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Original Paper

Electric power generation technology of natural gas pressure reduction: Insights from black box-gray box hierarchical exergy analysis and evaluation method

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A B S T R A C T

Based on the “three box” exergy analysis model, a black box-gray box hierarchical exergy analysis and evaluation method is put forward in this paper, which is applied to evaluate the power generation technology of differential pressure produced by natural gas expansion. By using the exergy analysis theory, the black box - gray box hierarchical exergy analysis models of three differential pressure power generation technologies are established respectively. Firstly, the “black box” analysis models of main energy consuming equipment are established, and then the “gray box” analysis model of the total system is established. Based on the calculation results of exergy analysis indexes, the weak energy consumption equipment in the whole power generation process is accurately located. Taking a gas field in southwest China as an example, the comprehensive energy consumption evaluation of the three power generation technologies is carried out, and the technology with the best energy consumption condition among the three technologies is determined. Finally, the rationalization improvement measures are put forward from improving the air tightness, replacing the deflector and reducing the flow loss.

1. Introduction

In recent years, with the improvement of the consumption level all over the world, environmental problems have increasingly become the top priority of all countries. The global energy consumption structure has gradually transformed to the direction of low-carbon, environmental protection and sustainable development. As one of the cleanest primary energy sources, the annual consumption proportion of natural gas is also increasing (Li et al. 2016, 2019; Liu et al., 2008; Ma and Li, 2010; Wang, 2019; Xu et al., 2009; Zhao and Liu, 2020). Most of the natural gas in the gas field (Bluesky, 2020; Li et al., 2019; Tiangong, 2019) is transported by high-pressure pipeline from the gas reservoir to the wellhead, from the wellhead to the gas gathering station, from the gas gathering station to the natural gas treatment plant (Aghbashlo et al., 2018; Arabkoohsar et al., 2015), then processed as qualified commercial natural gas in the treatment plant, and exported to the pressure regulating station through the natural gas pipeline network (Rafiee and Hejazi, 2021), finally transported to the users (Arabkoohsar et al., 2017; Arabkoohsar and Andresen, 2018; Borelli et al., 2018; Lo Cascio et al., 2017). In many links among them, the pressure needs to be reduced by the pressure regulating valve, at the same time, the sudden drop of temperature leads to ice jam and other safety accidents, which causes amount of pressure energy loss and cold energy loss (Zeng et al., 2019; Yu et al., 2017; Chen et al., 2012). Therefore, scholars at home and abroad study and put forward the reasonable recycling of this part of wasted energy, in order to reduce the waste of resources and take a solid step for building a resource-saving and environment-friendly society.

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Recently, there are more and more research methods for utilizing natural gas pressure drop to generate power. From the perspective of energy, in 2013, Chen Yang (Chen, 2013) discussed the problem of burning natural gas but not fuel oil in Zhenhai Power Plant's gas turbine unit, the energy saving transformation process of using turbo expander to generate power from residual pressure instead of pressure reducing valve was simulated. The throttling loss was calculated about 500 kW h through energy analysis. In 2016, Huang (Huang et al., 2016) proposed a device of natural gas pressure difference power generation. Taking a gas transmission station of PetroChina as an example, it is calculated that more than 800000 kW h electricity can be generated every month. In 2017, Kolasiński P (Kolasiński et al., 2017) studied the process of using expander to recycle natural gas pressure energy in natural gas decompression station, and comprehensively analyzed the influence of different sizes of expander components and thermal properties of natural gas at the inlet and outlet of expander on the output power of expander. The results of energy analysis showed that the rolling piston expander can well recover the pressure energy of natural gas. From the perspective of technical economics, in 2012, Sanaye S (Sanaye and Nasab, 2012) took a city gate station of natural gas as an example, CHP system of cogeneration was used to replace the expansion valve, the actual annual benefit was taken as the objective function, the shortest payback period is 1.23 years. From the perspective of exergy analysis, in 2014, Kostowski WJ (Kostowski et al., 2014) combined the exergoeconomic analysis theory with the thermal ecological cost theory, and proposed a new method to evaluate the pressure energy power generation process of natural gas decompression station. In 2019, Olfati M (Olfati et al., 2019) proposed a new improvement scheme for the reconstruction of natural gas decompression station. Through calculation, it is found that the energy loss and exergy loss after the reformation were reduced by 33% and 15% respectively. According to the analysis methods of natural gas pressure power generation by scholars at home and abroad, although the analysis system from the perspective of energy is relatively perfect, it is not enough to evaluate the whole energy system from the perspective of energy quantity alone, and it needs to be further analyzed from the perspective of energy quality. There are many studies on the analysis method of energy quality at abroad, but few at home, and only a simple analysis and calculation has been carried out for equipment in the energy system. Therefore, it is urgent to find a new evaluation method to comprehensively and completely evaluate the natural gas pressure difference power generation system (Arabkoohsar et al., 2015).

Based on the “three box” exergy analysis method (Olfati et al., 2018; Farzaneh-Gord et al., 2014), a black box - gray box hierarchical exergy analysis and evaluation method is put forward in this paper, which can not only evaluate the energy consumption condition of each equipment from its own point of view, but also take the whole power generation system as the research object to evaluate the overall energy consumption from the entirety point of view. This method is also applied to the natural gas expansion differential pressure power generation system. Three different technologies suitable for natural gas expansion differential pressure power generation are proposed and this method is used to build and solve the model, the exergy efficiency, exergy loss and exergy loss rate of the three power generation technologies are calculated respectively. The energy consumption conditions of three power generation technologies are compared and analyzed and the optimal power generation technology is selected according to the specific examples. In the meantime, the weak link in the whole power generation process is located accurately, which lays a theoretical foundation for energy saving and consumption reduction of natural gas production and transportation.

