

Study on the multi-objective optimization of reliability and operating cost for natural gas pipeline network

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Abstract. The development of natural gas pipeline network towards larger scale and throughput has urged better reliability of the pipeline network to satisfy transportation requirement. Previously, studies of optimizing natural gas pipeline network have been mainly focused on reducing operating cost, with little concern on the reliability of pipeline network. For a natural gas pipeline network with a variety of components and complicated topology, a multi-objective optimization model of both reliability and operating cost is proposed in this study. Failure of each component and the state of pipeline network under failure conditions are taken into account, and minimum cut set method is employed to calculate the reliability of the pipeline network. The variables to be determined for the optimization objectives are the rotating speed of compressors and the opening of valves. Then the solving procedure of the proposed model is presented based on Decoupled Implicit Method for Efficient Network Simulation (DIMENS) method and NS-saDE algorithm. The validity of the optimization model is ascertained by its application on a complicated pipeline network. The results illustrate that the optimization model can depict the relative relationship between reliability and operating cost for different throughput, by which the operation scheme with both satisfying reliability and operating cost can be obtained. In addition, the customer reliability and the impact of the failure of each pipeline on the whole network can be evaluated quantitatively to identify the consumers and pipelines of maintenance priority. The pipeline network reliability can be improved through proper monitoring and maintenance of these consumers and pipelines.

Nomenclature

c_p	Specific heat capacity at constant pressure, J/(kg K)	H	Pressure head provided by a compressor, m
c_v	Flow coefficient of valve, $m^3/(h \text{ kPa})$	HA	Hydraulic Availability
CR	Crossover Rate	K	Total heat transfer coefficient, $W/(m^2 \text{ K})$
d	Internal diameter of pipe, m	K_e	Pipe absolute roughness, mm
D	External diameter of a pipe, m	L	Pipeline length, m
D_i	Joule-Thomson coefficient, K/Pa	m	Mass flow rate, kg/s
F	Failure probability	MC	The minimum cut set
FR	Valve opening	n	Rotational speed of a compressor, r/min
g	Acceleration of gravity, m/s^2	N	Number of components
G	Generation	N_c	Number of consumers
		NP	Population size
		p	Polytropic index
		P	Pressure, Pa
		q	The individual which represents an operation scheme

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Q	Volume flow rate, m ³ /s
Ra	Specific gas constant of air, J/(kg K)
Rj	Pipeline network reliability of the system
Re	Reynolds number
t	Period considered, h
Sc	Number of compressors
T	Temperature, K
T_a	The ambient temperature, K
V	Specific volume, m ³ /kg
v_q, G	Mutation vector
x_q, G	Decision vector
z_q, G	Trial vector
Z	Compressibility factor
ZF	Amplification factor of difference vector

Greek symbols

β	Transmission coefficient
δ_p	Failure probability of a pipeline, (km h) ⁻¹
ε	Compression ratio
ϕ_k	State probability of component k
$\phi(\text{MC})$	Occurrence probability of MC
η	Efficiency of a compressor
λ	Friction factor
ν	Kinematic viscosity, m ² /s
ρ	Density, kg/m ³
ζ	Number of the minimum cut sets
Δ	Specific density of natural gas relative to air
θ	Heat transfer coefficient

Superscripts

req	Required
min	Minimum
max	Maximum
given	Known value

Subscripts

*	Standard state
j	Index of consumer
k	Index of component
in	Inlet
out	Outlet

1 Introduction

The worldwide concern about fuel pollution and the urgent need to upgrade energy structure mean that natural gas as a clean fuel plays a more important role in energy consumption. In the year 2018, global consumption of natural

gas gained the fastest growth since 1984 by an amount of 195 billion cubic meters with a growth rate of 5.3% [1]. It is predicted that global consumption of natural gas will keep at an annual growth rate of 2.9% ~ 3.2% until the year 2030 [2]. There is no doubt that natural gas industry will continue to develop rapidly in the future [3]. Generally, natural gas sources are far from the consumption sites, and the transportation is realized by natural gas pipeline network which extends over larger and larger areas along with the increase of natural gas consumption. As a result, safe and efficient operation of the pipeline network become more important than at any time in the past. Besides, characterized with fluctuating gas consumption and limited allowable pressure, natural gas pipeline network may easily operate deviating from the optimal condition. Therefore, conducting research to determine the optimal operation scheme is extremely essential for the proper and smooth running of natural gas pipeline network.

