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Research Article

Research on the Safe Operation of Natural Gas Pipeline Network Based on an Improved Multi-Objective Comprehensive Evaluation Method

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Abstract: The climate change, industrial production and other factors will affect the safety and steady operation of natural gas pipeline network in some cold areas. The aim of this study is to evaluate the operation scheduling schemes for the pipeline network. To this end, the effect of temperature change, pipeline pressure drop, transportation volume and gas storage capacity in the end section on the safety operation of natural gas pipeline network were comprehensively considered and then a multi-objective comprehensive evaluation model was established. In the presented model, for the sake of obtaining the operation schemes which satisfy the practical requirements, the TGNET software was adopted to build the natural gas pipe network simulation model; the Aspen HYSYS software was used to calculate the moisture content and provide the input data for the comprehensive evaluation model; the improved Analytic Hierarchy Process was utilized to establish the judgment matrix; the Grey Correlation method was selected to calculate the comprehensive correlation degree. Finally, the conclusion can be drawn that the multi-objective comprehensive evaluation method can be applied well to the decision on the natural gas pipeline network operation schemes for the cold area, so as to provide a reference approach for the future natural gas pipe network optimal operation.

Keywords: Comprehensive evaluation method, decision scheme, multi-objective, natural gas pipeline network, safe operation, temperature change

INTRODUCTION

With the development of Chinese economic growth and industrial production, the gas consumption of natural gas pipeline network users increased year by year and due to the seasonal gas heterogeneity, natural gas load in winter is higher than that in summer, which may lead to the existing natural gas network cannot meet the gas demand of users in different season, thus affecting the safe operation of the pipeline network. For example, in the northern part of *Xinjiang province*, due to the thermal recovery of heavy oil in the winter (40% of the total gas consumption), the winter gas consumption is significantly higher than that in the summer. Meanwhile, it is affected by the winter temperature, the natural gas is easily formed gas hydrate during the transportation process and then the gas hydrate may block the pipeline, valves and etc., which affecting the operation of pipeline network safety. Therefore, it is necessary for this kind of natural gas pipeline network which is highly affected by seasons and higher consumption by industry to do some research on operation schemes.

Usually, the single-objective evaluation method was used to make a decision on natural gas pipeline network's operation. For example, the minimum operating cost of the compressor stations as the objective function, or to the maximum operating efficiency of natural gas pipeline as the objective function to establish a mathematical model according to the research by Liu *et al*. (2009) and Liu (2014). However, the gas pipeline network has its own characteristics such as structural complexity and function integrated. It is also a system that has multi-input, multi-output, multi-objective, multi-parameters and multi-disturbance. Therefore, Yao *et al*. (2013) had found that it needed to make a decision based on a large amount of information and engineering management. Obviously, the single-objective evaluation method cannot meet the demand of large-scale gas network safe operation optimization. So, it is necessary to apply the multi-objective comprehensive evaluation method to gas network safe operation optimization by Yang (2006).

Generally, the comprehensive evaluation method is applied to pipeline corrosion harm evaluation and risk