2. Establishment of the model of differential expansion pressure power generation system

On the basis of establishing the general model of engineering exergy balance, according to three different demands of rough analysis, fine analysis and sub fine analysis, the “black box” analysis model, “white box” analysis model and “gray box” analysis model are defined respectively (Cheng et al., 2020; Golchoobian et al., 2021). On the basis of “three box” analysis method, this paper proposes a black box-gray box hierarchical exergy analysis and evaluation method. Firstly, the “black box” analysis models of each equipment are established according to the energy consumption conditions of each equipment in the system. All the individual “black box” models constitute the first level of the hierarchical method. The main function of this level is to evaluate the energy consumption of each equipment separately. Next, the first level guides the second level, in another word, the “gray box” analysis model of the whole system is established according to the “black box” analysis model of each equipment. The role of this level is to take the whole system as the research object, analyze the energy consumption of the whole system according to the exergy efficiency, exergy loss and other evaluation indicators, and finally determine the energy consumption condition in the system, in order to identify the weak links or equipment. At the same time, this method is used to calculate three different expansion differential pressure power generation technologies. According to the calculation results of exergy efficiency, exergy loss and other evaluation indexes, the technology with the best energy consumption condition among the three power generation technologies is found out, and the weak link in the process of power generation is determined.

2.1. Primary expansion differential pressure power generation technology

2.1.1. Physical model

Primary expansion differential pressure power generation technology is the basic technology in the field of natural gas pressure difference power generation. High pressure natural gas directly enters the expander for free expansion, which converts its own pressure energy into the mechanical energy of the expander, thus driving the generator to generate electricity. The technology has the advantages of simple technological process, less area occupancy, convenient operation and low requirement for manpower and material resources. The physical model is shown in the Fig. 1.

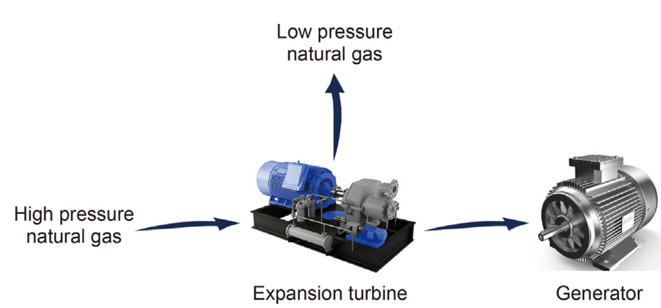

Fig. 1. Physical model of primary expansion differential pressure power generation technology.

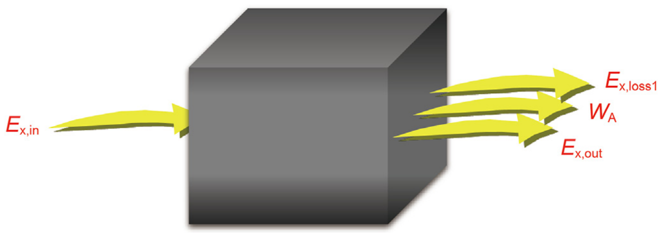

Fig. 2. “Black box” model of expander.

2.1.2. *Exergy analysis model*

1) “Black box” model of expander (shoen in Fig. 2)

$$E_{x,in} = E_{x,loss1} + E_{x,out} + W_A \quad (1)$$

where, $E_{x,in}$—Inlet exergy of expander, kJ/kg; $E_{x,out}$—Outlet exergy of expander, kJ/kg; $E_{x,loss1}$—Exergy loss of expander, kJ/kg; W_A—Exergy produced by shaft, kJ/kg。.

2) “Black box” model of generator (shown in Fig. 3)

$$W_A = E_{x,loss2} + E_{x,ele} \quad (2)$$

where, $E_{x,loss2}$—Exergy loss of generator, kJ/kg; $E_{x,ele}$—Electricity exergy, kJ/kg.

3) “Gray box” model of primary expansion differential pressure power generation technology (shown in Fig. 4)
4) Exergy efficiency

Exergy efficiency represents the effective utilization of exergy input into the system. In the primary expansion differential pressure power generation technology, the total exergy efficiency is as follows:

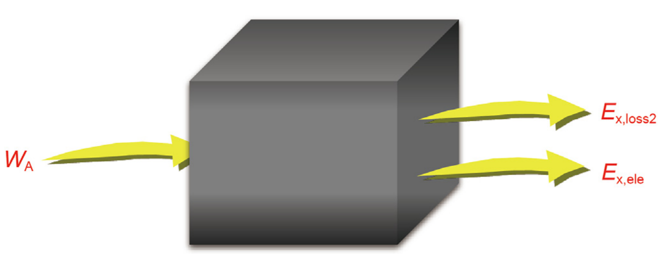

Fig. 3. Generator “black box” model.

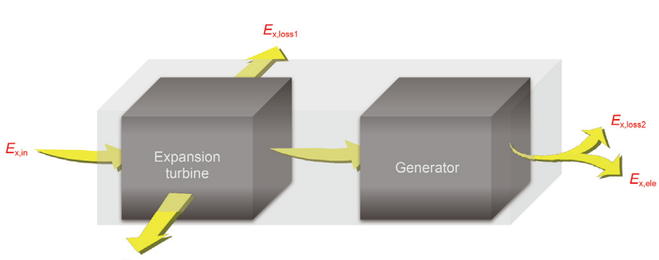

Fig. 4. “Gray box” model of primary expansion differential pressure power generation technology.

$$\eta_{ex} = \frac{E_{x,ele}}{E_{x,in} - E_{x,out}} \times 100\% \quad (3)$$

where, η_{ex}—Total exergy efficiency of the system,%.

5) Exergy loss

Exergy loss refers to the loss of exergy value. In the primary expansion differential pressure power generation technology, the total exergy loss is as follows:

$$E_{x,loss} = E_{x,loss1} + E_{x,loss2} = E_{x,in} - E_{x,out} - E_{x,ele} \quad (4)$$

where, $E_{x,loss}$—Total exergy loss of system, kJ/kg.

2.2. *Double expansion differential pressure power generation technology*

2.2.1. *Physical model*

The process flow of double expansion differential pressure power generation technology is as follows: high pressure natural gas is divided into two streams, one directly enters expander I for primary expansion and cooling, and drives generator I for power generation, and then enters the heat exchanger as cold flow; the other directly enters the heat exchanger as heat flow. After the two streams exchange heat in the heat exchanger, the cold stream heats up and then enters the pipeline for normal transportation. After the heat stream cools down, it enters the expander II for secondary expansion and then cools down again to below the dew point of natural gas. The by-product LNG is generated by liquefaction and drives the generator II to generate electricity. The physical model of this technology is shown in the Fig. 5.