Based on the number of optimization objectives, the natural gas pipeline network optimization can be classified into single-objective optimization and multi-objective optimization. The operation of natural gas pipeline network consumes huge amount of energy, with compressors accounting for 25% ~ 50% of the pipeline company's total operating budget [4] and 10% of the industrial electricity cost [5]. As a result, previous researches have focused on single-objective optimization to reduce the operating cost [6–8]. However, aspects such as safety, environmental protection and stability of natural gas pipeline network are all important factors besides operating cost. In recent years, multi-objective optimization has obtained more and more applications in oil and gas industry due to its comprehensive consideration of multiple motivations. For complex pipeline network structures, Botros *et al.* [9] adopted a multi-objective optimization model to study simultaneous optimization of operating cost and line-pack of natural gas pipeline network. Kashani and Molaei [10] proposed a three-objective optimization model to optimize the operation parameters for low throughput, reduced operating costs and CO₂ emissions. Panda and Ramteke [11] performed multi-objective optimization of oil transmission network scheduling to account for the transportation profit and flow fluctuation in an oil distillation unit. Many researchers have devoted efforts to multi-objective optimization of compressor and pump station [4, 12, 13] in terms of the power or fuel consumption of the stations, the number of stations and the outlet pressure of stations. In addition, considering the gas consumption for electricity generation, there has been combined multi-objective optimization of the gas network and the electricity network [14–16]. Multi-objective optimization has also been applied to pipeline-related equipment, such as sensor placement in the network [17], mini-Liquefied Natural Gas (LNG) plant [18] and gas drainage system [19]. Based on the references mentioned above, the optimized effect is greatly influenced by the optimization algorithm. The evolutionary algorithms are preferred due to their excellent capability of global search. Among the kinds of evolutionary algorithms, the Differential Evolution (DE) algorithm is proved to perform best [20, 21]. It can

overcome the difficulty in determining the value of algorithm control parameters using the Self-adapting approach [22]. To realize the multi-objective strategy, the DE algorithm can also combine with the Elitist Non-dominated Sorting method, named NS-DE algorithm, which has excellent convergence performance [23, 24].

During the operation of natural gas pipeline network, some unpredictable reasons, such as erosion, misguided use and quality defects, may threaten normal gas supply. The ability of the pipeline network to safely and stably complete the transportation task is referred to as the pipeline network reliability, which is tightly related to the topology, equipment status and transportation load of the pipeline network [25]. Study on the reliability of pipeline network is necessary to ensure safe and stable transportation and minimize the loss caused by component failure [26, 27]. Generally speaking, the pipeline network reliability declines as the power consumption of the compressor is reduced through traditional economic optimization. This is because a pipeline optimization scheme with low operating cost usually has relatively low internal pressure, which cannot provide sufficient energy to ensure the gas flow in the pipeline in failure situations of the pipeline network. Shinstine *et al.* [28] performed analysis of water supply network reliability, and it was found that reliability has a negative relationship with both the throughput and the pressure demand of consumers. Yu *et al.* [29] proposed that pipeline network reliability would decrease with increasing probability of the flow rate reaching extreme values. Therefore, operation scheme with best pipeline network reliability and economy is impossible, but instead balancing between reliability and economy is necessary.

There have been a limited number of researches considering reliability in the optimization of natural gas pipelines. The fundamental reason is that the traditional method to calculate the reliability of gas pipeline network, namely the Monte Carlo method [25, 27], is not suitable for the optimization due to its massive calculation. Therefore, the analytical methods are used to represent some characteristics of reliability in the following literature. To trade off the reliability and power demand, Su *et al.* [26] developed a multi-objective optimization method of minimizing power demand and the risk of gas supply shortage. The reliability is calculated by limit function, and sensitivity analysis is performed to demonstrate the influence of demand uncertainties on the optimization results. Li and Liu [30] used the recursive decomposition method to analyze the seismic capability reliability and seismic connectivity reliability for the water distribution system and gas network. Using the scenario reduction algorithm, Shabazbegian *et al.* [31] took into account the contingency analysis and role of flexibility options in the optimization process to increase gas supply stability. Moreover, the minimum cut-set method, which has been successfully applied to water supply network [32] but not found in the optimization of gas pipeline, is also an analytical method to evaluate the reliability of pressure supply. However, we found the following limitations from the literature review: (1) The failure possibility of multi-components was neglected in previous reliability optimization. (2) Reliability calculation has been restricted

to the assumption of simple network topology. (3) The reliability was considered to have little relationship with the hydraulic-thermal state of fault pipeline network containing failed components.

To address the above issues, this paper proposes a multi-objective optimization model considering both reliability and operating cost, applicable to natural gas network with multi-source, multi-consumer, multiple components and complicated topology. In the optimization process, the fault pipeline network involving failed components is considered, and the hydraulic-thermal state of the fault pipeline network is included into the reliability evaluation by adopting the minimum cut-set method. By using the presented model, the relationship balancing between pipeline network reliability and economical consideration is investigated in detail for the nature gas pipeline network under different throughputs.

The remaining of the paper is organized as follows: Section 2 presents the introduction of reliability and governing equations of the pipeline network. Then, the multi-objective optimization model of reliability and operating cost for natural gas pipeline network operation is proposed in Section 3. The solving method of the model and the overall calculation procedure are illustrated in Section 4. The cases, optimal results and discussion are given in Section 5. The final conclusion is drawn in Section 6.