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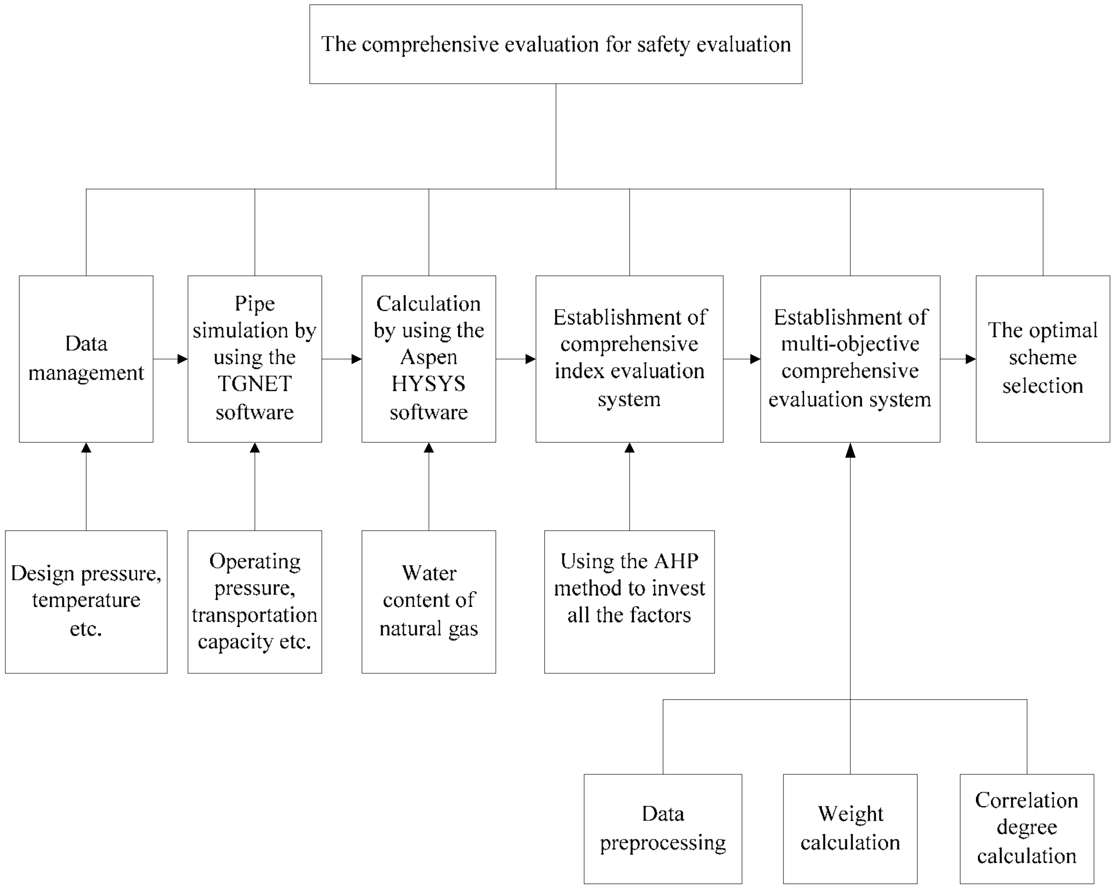

Fig. 1: Comprehensive evaluation system of safety operation

evaluation at present, while little research on natural gas pipeline network's operation optimizing. Ai *et al*. (2011) used the multi-objective decision-making optimizing technology to comprehensively evaluate gas pipeline network. Pipeline pressure, gas storage capacity, compressor energy consumption were taken into consideration. Zhu *et al*. (2012) built a multi-objective optimizing model, which considered gas company benefits, users benefits and government regulation on natural gas price. Cai (2014) put simulation software SPS into use. According to the SPS software simulating parameters, such as pipeline pressure and flow, a multi-objective comprehensive assessment was made to evaluate peak-load shaving of large-scale natural gas pipeline network.

Considering the low temperature and high gas load in the winter in northwest and northeast regions of China, such as *Xinjiang province* and *Inner Mongolia province*. This study imported four indexes which were the pipeline pressure variation, the gas storage capacity of long-distance pipeline, the maximum transportation capacity and the hydrate harm due to extreme low temperature. A multi-objective comprehensive evaluation model was built to estimate different operation scheduling schemes. The TGNET software was used to emulate the natural gas pipeline network and the Aspen HYSYS software was applied to calculate water content of natural gas.

THE MULTI-OBJECTIVE EVALUATION MODEL

According to the multi-objective evaluation model, which considers all factors that influent the running system, a comprehensive evaluation system can be built by He *et al*. (2011). We have found that this system is widely used in many regions, such as social aspects or economic aspects. Similarly, this system also can be used in the area of gas transportation scheme decision making.