Double expansion differential pressure power generation technology is an entirely new technology based on primary expansion differential pressure power generation technology. The advantage of this technology is that it not only recycles the pressure energy of natural gas to generate power, but also utilizes the cold energy produced by the depressurization process of natural gas, and the by-product LNG is produced, which can maximize the recovery and utilization of energy loss in the process of natural gas depressurization.

2.2.2. *Exergy analysis model*

The “black box” models of expander I, II and generator I, II refer to the primary expansion differential pressure power generation technology, which will not be repeated here.

2) “Black box” model of heat exchanger (shown in Fig. 6)

$$E_{x,loss3} = E_{x,in2} + E_{x,out1} - E_{x,out2} - E_{x,out3} \quad (5)$$

where, $E_{x,in2}$—Exergy of natural gas flowing into heat exchanger, kJ/kg; $E_{x,loss3}$—Exergy loss of heat exchanger, kJ/kg; $E_{x,out1}$—Exergy out of expander I, kJ/kg; $E_{x,out2}$—Exergy from heat exchanger to expander II, kJ/kg; $E_{x,out3}$—Exergy from heat exchanger to pipe, kJ/kg。

3) “Gray box” model of double expansion differential pressure power generation technology (shown in Fig. 7)
4) Exergy efficiency

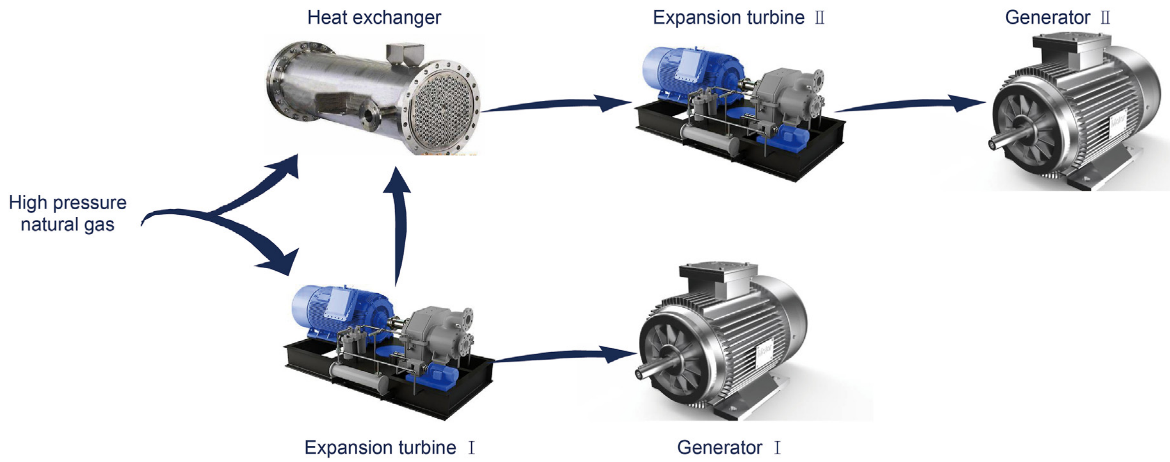

Fig. 5. Physical model of double expansion differential pressure power generation technology.

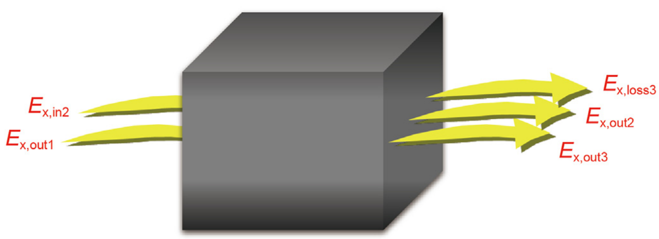

Fig. 6. “Black box” model of heat exchanger.

$$\eta_{ex} = \frac{E_{x,ele1} + E_{x,ele2} + E_{x,in2} - E_{x,out4}}{E_{x,in1} - E_{x,out3}} \tag{6}$$

where, $E_{x,in1}$—Exergy of natural gas flowing into expander I, kJ/kg; $E_{x,ele1}$—Electricity exergy generated by generator I, kJ/kg; $E_{x,ele2}$—Electricity exergy generated by generator II, kJ/kg; $E_{x,out4}$—Exergy from expander II into pipeline, kJ/kg.

5) Exergy loss

$$\begin{aligned} E_{x,loss} &= E_{x,loss1} + E_{x,loss2} + E_{x,loss3} + E_{x,loss4} + E_{x,loss5} \\ &= E_{x,in1} + E_{x,in2} - E_{x,out3} - E_{x,out4} - E_{x,ele1} - E_{x,ele2} \end{aligned} \tag{7}$$

where, $E_{x,loss1}$, $E_{x,loss2}$—Exergy loss of expander I, and generator I, respectively, kJ/kg; $E_{x,loss3}$—Exergy loss of heat exchanger, kJ/kg; $E_{x,loss4}$, $E_{x,loss5}$—Exergy loss of expander II and generator II respectively, kJ/kg.

2.3. Expansion and compression differential pressure power generation technology

2.3.1. Physical model

The process flow is as follows: high pressure natural gas is divided into two streams, one stream enters the expander to expand and drive the generator to generate electricity, and the other stream enters the compressor to pressurize and get high pressure natural gas. Then they exchange heat. The low-pressure natural gas enters the pipeline for normal transportation after heating up, and the by-product CNG is obtained after cooling of high-pressure natural gas. The physical model of this technology is shown in the Fig. 8.