2 Reliability and governing equations

2.1 Reliability of the pipeline network

The optimization of complex gas pipeline network involves evaluation of a large number of operation schemes, meaning that effective and quick evaluation of each scheme is necessary. The minimum cut-set method is a favorable choice for pipeline network optimization due to its ability of comprehensively assessing the pipeline network with a small amount of calculation. Also the minimum cut-set method is applicable to the reliability evaluation of natural gas pipeline network with multi-components and complicated topology.

In this subsection, the minimum cut-set method is introduced [33]. Provided that there is a set of components in a network system, which when failed causes the failure of this system. While, when any component of the set doesn't fail, the failure of the network system does not occur. Then, this set of components is the minimum cut set of the network system. The minimum cut set of the pipeline network is the combination of different number of pipelines, valves and compressors. The minimum cut set is determined by whether the demand of consumers in the system is satisfied, that is whether the pressure or gas flow rate reaches the required level. Thus, the evaluation of consumer reliability is first performed through its corresponding minimum cut sets, and then the reliability of the pipeline network can be evaluated.

Here we assume consumer j has ζ_j minimum cut sets, and the i th minimum cut set is MC_i which has N components. When all the components are in failure status,

MC_i occurs. Then the occurrence probability of this minimum cut set can be written as:

$$\phi_j(MC_i) = \prod_{k=1}^N \phi_k. \quad (1)$$

For consumer j , the failure probability and the consumer reliability are respectively described as:

$$F_j = \sum_{i=1}^{\xi_j} \phi_j(MC_i), \quad (2)$$

$$R_j = 1 - F_j = 1 - \sum_{i=1}^{\xi_j} \phi_j(MC_i). \quad (3)$$

In a gas transmission project, the gas volume supplied to one consumer is related to the pressure at this consumer, and thus we consider the influence of the pressure at consumers on the pipeline network reliability. Therefore, hydraulic availability is introduced [34]:

$$HA_j \begin{cases} 0 & P_j < P_j^{\min} \\ \sqrt{\frac{P_j - P_j^{\min}}{P_j^{\text{req}} - P_j^{\min}}} & P_j^{\min} < P_j < P_j^{\text{req}} \\ 1 & P_j > P_j^{\text{req}} \end{cases} \quad (4)$$

It should be noted that, the pressure is closely related with the hydraulic-thermal state of the fault pipeline network, obtained by solving the hydraulic equations and thermodynamic equations, which is introduced in the next section.

The hydraulic availability can better describe the gas supply ability of the pipe network under abnormal conditions, by introducing which, the reliability at consumer node j is redefined as:

$$R_j = 1 - \sum_{i=1}^{\xi_j} (1 - HA_j^i) \phi_j(MC_i). \quad (5)$$

In equation (5), the $(1 - HA)$ can be regarded as the hydraulic unavailability of a consumer node. Thus, the occurrence probability of MC_i is multiplied by $(1 - HA_j^i)$ to formulate the reduction degree of the gas supply ability to consumer j . Therefore, by equation (5), a continuous hydraulic availability concept is used.

After calculating the hydraulic reliability of each consumer node, the gas supply reliability of the pipeline network can be calculated by weight factor method as the weighted average of all the consumer nodes. And the consumption amount of each consumer node acts as the weighted value. The pipeline network reliability can be calculated by:

$$R_s = \frac{\sum_{j=1}^{N_C} m_j^{\text{req}} R_j}{\sum_{j=1}^{N_C} m_j^{\text{req}}}. \quad (6)$$

2.2 Governing equations

The pipeline network is a complex system, the pressure, flow rate, and temperature of which satisfy certain governing equations including hydraulic equation, thermodynamic equation, node equation and gas state equation. For convenience, we involve two assumptions: (1) The pipeline network is simplified as a structure composed of nodes and components. Pipelines, valves and compressors are seen as components, while sources, consumers and component-to-component connections are nodes. (2) The pipelines are horizontal and the flow in the pipe network is steady.

2.2.1 Hydraulic equations

The hydraulic equations describe the relationship between flow rate and pressure drop of the components. For the pipelines, valves and compressors, the hydraulic equations are presented as follows.

Hydraulic equation of a pipeline with gas flow [35, 36]:

$$P_{\text{in}}^2 - P_{\text{out}}^2 = \frac{\lambda Z \Delta T L}{C_*^2 d^5} Q_*^2, \quad (7)$$

where $C_* = \frac{\pi}{4} \frac{\sqrt{R_a T_*}}{P_*}$.

Hydraulic equation of a compressor [35]:

$$P_{\text{out}} - \varepsilon P_{\text{in}} = 0. \quad (8)$$

Hydraulic equation of a valve [37]:

$$Q_{\text{in}} - Cv \sqrt{\frac{(P_{\text{in}}^2 - P_{\text{out}}^2)}{Z \Delta T_{\text{in}}}} = 0, \quad (9)$$

where $Cv = f(FR)$.