Methods and steps: Based on the multi-objective evaluation theory and natural gas pipeline transportation theory, a frame of multi-objective comprehensive evaluation system is set and as is shown in Fig. 1.

The steps of model establishment and calculation are as follows:

(1) Data management. Data contains natural gas physical parameters, climatic variation factors, friction loss coefficient, heat transfer coefficient,

pipeline design pressure and operating pressure, transportation capacity and others. It is prepared for gas pipeline network data input.

(2) Establishment of the pipeline network's emulation system and simulation of operation schemes. The TGNET software is implied to build the pipeline network's emulation system based on data from step (1). The initial conditions, the boundary conditions and the constraint conditions are imported when using the TGNET software to meet the demand of the pipeline network's technological characteristics. The simulation results such as gas pipeline network pressure, operating temperature, flow rate, gas storage capacity etc., are input data of a multi-objective comprehensive evaluation model.

(3) Hydrate prediction. Using the data from step (2) and the parameters from step (1), the Aspen HYSYS software is introduced to calculate water content of the natural gas pipeline network. Therefore, the hydrate formation condition can be predicted.

(4) Establishment of the comprehensive index evaluation system. The Analytic Hierarchy Process (AHP) method is introduced to investigate all the factors which affect safe operation of the gas network running system.

(5) Establishment of the multi-objective comprehensive evaluation systems. Data from step (2) and data from step (3) are imported to the comprehensive index evaluation system which is built by step (4). Hence multi-objective comprehensive evaluation systems can be set up by using mathematical method.

(6) The optimal scheme selection. From the results of step (5), the best running scheme can be selected.

Establishment of comprehensive evaluation system: After using the TGNET software for simulating pipeline network simulation, the Aspen HYSYS software for calculating the natural gas water content and the AHP method of establishing a comprehensive evaluation index system, a multi-objective comprehensive evaluation system can be established. Before that, the weight calculation and the comprehensive correlation calculation are necessary.

This study introduces an improved weighting method based on AHP method. It is given as follows:

(1) Constructing the initial judgment matrix A, set $A=\left[a_{i,j}\right]$, which $a_{i,j}=1/a_{j,i}$

(2) Solving the anti-symmetric matrix B of the matrix A:

$$B=\lg A\,(b_{i,j}=\lg a_{i,j}) \tag{1}$$

(3) Solving the optimal transfer matrix C of the matrix B:

$$c_{i,j}=\frac{1}{n}\sum_{k=1}^{n}\left(b_{i,k}-b_{j,k}\right) \tag{2}$$

(4) Deriving the homogeneous matrix v of the matrix A:

$$v_{i,j}^{*}=10^{c_{i,j}} \tag{3}$$

(5) Solving the eigenvectors of v to obtain the weight values of the influencing factors of a given initial matrix. In this study, the square root method was adopted to solve the weight of the judgment matrix which conforms to the consistency test.

Computing the product of each row of the matrix v:

$$M_i=\prod_{j=1}^{n}v_{i,j}\quad(i=1,2,\cdots,n) \tag{4}$$

Square root:

$$\overline{W}_i=\sqrt[n]{M_i} \tag{5}$$

Doing normalization for the vector $\overline{W}=\left(\overline{W_1},\overline{W_2},\cdots,\overline{W_n}\right)^T$:

$$W_i=\frac{\overline{W}_i}{\sum_{i=1}^{n}\overline{W}_i} \tag{6}$$

$W=(W_1, W_2,\ldots, W_n)$ is the weight vector.