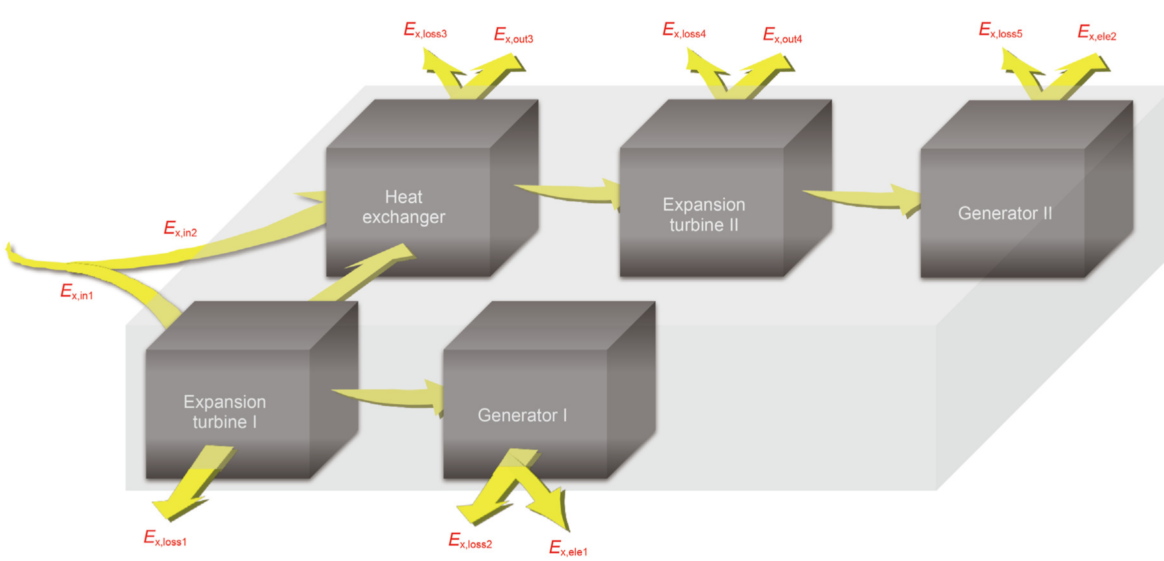

Fig. 7. “Gray box” model of double expansion differential pressure power generation technology.

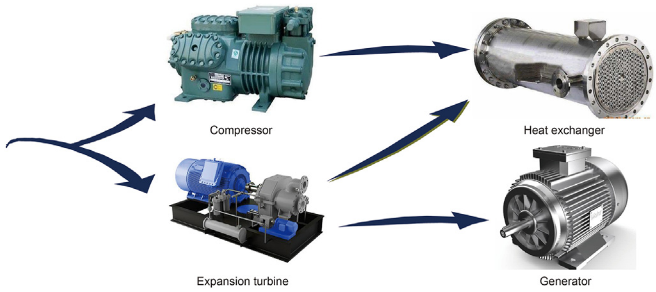

Fig. 8. Physical model of expansion and compression differential pressure power generation technology.

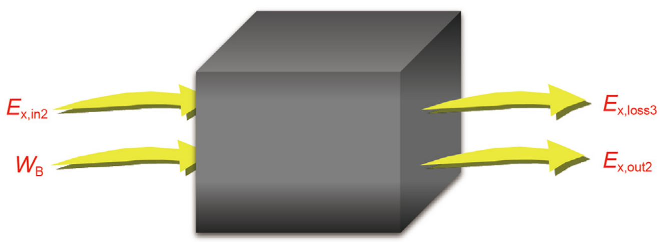

Fig. 9. Compressor “black box” model.

The advantage of this power generation technology is that it not only recycles the pressure energy of natural gas to generate power, but also utilizes the cold energy produced by the depressurization process of natural gas, which improves the utilization rate of energy, produces by-product CNG, and improves the economic benefits of the product.

2.3.2. Exergy analysis model

1) The “black box” model of expander, generator and heat exchanger refers to the double expansion differential pressure power generation technology, which will not be repeated here.
2) Compressor “black box” model (shown in Fig. 9)

$$E_{x,loss3} = E_{x,in2} + W_B - E_{x,out2} \quad (8)$$

where, $E_{x,in2}$—Exergy of nature gas flowing into compressor, kJ/kg; $E_{x,out2}$—Exergy of natural gas flowing out of expander, kJ/kg; $E_{x,loss3}$—Exergy loss of compressor, kJ/kg; W_B—Electricity exergy consumed by compressor, kJ/kg.

3) “Gray box” model of expansion and compression differential pressure power generation technology (shown in Fig. 10)
4) Exergy efficiency

$$\eta_{ex} = \frac{E_{x,ele} + E_{x,in2} - E_{x,out4}}{E_{x,in1} - E_{x,out3} + W_B} \times 100\% \quad (9)$$

where, $E_{x,in1}$—Exergy of natural gas flowing into expander, kJ/kg; $E_{x,ele}$—Electricity exergy generated by generator, kJ/kg; $E_{x,out3}$—Exergy from the heat exchanger into the pipe, kJ/kg; $E_{x,out4}$—Exergy of CNG produced, kJ/kg.

5) Exergy loss

$$\begin{aligned} E_{x,loss} &= E_{x,loss1} + E_{x,loss2} + E_{x,loss3} + E_{x,loss4} \\ &= E_{x,in1} + E_{x,in2} + W_B - E_{x,out3} - E_{x,out4} - E_{x,ele} \end{aligned} \quad (10)$$

where, $E_{x,loss1}$, $E_{x,loss2}$—Exergy loss of expander and generator respectively, kJ/kg; $E_{x,loss3}$—Exergy loss of compressor, kJ/kg; $E_{x,loss4}$—Exergy loss of heat exchanger, kJ/kg.

3. The solution of the model of differential expansion pressure power generation system

According to three kinds of black box-gray box hierarchical exergy analysis models established in the previous chapter, the exergy analysis model is solved by taking a gas field in southwest China as an example.