2.2.2 Thermodynamic equations

The thermodynamic equations mainly describe the temperature variations of components, which are provided below for the pipelines, valves, and compressors respectively.

Thermodynamic equation of a pipeline [35]:

$$T_{\text{out}} = T_a + (T_{\text{in}} - T_a) e^{-\theta L} - D_i \times \frac{P_{\text{in}} - P_{\text{out}}}{\theta L} (1 - e^{-\theta L}), \quad (10)$$

where $\theta = \frac{K\pi D}{mc_p}$.

Thermodynamic equation of a compressor [37]:

$$T_{\text{out}} - T_{\text{in}} \varepsilon^{\frac{\gamma-1}{\gamma}} = 0. \quad (11)$$

Thermodynamic equation of a valve [37]:

$$T_{\text{out}} - T_{\text{in}} + (P_{\text{out}} - P_{\text{in}}) \left\{ \frac{1}{c_p} \left[\frac{T}{\rho^2} \frac{(\partial P / \partial T)_{\rho}}{(\partial P / \partial \rho)_T} - \frac{1}{\rho} \right] \right\}_{\text{out}} = 0. \quad (12)$$

2.2.3 Node equations

According to mass conservation, the mass entering a node is equivalent to the mass flowing out of that node, expressed as:

$$\sum m_{\text{in}} = \sum m_{\text{out}}. \quad (13)$$

The temperature of natural gas flowing out of a node is calculated by [37]:

$$T_{\text{out},1} = T_{\text{out},2} = \dots = \frac{\sum |c_p m T|_{\text{in}}}{\sum |c_p m|_{\text{out}}}. \quad (14)$$

Gas is pushed into the network through the source node, while released from the network at the consumer node. External boundary conditions associated with pressure, flow rate and temperature are applied to the source node and the consumer node as follows [37, 38]:

$$P = P^{\text{given}}, \quad (15)$$

$$m = m^{\text{given}}, \quad (16)$$

$$T = T^{\text{given}}. \quad (17)$$

2.2.4 Gas state equations

Natural gas is a mixture of many components. The relationships (including partial differential relationships) among P , T and ρ of the components are obtained by the **Benedict-Webb-Rubin-Starling** (BWRS) equation [39]:

$$\begin{aligned} P = \rho R T + & \left(B_0 R T - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho^2 \\ & + \left(b R T - a - \frac{d}{T} \right) \rho^3 + \alpha \left(a + \frac{d}{T} \right) \rho^6 \\ & + \frac{c \rho^3}{T^2} (1 + \gamma \rho^2) \exp(-\gamma \rho^2), \end{aligned} \quad (18)$$

where A_0 , B_0 , C_0 , D_0 , E_0 , a , b , c , d , α , and γ are the coefficients, and for their calculation refer to Ref. [39].

Generally, the gas flow in a pipeline is turbulent, and the F. Colebrook formula is used to calculate the friction factor:

$$\frac{1}{\sqrt{\lambda}} = -2 \lg \left(\frac{K_e}{3.7d} + \frac{2.51}{\text{Re} \sqrt{\lambda}} \right), \quad (19)$$

where $\text{Re} = \frac{4Q}{\pi d v}$.

The following formula is used to calculate the Joule-Thomson coefficient [36]:

$$D_i = \frac{1}{c_p} \left(T \left(\frac{\partial V}{\partial T} \right)_P - V \right). \quad (20)$$

3 The multi-objective optimization model

3.1 Objective functions

1. Pipeline network reliability

In the process of optimization, better reliability of the gas supply system is preferred, and thus in terms of network reliability, the optimization objective is:

$$\max \{R_S\}. \quad (21)$$

2. Total power of compressors

For a natural gas pipeline network, most of the operating cost comes from the compressors, and reducing the total power of the compressors can effectively decrease the operating cost. In this study, the compressor power is used to represent the operating cost of the pipeline system. From the aspect of operating cost, the optimization objective is expressed as:

$$\min \left\{ \sum_{k=1}^{S_C} m_k \frac{(P_{\text{out}} - P_{\text{in}})_k}{\eta_k} \right\}. \quad (22)$$