The natural gas pipeline network is a complex system, among which the indicators need to dimension. To this end, the Grey Correlation Analysis was adopted to establish a comprehensive comparison mechanism by Liu *et al*. (2014). The method consists of the following major steps:

Setting up operation schemes: The TGNET software is introduced to calculate the pipe network operation plans as shown in Fig. 2. The Aspen HYSYS software is used to calculate moisture content. The process parameters of the various schemes are denoted as node pressure: P_1, P_2,……, P_n, node flow: Q_1, Q_2,……Q_n, operating temperature: T_1, T_2, ……, T_n. A set of process parameters is formed as $\{P_i\}$, $\{Q_i\}$, $\{T_i\}$ *et al*.:

Constructing the pre-selected scheme sequences: The set of indicators for the pre-selected scheme are constructed from the scheme generated in Fig. 2:

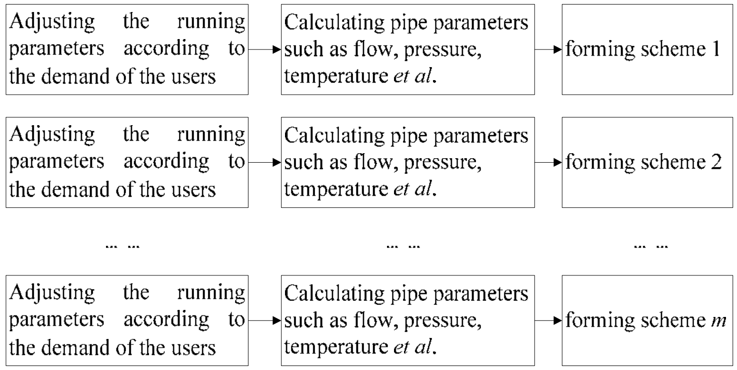

Fig. 2: The running project design

$$\begin{cases} \{x_1\} = \{x_1(1), x_2(2), \cdots, x_n(n)\} \\ \{x_2\} = \{x_2(1), x_2(2), \cdots, x_2(n)\} \\ \quad\quad \cdots\cdots \\ \{x_m\} = \{x_m(1), x_m(2), \cdots, x_m(n)\} \end{cases} \tag{7}$$

where, x_1, x_2,.., x_m show scheme 1 to scheme m respectively and n is the number of indicators.

Constructing one sequence of ideal indicators: The ideal scheme is selected from the pre-selected program of step (2). Selection method: trends upward is better, representing the more upward the better the indicator is, such as economic benefits and so on. Trends down is better, representing the more downward the better the indicator is, such as pressure variation and so on. Trends intermediate is better. In accordance with the principles, this study selects the optimal indicators to form the ideal sequence:

$$\{x_0\} = \{x_0(1), x_0(2), \cdots, x_0(n)\}$$

Data normalization: In order to unify the indicators' unit and to realize the comparability of data series, this study adopts the method of minimization normalization presented by Li *et al*. (2004) to carry out dimensionless processing on each indicator.

Calculating the comprehensive correlative degree between the comparison sequence and the ideal sequence: The Grey Correlative Degree is a measurement to describe tightness between the different sequences of the system and it is a trend measurement of the system. In this study, we used the Den's correlation coefficient, which is firstly used by Li *et al*. (2012), as follows:

$$\xi_j(k) = \frac{\min\limits_j \min\limits_k \left|x_0(k) - x_j(k)\right| + \rho \max\limits_j \max\limits_k \left|x_0(k) - x_j(k)\right|}{\left|x_0(k) - x_j(k)\right| + \rho \max\limits_j \max\limits_k \left|x_0(k) - x_j(k)\right|} \tag{8}$$

where, $\xi_j(k)$ represents the relative difference between the $x_j(k)$ factor of the comparison program sequence $\{x_j(k)\}$ and the $x_0(k)$ factor of the ideal program sequence and the relative difference in this form is called the correlation coefficient of $x_j(k)$ to $x_0(k)$. The parameter ρ is called resolution factor, its value is taken as 0.5. After the processing, a grey correlation coefficient matrix can be listed as follows:

$$\xi = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \xi_{m1} & \xi_{m2} & \cdots & \xi_{mn} \end{bmatrix} \tag{9}$$

Selecting the optimal solution: For the comparison sequence is more, the number of relevance $\xi_j(k)$ will be a lot. To this end, the weighted average method in the grey system is used to deal with the information centrally, which is:

$$R_j = \frac{1}{n}\sum_{k=1}^{n} W_k \xi_j(k) \tag{10}$$

In the formula, R_j is called the comprehensive correlative degree of the comparison sequence $\{x_j\}$, compared the ideal sequence $\{x_0\}$. The bigger the R_j is, the $\{x_j\}$ is more closer to the $\{x_0\}$ and the scheme is better.