3.1. Basic parameters

Taking a natural gas field in southwest China as an example, the

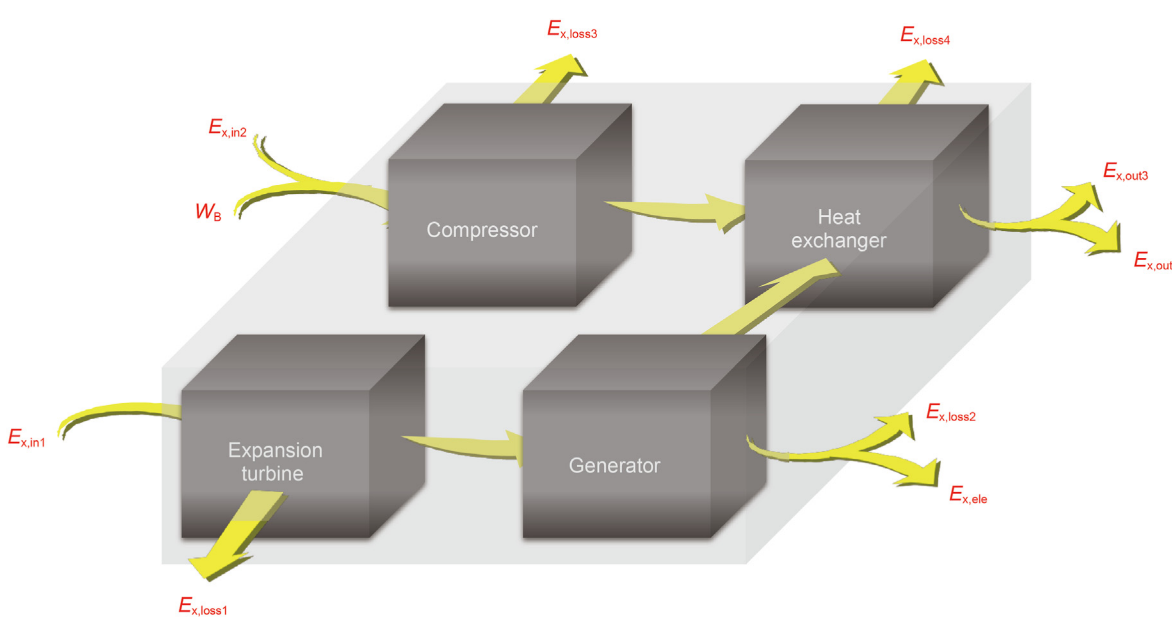

Fig. 10. “Gray box” model of expansion and compression differential pressure power generation Technology.

Table 1
Components of natural gas.

Component	Molecular formula	Mole fraction
Methane	CH_4	0.9776
Ethane	C_2H_6	0.0089
Propane	C_3H_8	0.0022
i-Butane	C_4H_{10}-2	0.0006
n-Butane	C_4H_{10}-1	0.0006
i-Pentane	C_5H_{12}-2	0.0004
n-Pentane	C_5H_{12}-1	0.0004
n-Hexane	C_6H_{14}-1	0.0004
Nitrogen	N_2	0.0082
Water	H_2O	0.0001
Carbon-Dioxide	CO_2	0.0005
Methyl-Mercaptan	CH_3SH	0.0001

total natural gas transmission volume is 2300000Nm^3/d, the gas temperature is 30 °C, the pressure is reduced from 10 MPa to 1.9 MPa, the local ambient temperature is 25 °C, and the atmospheric pressure is 0.1 MPa. The specific natural gas components are shown in Table 1.

3.2. Model solution

3.2.1. Primary expansion differential pressure power generation technology

The technological process is simulated by Aspen plus. Firstly, the process flow model of primary expansion differential pressure power generation technology is established. In the software, the expander and generator are combined into one equipment, and the model is shown in the Fig. 11.

The required parameters are entered in the input interface of materials flow 1, including pressure, temperature, mole fraction of each component and flow rate, the simulation results are shown in the Table 2.

Using the traditional energy analysis method and the black box-gray box hierarchical exergy analysis method, combined with the parameters in the Table 2, the model of primary expansion differential pressure power generation technology is solved, and the calculation results of relevant energy consumption evaluation indexes are shown in the Table 3. In order to reflect the weak link or equipment in power generation system more intuitively, a new

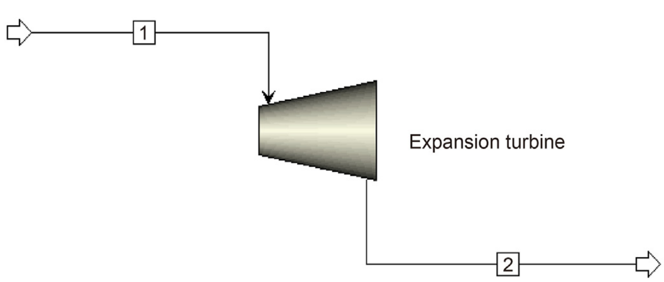

Fig. 11. The model of primary expansion differential pressure power generation technology.

Table 2
Simulation parameter results.

Parameter	Value
Inlet mass enthalpy (h_1)	−4584.9 kJ/kg
Outlet mass enthalpy (h_2)	−4795.29 kJ/kg
Inlet mass entropy (s_1)	−7.36 kJ/(kg·K)
Outlet mass entropy (s_2)	−6.92 kJ/(kg·K)

Table 3
Calculation results of the primary expansion differential pressure power generation technology.

Parameter	Value
Net power generation	1.64×10^8 kJ/d
Energy efficiency	78.00%
Exergy efficiency	48.34%
Exergy loss	1.75×10^8 kJ/d

evaluation index-exergy loss rate is added, which is the ratio of the exergy loss of a process or link to the total exergy loss of the system.

Through calculation, it is found that the energy efficiency of primary expansion differential pressure power generation technology is 78.00%, while the exergy efficiency is far less than the energy efficiency, which is only 48.34%. It can be seen that it is very necessary to analyze the power generation technology from the perspective of energy quality, which can make a more comprehensive and complete analysis and evaluation of power generation technology. As the main energy consumption equipment of the power generation technology is only expander, the exergy loss of expander is 1.75×10^8 kJ/d, and the exergy loss rate of expander is 100%.