3.2 Constraints

1. Restriction of decision variables

This paper focuses on the optimization of natural gas pipeline network from the operation perspective. Therefore, the decision variables to be determined for optimization include the compressor rotational speed n and the valve opening FR. Considering practical engineering, the two parameters are bounded as follows:

$$n^{\min} \leq n \leq n^{\max}, \quad (23)$$

$$\text{FR}^{\min} \leq \text{FR} \leq \text{FR}^{\max}. \quad (24)$$

2. Volume flow rate of compressors

The flow in the compressor is restricted between the surge flow (minimum flow) and the block flow (maximum flow), and thus the flow rate of each compressor has the following constraint:

$$Q^{\min} \leq Q_{\text{in}} \leq Q^{\max}. \quad (25)$$

3. Outlet temperature of compressors

The outlet temperature of compressors should not exceed the limit value to protect the insulating layer [36]:

$$T_{\text{out}}^{\text{compressor}} \leq T^{\max}. \quad (26)$$

4. Node pressure of the pipeline network

The node pressure in the pipeline network is restricted as:

$$P^{\min} \leq P \leq P^{\max}. \quad (27)$$

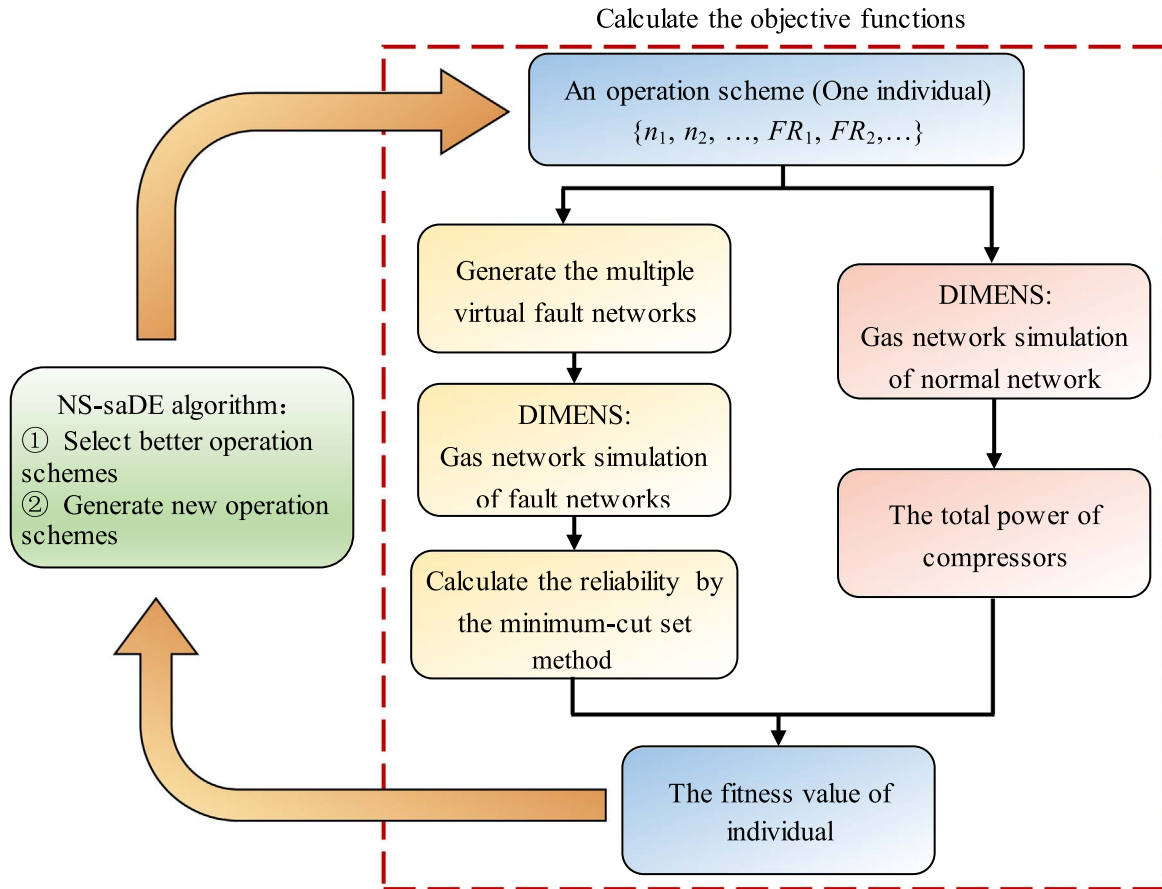


Fig. 1. The overall calculation process.

Equation (27) is applicable to the inlet and outlet pressure of all components, including pipeline, valve and compressor.

5. Transmission coefficient

Transmission coefficient β is defined for each consumer node to characterize the throughput of the pipeline network:

$$\beta = \frac{m_1^{\text{req}}}{m_1^0} = \dots = \frac{m_j^{\text{req}}}{m_{j-1}^0} = \dots = \frac{m_{N_c}^{\text{req}}}{m_{N_c}^0}. \quad (28)$$

4 Solution methods

The overall calculation process is presented in Figure 1. Aimed at optimizing the operation scheme of natural gas pipeline network, operation parameters are the variables to be determined, including the rotation speed of each compressor and the valve opening of each valve. The optimal operation scheme is determined by the combination of compressor speed and valve opening. The optimization has two

objectives, one is good pipeline network reliability, and the other is relatively low total power of the compressors. The optimization process consists of two modules, one module to make evaluation of an operation scheme, that is, to calculate the optimization objectives of this operation scheme and get the fitness value of individuals, the other to generate new operation schemes and select better operation schemes. The two modules are nested with each other to form an iteration of calculation. The optimization process proceeds until a planned number of iterations.