According to the size of the R_j value of each comparison sequence, the various schemes are sorted by comprehensive correlative degree. The greater the comprehensive correlative degree is, the closer the comparison scheme and the ideal scheme, that is, the greatest comprehensive correlative degree of the comparison scheme is the best solution.

APPLICATION

Pipeline network overview: The natural gas pipeline network stretch across more than 300 km, about 180 km north-south. It has extreme weather with the annual maximum temperature of 43°C, the annual minimum

Table 1: Maximum throughput simulation results

	Peaking gas source		Industrial users
Pre-selection	C	D	Sum
Scheme 1	0	430	317.17
Scheme 2	50	390	327.17
Scheme 3	100	349	336.17
Scheme 4	150	296	333.17
Scheme 5	200	243	331.17
Scheme 6	250	191	328.17
Scheme 7	300	139	326.17
Scheme 8	350	85	322.17
Scheme 9	400	28	315.17
Scheme 10	424	0	311.17

temperature of -36°C and the average annual temperature of 8°C. From the gas supplies to the gas users, there are 31 pipelines with the total length of 1292.3 km. The whole pipeline network contains gas of 1130×10^4 m^3/d and the pipe network is operating under high pressure all year round. There are 22 gas supplies, among which gas supplies numbering A, B, C, D are used as peak shaving gas supply source (where gas supply C, D are the main peak shaving gas source and they download natural gas from the same source). The gas supplies A, B, C, D are mainly located in the southern pipeline system.

The natural gas pipeline system has 25 users, of which there are 4 large industrial users named E, F, G, H (now the typical gas consumption of 235.8×104 m^3/d), located in the northwest of the pipe network system. The gas consumption amount of the 4 industrial users accounts for more than 20% of the total gas consumption amount of all users, showing a rapid upward trend year by year. At the same time, the pipeline system has not yet form a circular pipe network to ensure the safety of gas usage. Therefore, we need to give this pipeline system a comprehensive evaluation of safe operation.

Simulation: The simulation model of the pipeline network system was established by using the TGNET software. The initial conditions, boundary conditions and constraint conditions were set according to the actual situation and the calculation accuracy of the pipe network system model was verified. The calculated error of the system is less than 3%, which is considered to conform to reality. The calculation model only considered the change of the industrial users E, F, G, H, while gas supply and other gas users remain unchanged.

Calculating the maximum gas consumption: Since C and D are from the same gas source, the supply of natural gas to the peak gas source C is gradually increased and the supply of the peak gas source D is gradually reduced. The results which are listed in Table 1 can be obtained.

From Table 1, it can be seen that when the peak gas source C downloads the volume of natural gas as 100×10^4 m^3/d, the peak gas source D downloads the volume of natural gas as 349×10^4 m^3/d, the maximum gas supplies of E, F, G and H is 336.17×10^4 m^3/d, which is 100.37×10^4 m^3/d more than the typical working condition of 235.8×10^4 m^3/d. In the 10 largest gas supply schemes, the gas supply trends up is better. Conclusion: Scheme 3> Scheme 4> Scheme 5> Scheme 6> Scheme 2> Scheme 7> Scheme 8> Scheme 1> Scheme 9> Scheme 10.

The pipeline and station pressure fluctuations calculation: Pressure fluctuation follows the "bucket principle", that is, the entire pipeline network uniform pressure safety index is the pipe network in most insecure pipe pressure safety index (Li *et al*., 2012). The maximum pressure fluctuation is the C-D line between the peak gas source C and the peak gas source D and the pressure drop results are shown in Table 2.