3.2.2. Double expansion differential pressure power generation technology

Under the condition of adopting the double expansion differential pressure power generation technology, natural gas is divided into two streams. One stream flows into the heat exchanger with a flow rate of 943000 m^3/d, and the other stream flows into the expander with a flow rate of 1357000 m^3/d. Similar to the primary expansion differential pressure power generation technology, the process flow model of the double expansion differential pressure power generation technology is established in Aspen Plus, as shown in the Fig. 12.

The simulation results of mass enthalpy and mass entropy are listed in Table 4.

The results of energy analysis and exergy analysis of the double expansion differential pressure power generation technology are shown in Fig. 13.

From the whole point of view, through the calculation of the black box-gray box hierarchical exergy analysis models of double expansion differential pressure power generation technology, the total exergy loss is 1.22×10^8 kJ/d, and the total exergy efficiency of the system is 57.39%. It is necessary to analyze the energy consumption of each equipment in the system, so as to find out the equipment with weak energy consumption, and make targeted improvement with the aim of increasing the overall energy-saving efficiency of the system.

From the local point of view, the exergy loss of expander is the largest, and the exergy efficiency is relatively low, the exergy loss rate of expander I is 68.28%, and that of expander II is 25.00%, the total exergy loss rate of expanders is 93.28%. The expanders are considered to be the weak equipment of energy consumption in the system. However, the exergy loss of the heat exchanger is relatively low, with a better energy consumption status, the exergy efficiency is relatively high and the exergy loss rate is only 6.72%. According to the above analysis, the expander is the weak energy consumption equipment in the whole power generation process, which can be improved pertinently.

3.2.3. Expansion and compression differential pressure power generation technology

Under the condition of adopting the expansion and compression differential pressure power generation technology, the inflow of

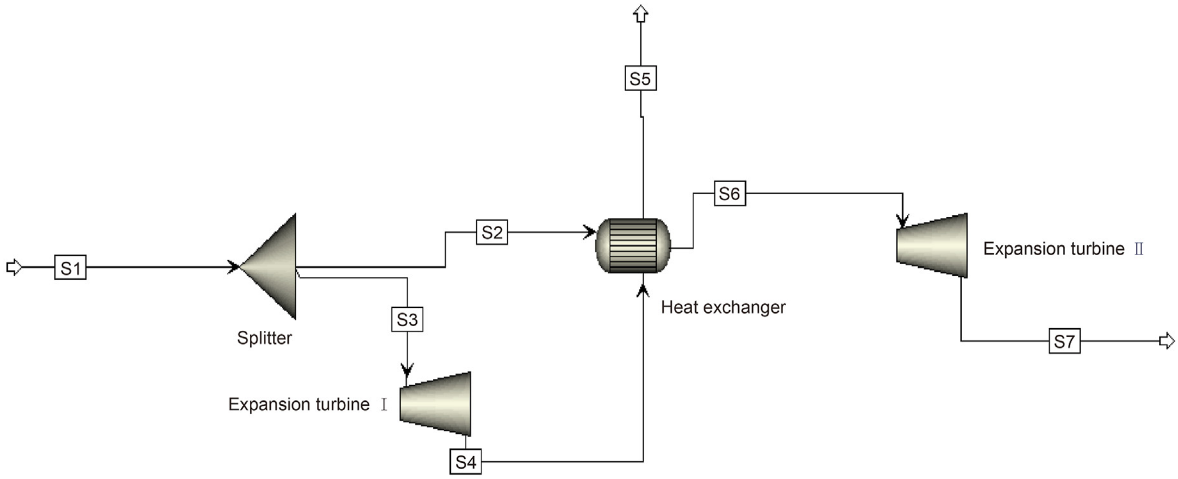

Fig. 12. The model of the double expansion differential pressure power generation technology.

Table 4
Simulation parameter results.

Exergy flow	Mass enthalpy, kJ/kg	Mass entropy, kJ/(kg·K)
S1	−4584.9	−7.36
S2	−4584.9	−7.36
S3	−4584.9	−7.36
S4	−4795.29	−6.92
S5	−4533.14	−5.77
S6	−4962.14	−8.84
S7	−5041.9	−8.64

natural gas is divided into two streams. One stream flows into the compressor with a flow rate of 690000 m^3/d, and the other stream flows into the expander with a flow rate of 1610000 m^3/d. The process flow model is established in Aspen Plus, as shown in the Fig. 14.

The simulation results of mass enthalpy and mass entropy are listed in Table 5.

According to the parameters in the Table 5, the results of energy analysis and exergy analysis of the expansion and compression

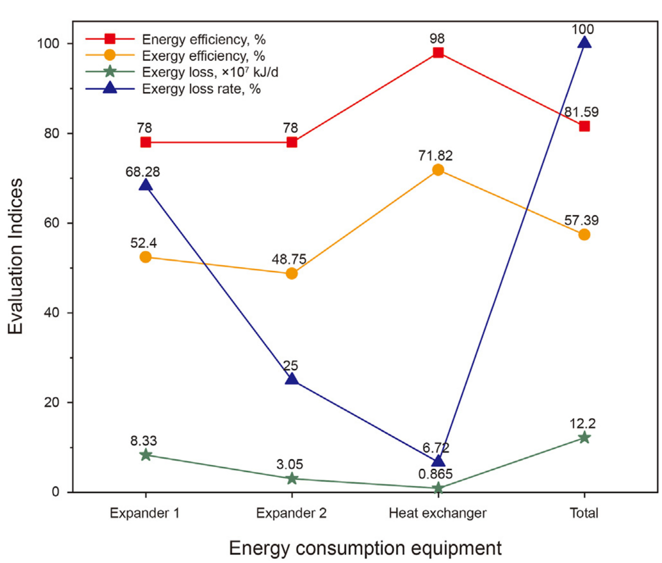

Fig. 13. Calculation results of the double expansion differential pressure power generation technology.

differential pressure power generation technology are shown in Fig. 15.

According to the calculation results of this technology, the total exergy efficiency is 45.69%, and the total exergy loss is 1.57 × 10^8 kJ/d. The overall energy consumption is poor. The expander has the lowest exergy efficiency and the largest exergy loss among all energy consuming equipment, the exergy loss rate is the highest, which is 78.34%. In summary, the expander is considered to be the weak energy consuming equipment in the process of power generation. Therefore, targeted improvement measures should be taken.