When calculating the pipeline network reliability, the components in the pipeline network are assumed to fail one by one, in which a multiple of virtual fault networks is firstly generated. Then, the hydraulic-thermal state of the various fault networks is obtained by the gas network simulation. Thus, the pipeline network reliability can be quantified by the minimum cut-set method. When calculating the total power of compressors, the hydraulic-thermal state of the normal network is also determined by gas network simulation.

To realize the gas network simulation, the Decoupled Implicit Method for Efficient Network Simulation

(DIMENS) method, which was proposed in our previous papers [37, 38], is adopted. By this method, the flow governing equations (Eqs. (7)–(9), (13) and (15)–(16)) and the thermal governing equations (Eqs. (10)–(12), (14) and (17)) are solved separately, as shown in Figure 2. The hydraulic-thermal state of the network can be depicted efficiently and accurately.

To generate and select operation schemes, this paper adopts a hybrid evolutionary algorithm based on the Elitist Non-dominated Sorting method [40] and Self-adapting Differential Evolution (saDE) algorithm [20, 22], which is named NS-saDE algorithm. This algorithm shows excellent convergence performance [41] and overcomes the difficulty in determining the value of algorithm control parameters. The NS-saDE algorithm mainly includes the following parts: Initialization, saDE mutation, saDE crossover, calculation of objective functions, sharing fitness, non-dominated sorting, crowding distance assignment and selection, as shown in Figure 3. For the constraints in Section 3.2, the restriction of decision variables is reflected in the initialization and saDE mutation. The other constraints in Section 3.2 are limited by the non-dominated sorting, which can exclude the operation schemes that dissatisfy them.

5 Results and discussion

5.1 Case description

In this paper, a large-scale natural gas transmission network with a complex topology is considered and shown in Figure 4. The pipeline network is composed of 4 sources, 21 consumers, 42 pipelines, 4 compressors and 5 valves.

1. Pipeline parameters

All pipes are horizontal with a roughness and wall thickness of respectively 0.23 mm and 8 mm. The serial number, length and external diameter of each pipeline can be seen in Appendix Table A1. The allowable pressure of a pipe is between 3.5 and 7.0 MPa, which is also applicable to compressors and valves. The minimum outlet temperature of pipe is 278.15 K.

The standard pressure and temperature are 101.325 kPa and 293.15 K, respectively. The total heat transfer coefficient is $1.5 \text{ W}/(\text{m}^2 \text{ K})$, and the environmental temperature is maintained at 293.15 K.

For a pipeline, the failure probability within a period can be obtained by the following formula:

$$F = 1 - e^{-\delta_p L t}, \quad (29)$$

where $\delta_p = 1.46 \times 10^{-8}/(\text{km h})$ [29].

2. Compressor parameters

For each station, there is one compressor in operation, with the rotational speed adjustable between 4400 and 7200 r/min. The maximum outlet temperature of compressor is 328.15 K. The serial number of each compressor can

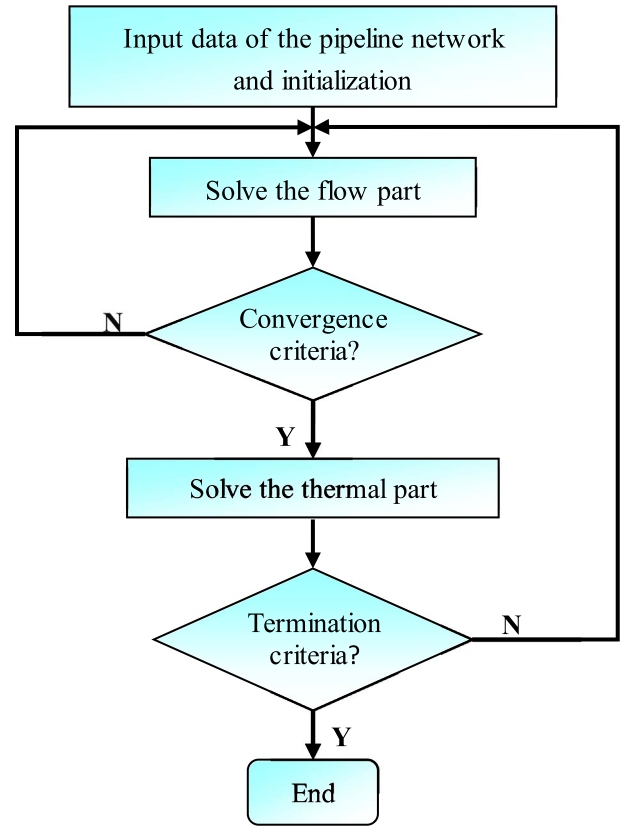


Fig. 2. The DIMENS method.

