under the condition of a smooth pipeline transportation, the heating furnace needs to be at a higher load state.

(3) To meet the requirements of maintaining a higher load rate of heating furnaces under different ambient temperatures, it is possible to design heating furnaces with different loads in parallel.

(4) The heating furnace can be designed with a variable rated load, which may occur by adjusting the space size of the furnace and flue.

5. Conclusions

(1) Except for the months with mixing water, the energy level equilibrium coefficients in the oil transfer station subsystem are all approximately 0.8, which is well above that in the pipeline network subsystem, and during months with mixing water, the energy level equilibrium coefficients are smaller, which can indicate that the heating furnace is the weak link of energy utilization in the oil transfer station subsystem.

(2) The oil transfer station system is evaluated from the perspective of the energy level analysis. The annual energy level difference and energy level equilibrium coefficient of the pipeline network subsystem are both at a lower level, in which the energy level difference changes within the range of 0.005–0.026 and the energy level equilibrium coefficient changes within the range of 0.1–0.25. In the nonheated months with the mixing water, the energy level equilibrium coefficients in the oil transfer station subsystem and the pipeline network subsystem are approximate. In contrast, in months with the water mixing process, the two evaluation indexes are both at a higher level, the energy level difference ranges from 0.4 to 0.5 and the energy level equilibrium coefficient ranges from 0.81 to 0.88. In summary, the oil transfer station subsystem is the weak link of energy utilization in the whole system.

(3) From the EUD, more than 95% of the supply energy in the oil transfer station subsystem is supplied by gas and the rest is

from electrical energy. The EUD can intuitively prove that the heating furnace is the weak link of energy utilization in the oil transfer station subsystem, and the corresponding improvement measures are proposed.

(4) After determining the heating furnace as the weak energy utilization equipment, further analysis should be carried out to find out the main factors affecting efficiency and energy level balance coefficient of the heating furnace. In view of these factors, more precise and effective improvement measures should be put forward to improve the rationality of energy utilization of the heating furnace, so as to improve the efficiency of energy utilization of the whole system, which has guiding significance for future energy saving optimization.

Nomenclature

Ω	Energy level
T	The temperature of the system
T_0	The ambient temperature
Q	The energy exchanged to each other from each unit
E	Mutual exergy
η_{ex}	Exergy efficiency of equipment
η_t	The energy efficiency of equipment
Ω_{im}	The energy level of input energy of equipment
Ω_u	The level of energy required for users
$\Delta\Omega$	The energy level difference
Ω_{in}	The energy level of logistics input
ξ_{Ω}	The energy level equilibrium coefficient
E_{m1}	The energy input by the production fluid on the wellhead
E_f	The fuel energy supplied to the heating furnace
E_{e1}	The electrical energy supplied to the efflux pump
E_{e2}	The electrical energy supplied to the water mixing pump
E_{xm1}	The logistical exergy of the mixture including the oil, gas and water input oil transfer station
E_{xf}	The fuel exergy consumed by the heating furnace
E_{xe1}	The fuel exergy consumed by electrical exergy supplied to the efflux pump
E_{xe2}	The fuel exergy consumed by the water mixing pump
E_{xm}	The logistical exergy
H	The enthalpy value of logistics
H_0	The enthalpy value of the environment
S	The entropy value of logistics
S_0	The entropy value of the environment
Ω_{out}	The logistical energy level output
E_{m2}	The energy output by the efflux fluid
E_w	The energy output by the circulating water
E_g	The energy output by the separating gas
E_{xm2}	The exergy of the water cut crude oil output of the oil transfer station
E_{xw}	The exergy of the water mixing after heating and pressurizing
E_{xg}	The exergy of the natural gas separated from the station
$\xi_{\Omega sub}$	The energy level equilibrium coefficient of the oil transfer station subsystem

$\xi_{\Omega p}$	The energy level equilibrium coefficient of the pipeline network subsystem
$\xi_{\Omega h}$	The energy level equilibrium coefficient of the heating furnace

CRedit authorship contribution statement

Qinglin Cheng: Conceptualization, Methodology. **Zhidong Li:** Writing - review & editing. **Daming Song:** Formal analysis. **Wei Gao:** Data curation, Writing - original draft. **Hao Wu:** Supervision, Software. **Hongjun Xie:** Supervision, Software. **Youwang Chen:** Visualization, Investigation. **Limin Gu:** Visualization, Investigation. **Yang Liu:** Conceptualization, Methodology.

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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