3.2.4. *Analysis and comparison of calculation results of three power generation technologies*

The energy analysis and exergy analysis results of the three power generation technologies are shown in Fig. 16.

According to the calculation results of exergy analysis, it can be seen that the exergy efficiency of the double expansion differential pressure power generation technology is 57.39%, and the total exergy loss is 1.22 × 10^8 kJ/d. After analysis, the reason is that in the process of expansion power generation, the technology not only consumes no extra energy, but also produces additional effective exergy product-LNG, while in the expansion and compression differential pressure power generation technology, the compressor consumes additional power, which leads to the low exergy efficiency of the total system. Therefore, under the current operating conditions, it is recommended to use the double expansion differential pressure power generation technology to recycle the pressure energy of natural gas. At the same time, in the three power generation technologies, the expanders are all the equipment with the largest exergy loss rate, so the expander is regarded as the equipment with weak energy consumption, and the corresponding improvement measures need to be put forward.

3.3. *Improvement measures*

Through calculation and analysis, it is determined that the expander is the weak energy consumption equipment in the expansion pressure difference power generation technology. The following puts forward some improvement measures for the expander to improve its energy utilization efficiency.

3.3.1. *Improve gas tightness*

Improve the gas tightness of the expander device, including adjusting the clearance between the impeller and the shell and

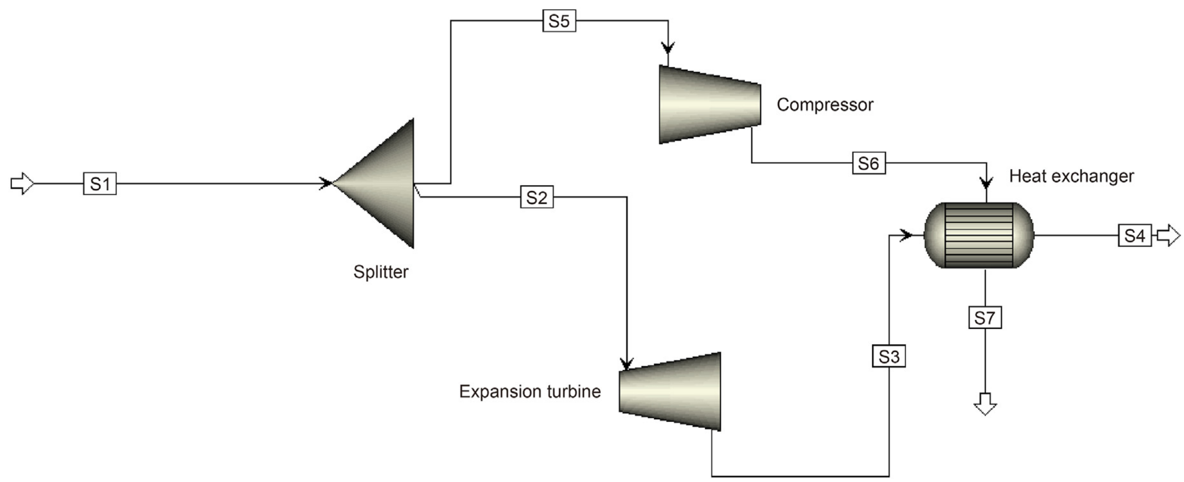

Fig. 14. The model of expansion and compression differential pressure power generation technology.

Table 5
Simulation parameter results.

Exergy flow	Mass enthalpy, kJ/kg	Mass entropy, kJ/(kg·K)
S1	−4584.9	−7.36
S2	−4584.9	−7.36
S3	−4795.29	−6.92
S4	−4533.14	−5.77
S5	−4584.9	−7.36
S6	−4445.58	−7.27
S7	−5057.27	−9.45

between the diffuser and the working wheel, can not only reduce the loss of internal leakage, but also make the pressure of natural gas more efficiently converted into the mechanical energy of the impeller, and improve the utilization rate of energy.

3.3.2. Replace the deflector

Check whether the deflector is damaged, mainly in the flow channel, the incision, and the deflector. The fault of these positions will cause a great deviation in the enthalpy drop and kinetic energy increase of the internal gas, which greatly reduces the energy conversion efficiency of natural gas. By replacing the deflector, the outlet pressure can be reduced and the energy conversion efficiency of internal natural gas can be enhanced.

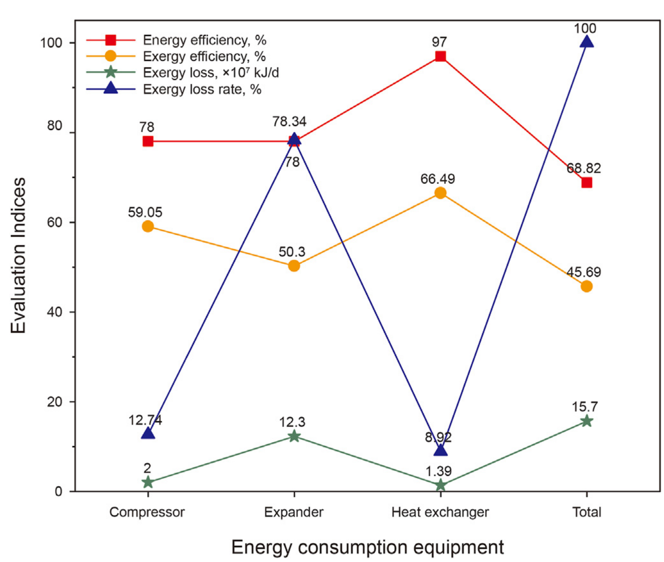

Fig. 15. Calculation results of the expansion and compression differential pressure power generation technology.

3.3.3. Reduce flow loss

There are many reasons that affect the flow loss, including whether the flow channel of expander matches the flow direction of natural gas, the smoothness of the internal surface of the flow channel, the internal wear of the flow channel, the friction loss of various parts of the equipment, etc. It is necessary to clean the inside of the flow channel to remove the impurities on the surface. If the wear is serious, it needs to be replaced in time. Lubricating oil can be added at the impeller rotor to reduce the friction loss. Reducing the flow loss is helpful to the more efficient recovery and utilization of natural gas pressure energy and cold energy.