be seen in Appendix Table A2. According to the performance data given in Appendix Table A3, the fitting formula of compression ratio e and inlet flow Q_{in} is shown as,

$$e(Q_{\text{in}}, n) = a_0 Q_{\text{in}}^2 + b_0 Q_{\text{in}} + c_0, \quad (30)$$

where the coefficients a_0 , b_0 and c_0 are fitted with rotational speed by optimal square approximation:

$$a_0 = a_1 n^2 + a_2 n + a_3, \quad (31)$$

$$b_0 = b_1 n^2 + b_2 n + b_3, \quad (32)$$

$$c_0 = c_1 n^2 + c_2 n + c_3. \quad (33)$$

In addition, the efficiency of compressor $\eta(Q_{\text{in}}, n)$ can also be obtained by using the above fitting formulas. The surge flow $Q^{\text{min}}(n)$ and block flow $Q^{\text{max}}(n)$ are fitted with rotational speed by optimal square approximation, respectively.

3. Valve parameters

The network has five valves, and the serial number of each valve can be seen in Appendix Table A4. The valve opening varies from 0.5 to 1.0. It is assumed that the flow

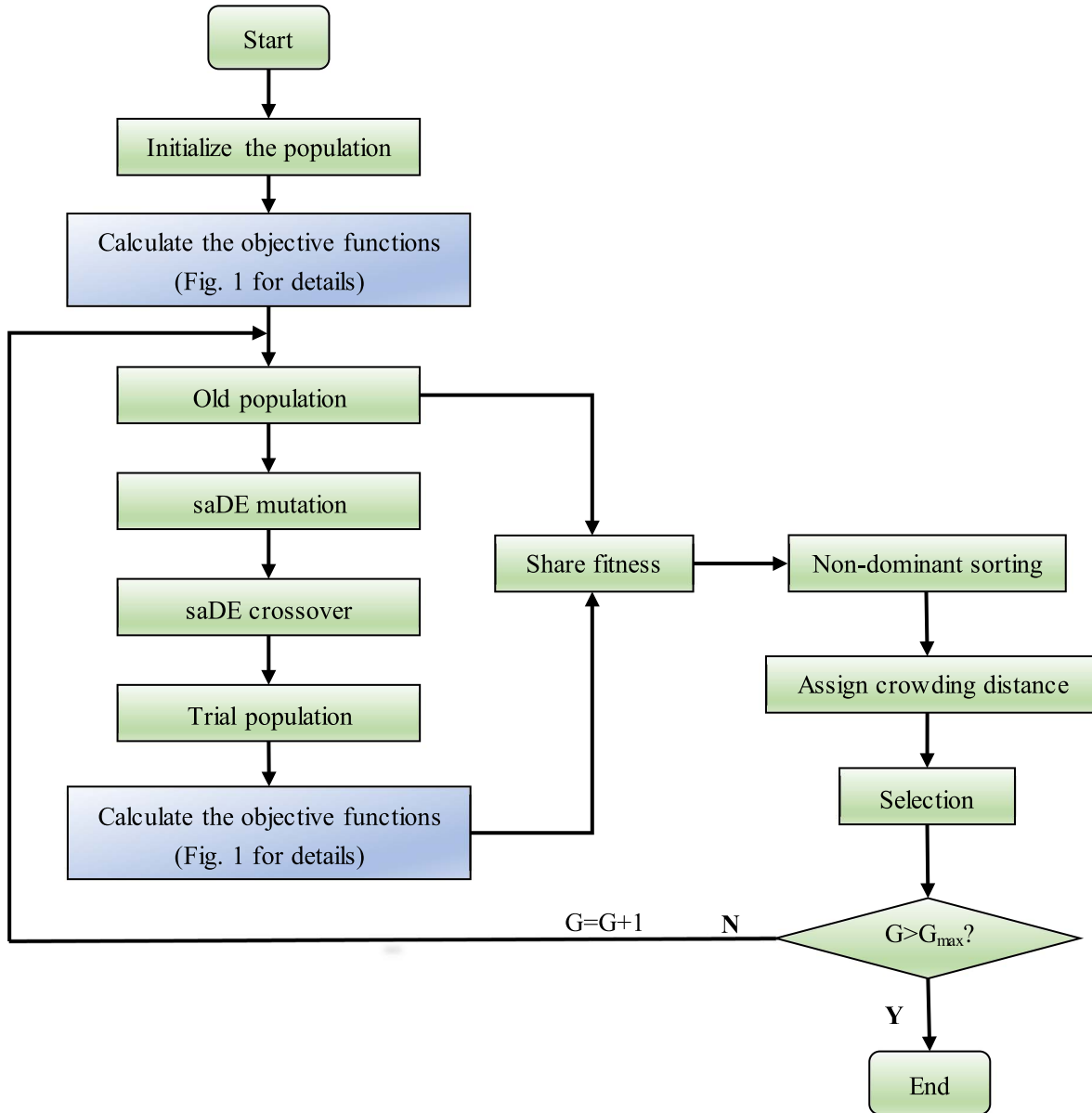


Fig. 3. The NS-saDE algorithm.

coefficient of the valve FR is linearly related with the valve opening, having,

$$FR = \frac{Cv_{\max} - Cv}{Cv_{\max} - Cv_{\min}}, \quad (34)$$

where FR is the flow coefficient of the valve, Cv_{\max} is $250 \text{ m}^3/(\text{h kPa})$ and Cv_{\min} is 0. The valve failure is considered to happen 0.5×10^{-3} times per year.