It can be seen from Table 2 that the pressure in station D from scheme 1 to scheme 5 is higher than that of station C and the natural gas flow is from station D to station C. The pressure in station D from scheme 6 to scheme 10 is lower than that in station C and the natural gas flow is from Station C to station D. Pipeline pressure fluctuates trend down is better, so the conclusion is that, Scheme 6> Scheme 5> Scheme 7> Scheme 4> Scheme 8> Scheme 3> Scheme 9> Scheme 10> Scheme 2> Scheme 1.

The gas storage capacity of pipeline: The gas storage capacity of the pipeline represents the gas supply sustainability of the pipeline. Table 3 lists the different

Table 2: The C-D line pressure drop/(MPa)

Name	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Station C	3.39	3.51	3.62	3.64	3.64
Station D	3.80	3.80	3.80	3.73	3.67
Pressure drop of C-D line	0.41	0.29	0.18	0.09	0.03
Name	Scheme 6	Scheme 7	Scheme 8	Scheme 9	Scheme 10
Station C	3.64	3.64	3.65	3.65	3.65
Station D	3.64	3.60	3.54	3.43	3.37
Pressure drop of C-D line	0	0.04	0.11	0.22	0.28

Table 3: Gas storage of the pipeline end section

Name	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Gas storage capacity	11867	11885	11903	11897	11891
Name	Scheme 6	Scheme 7	Scheme 8	Scheme 9	Scheme 10
Gas storage capacity	11887	11883	11876	11863	11856

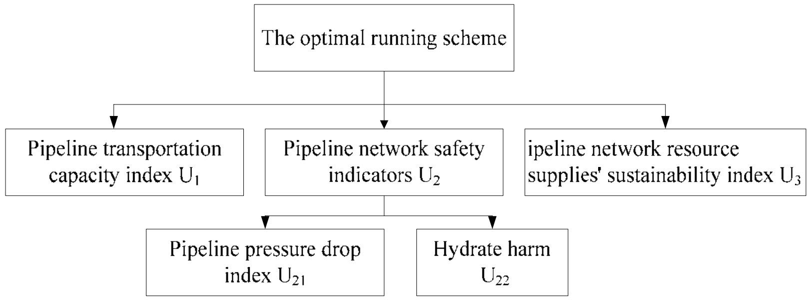

Fig. 3: Comprehensive evaluation system

Table 4: Water dew point, water dew point pressure, water content, uncertainty calculation results

No.	Water dew point/(°C)	Pressure/(MPa)	Water content/(mg/m^3)	Uncertainty/(mg/m^3)
E	-5.3	0.5	624.8	619~659
F	11.4	0.36	2818.5	2931~2971
G	-10.4	0.32	647.6	643~683
H	-1.4	0.55	761.9	764~804
C	-10.1	3.4	76.2	58~98
D	-10.1	3.4	76.2	58~98

Table 5: Comprehensive evaluation results

Name	Transportation capacity index U_1	Safety indicator U_2	Gas storage capacity index U_3	Correlative degree	Scheme merits list
Scheme 1	0.2563	0.3333	0.2369	0.2972	10
Scheme 2	0.7157	0.3866	0.6179	0.496	7
Scheme 3	1	0.434	1	0.664	4
Scheme 4	0.9361	0.5442	0.9459	0.7059	3
Scheme 5	0.8521	0.6655	0.8754	0.7472	1
Scheme 6	0.8248	0.7381	0.7044	0.7433	2
Scheme 7	0.6284	0.7131	0.5472	0.6585	5
Scheme 8	0.4039	0.6069	0.3591	0.5132	6
Scheme 9	0.2169	0.4994	0.2023	0.3810	8
Scheme 10	0.1571	0.5232	0.1621	0.3757	9

schemes for the calculation of the gas storage of the pipeline end section.