4. Conclusions

Based on the establishment and solution of three different models of natural gas expansion pressure difference power generation, the following conclusions are obtained.

(1) Based on exergy analysis theory and “three box” analysis theory, exergy analysis method is combined with “three box” analysis model, a black box-gray box hierarchical exergy analysis and evaluation method is proposed. By establishing the black box-gray box hierarchical exergy analysis model, the energy consumption conditions of three different natural gas expansion pressure difference power generation technologies are evaluated and compared. This method can not only evaluate the energy consumption condition of each equipment from its own point of view, but also take the whole power generation system as the research object to evaluate the overall energy consumption from the entirety point of view.

(2) Taking a gas field in southwest China as an example, the models of three technologies are established and solved respectively. Firstly, the “black box” analysis models of all energy consuming equipment are established, and each energy consuming equipment in the system is evaluated according to a separate “black box” model, so as to form the first level. Then, the first level guides the second level, that is, in terms of the “black box” model established by the upper level, and the energy consuming conditions of equipment are

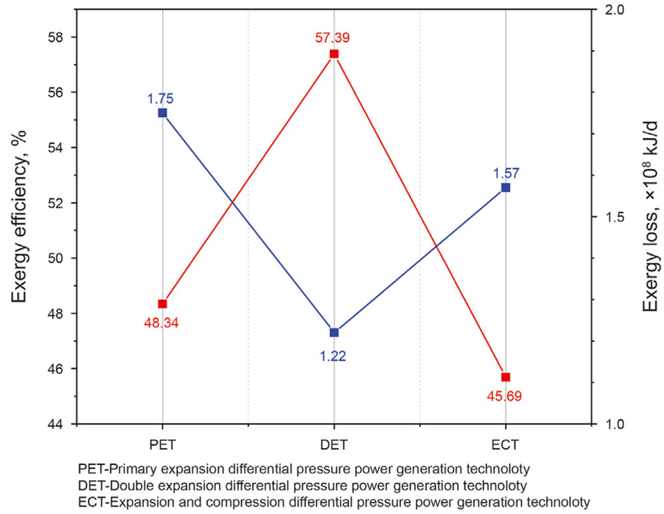

Fig. 16. Comparison of energy analysis and exergy analysis results of three technologies.

taken into consideration, the “gray box” exergy analysis model of the total system is established, which forms the second level. By calculating and analyzing the exergy analysis indexes of each energy consuming equipment in the system, it is found that the exergy loss rate of expander is the largest among all the three power generation technologies, which are 100%, 93.28% and 78.34% respectively, so the expander is located as the equipment with weak energy consumption in the whole power generation process. By comparing the exergy analysis results of the three technologies, it is concluded that the total exergy loss of the double expansion differential pressure power generation technology is 1.22×10^8 kJ/d, which is the lowest among the three technologies, and the total exergy efficiency of the system is 57.39%, which is the highest among the three technologies. Therefore, the double expansion differential pressure power generation technology is recommended for the natural gas condition in this example.

(3) In view of the determined weak energy consumption equipment, the reasonable improvement measures are put forward, and suggestions are given from three aspects: improving the air tightness, replacing the deflector and reducing the flow loss, which is helpful to better recycle the pressure energy and cold energy lost in the depressurization process of natural gas, which has a positive effect on promoting the energy saving and consumption reduction of natural gas production and transportation, and even the whole gas field.

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Nomenclature

$E_{x,in}$	Inlet exergy of expander, kJ/kg
$E_{x,out}$	Outlet exergy of expander, kJ/kg
$E_{x,loss1}$	Exergy loss of expander, kJ/kg
W_A	Exergy produced by shaft, kJ/kg
$E_{x,loss2}$	Exergy loss of generator, kJ/kg
$E_{x,ele}$	Electricity exergy, kJ/kg
η_{ex}	Total exergy efficiency of the system,%
$E_{x,loss}$	Total exergy loss of system, kJ/kg
$E_{x,in2}$	Exergy of natural gas flowing into heat exchanger, kJ/kg
$E_{x,loss3}$	Exergy loss of heat exchanger, kJ/kg
$E_{x,out1}$	Exergy out of expander I, kJ/kg
$E_{x,out2}$	Exergy from heat exchanger to expander II, kJ/kg
$E_{x,out3}$	Exergy from heat exchanger to pipe, kJ/kg
$E_{x,in1}$	Exergy of natural gas flowing into expander I, kJ/kg
$E_{x,ele1}$	Electricity exergy generated by generator I, kJ/kg
$E_{x,ele2}$	Electricity exergy generated by generator II, kJ/kg
$E_{x,out4}$	Exergy from expander II into pipeline, kJ/kg
$E_{x,loss1}$, $E_{x,loss2}$	Exergy loss of expander I, and generator I, respectively, kJ/kg
$E_{x,loss4}$, $E_{x,loss5}$	Exergy loss of expander II and generator II respectively, kJ/kg
$E_{x,in2}$	Exergy of nature gas flowing into compressor, kJ/kg
$E_{x,out2}$	Exergy of natural gas flowing out of expander, kJ/kg
$E_{x,loss3}$	Exergy loss of compressor, kJ/kg
W_B	Electricity exergy consumed by compressor, kJ/kg
$E_{x,in1}$	Exergy of natural gas flowing into expander, kJ/kg
$E_{x,ele}$	Electricity exergy generated by generator, kJ/kg
$E_{x,out3}$	Exergy from the heat exchanger into the pipe, kJ/kg
$E_{x,out4}$	Exergy of CNG produced, kJ/kg
$E_{x,loss1}$, $E_{x,loss2}$	Exergy loss of expander and generator respectively, kJ/kg
$E_{x,loss3}$	Exergy loss of compressor, kJ/kg
$E_{x,loss4}$	Exergy loss of heat exchanger, kJ/kg

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