Calculate the amount of gas storage at the end of the pipeline. Gas flow rate trend up is superior. The conclusion: Scheme 3> Scheme 4> Scheme 5> Scheme 6> Scheme 2> Scheme 7> Scheme 8> Scheme 1> Scheme 9> Scheme 10.

Using the aspen HYSYS software to calculate water content: According to Chinese standard GB 22634-2008, it is known that the water content of natural gas cannot be completely uniform and there are some errors in the determination of water dew point, so there will be an uncertainty (GB 22634-2008, 2008). Table 4 lists some major areas of water content calculation of a total of 6, the remaining situation is not listed one by one. From the calculation of water content, station F is the easiest to generate hydrate.

Establishment of comprehensive evaluation index system: According to the actual situation of the maximum gas supply capacity of the pipeline network, the multi-objective comprehensive evaluation index system of the gas pipeline dispatching scheme is established with the optimal operation plan. The system consists of the following 3 aspects: (1) Pipeline transportation capacity index U_1; (2) Pipeline network's safety indicators U_2; (3) Pipeline network resource supplies' sustainability U_3. The establishment of the maximum gas supply comprehensive evaluation index system is shown in Fig. 3.

Comprehensive evaluation of simulation schemes: Considering the evaluation results of the pipeline transportation capacity, the pipeline operation safety and the pipeline network sustainability, obtaining the comprehensive relational grade shown in Table 5, which reflects pros and cons about each index relativity of 10 kinds of scheduling schemes and holistic merit. The total transportation amount, the risk value and the gas storage capacity in Table 5 are the normalized results of the evaluation index. The value is in the range of 0 to 1. The larger the value is, the better the scheme is. The smaller the value is, the worse the scheme is. Using the formula (10) to calculate the comprehensive relational degree and the range of values is between 0 and 1. The comprehensive relational grade value is larger, indicating that the the scheme is better. On the contrary, the scheme is worse.

From Table 5, it can be seen that the maximum transportation amount value is the Scheme 3 and the minimum value is Scheme 10. The best security is

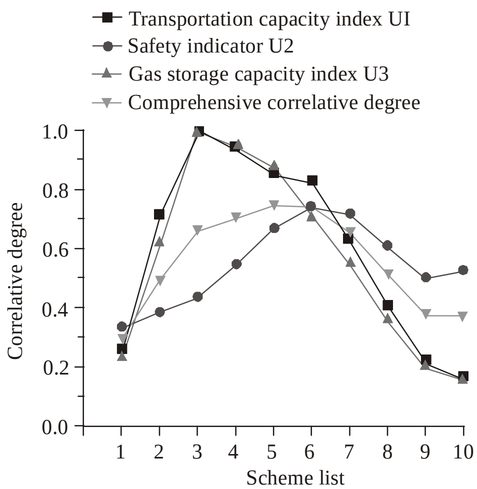

Fig. 4: The correlation coefficient of different schemes

Scheme 6, the worst is Scheme 2. The largest storage capacity is Scheme 3, The smallest is Scheme 10. The holistic results of the optimal program is Scheme 5 and the worst case is Scheme 1. Scheme 3 is the optimal one in gas storage capacity and transportation amount, but its risk value is the greatest because, in a certain range, the increase in gas delivery leads to an increase in pipe network risk, leading to the possibility of pipeline hydrate generation is greater. Under the working condition of Scheme 3. Although the maximum gas supply capacity of Scheme 5 is not as good as Scheme 3, the risk value is much lower. From Table 5, it reflects that the holistic merit of all schemes will not depend on the single indicator, but rather to all the indicators. The index correlation coefficient is plotted as shown in Fig. 4.

It can be seen from Fig. 4 that the sequence of the comprehensive correlation coefficient curve is similar to the sequence of the safety curve, but not exactly the same. The reason for it is that the sequence of comprehensive correlation coefficient curve is different from any single index and pipeline safety occupies the maximum weight value in all indicators. However, the comprehensive advantages and disadvantages of all indicators are the reflection of all the indexes.

CONCLUSION

- This study systematically discusses the selection of the comprehensive evaluation system and the establishment of the comprehensive evaluation system. It proves the feasibility and maneuverability of the multi-objective comprehensive evaluation method in the decision-making of the safe operation of the pipeline network.
- The pipeline network simulation model was established by using the TGNET software. Under the conditions of satisfying user's gas consumption need and pipe network pressure level, the maximum gas consumption of industrial users was carried out, obtaining the safe operation scheme and providing data support for the comprehensive evaluation process.
- In order to solve the special situation of natural gas hydrate in winter, using the Aspen HYSYS software to calculate water content of each pipe and each station, which provided data for the comprehensive evaluation process.
- Considering the effect of pipeline pressure drop, temperature, gas transportation volume and storage capacity of the pipeline on the safe operation of natural gas pipeline network and the natural gas water content is taken as an important part of comprehensive evaluation.
- The multi-objective comprehensive evaluation method can be well applied to the safe operation of pipe network simulation. At the same time, the evaluation conclusion shows that there are many factors that affect safe operation of the pipe network. To ensure the pipeline network's safety operation and economical scheduling, it is necessary to consider the various factors.

The related work started soon about natural gas pipe network safe operation and scheduling based on the multi-objective comprehensive evaluation method, leading to lack of mature experience. For different pipe network system, it needs to examine varied factors. Therefore, in the future work, it needs to further study the different aspects that affect the safe operation of the pipe network.

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REFERENCES

Ai, M.Y., Y. Jiang, F. Song, G.Q. Chen and J.G. Song, 2011. Research on operation optimization of multi-objective decision making for large-scale gas pipeline network. Oil Gas Storage Transport., 30(10): 739-742.

Cai, B.S., 2014. Research and application of a gas pipeline peak shaving project evaluation system (GPPES). Nat. Gas Ind., 34(10): 87-91.

GB 22634-2008, 2008. Conversion Between Natural Gas Water Content and Water Dew Point. Standardization Administration of China.

He, S., A.M. Ji and D.S. Chen, 2011. Application of fuzzy comprehensive evaluation in of security management assessment oil-drilling group. J. Safety Sci. Technol., 7(6): 156-161.

Li, L.G., Z.H. Zhang, Y.S. Dai, W.F. Sun and C.Q. Dong, 2012. Operation optimization based on improved pattern search algorithm in gas transmission networks. J. China Univ., Petrol. Edn. Nat. Sci., 36(4): 139-143.

Li, M.J., G.H. Chen and Y.T. Chen, 2004. Study on target standardization method of comprehensive evaluation. Chinese J. Manage. Sci., 12(s1): 45-48.

Liu, Q., 2014. Research on natural gas pipeline scheduling optimization. M.Sc. Thesis, Southwest Petroleum University.

Liu, S.F., Y.J. Yang and L.F. Wu, 2014. Grey System Theory and Its Application. 7th Edn., Science Press, Beijing.

Liu, W., P. Zhang and Y. Liu, 2009. Decision of optimal scheduling scheme for gas pipeline network. J. Southwest Petrol. Univ., Sci. Technol. Edn., 31(3): 146-149.

Yang, Y., 2006. Evaluation method on empowerment in multi-index comprehensive. Stat. Decis., 13: 17-19.

Yao, A.L., Z.G. Zhao and J.W. Zhang, 2013. Quality evaluation for oil and gas pipeline risk assessment. Nat. Gas Ind., 33(12): 111-116.

Zhu, K.J., L.L. Li and C.Z. Gong, 2012. Multi-objective optimizing model of time-of-use principle for natural gas industry customer. J. Beijing Inst. Technol. Soc. Sci. Edn., 14(1): 9-14.