4. Boundary parameters

The network has 21 consumers and 4 sources, and the serial number of each boundary node can be seen in [Appendix Table A5](#). Each inlet of a compressor corresponds

to a source, and all sources are at 5.0 MPa and 313.15 K. The components of natural gas in a source are listed in [Appendix Table A6](#). The design flow rate of consumers are listed in [Appendix Table A7](#). For all consumers, the minimum supply pressure and required pressure are 0.1 MPa and 4.0 MPa respectively.

A real large-scale pipeline network has several transmission schemes with set loads. To reduce the computation burden, transmission coefficient with discrete values is used, and they are $\beta \in \{0.6, 0.65, 0.7 \dots 1.05, 1.1\}$.

5.2 Analysis of results

For each transmission coefficient which belongs to $\{0.6, 0.65, 0.7 \dots 1.05, 1.1\}$, the population size is set as 100, and the number of iterations is set as 300. The calculation

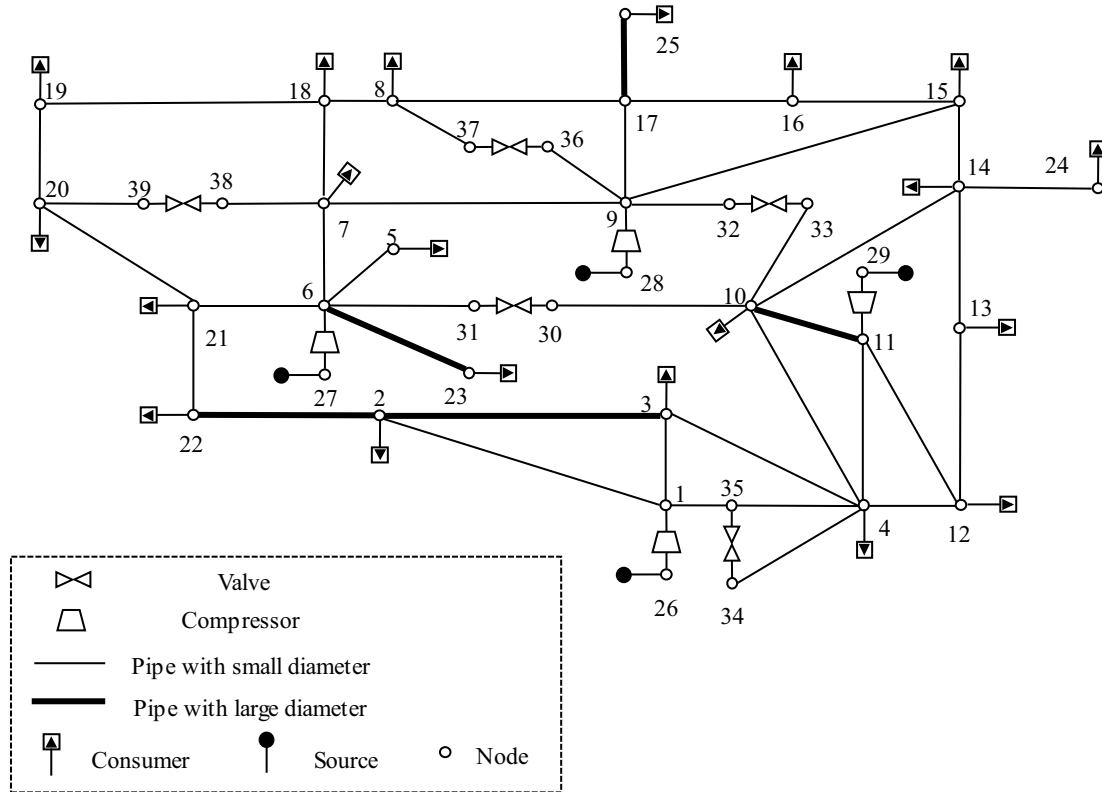


Fig. 4. The schematic diagram of the pipeline network.

was executed on a PC with Xeon W-2125 4.00 GHz processor and 16 GB RAM. Each transmission coefficient took about 1.5 million times of pipeline network simulation, which costs 11.5 h of computation time. To demonstrate the practical effect brought by the multi-objective optimization model considering pipeline network reliability, the Pareto fronts, the extreme value of objective properties, the consumer reliability and the impact of pipeline failure are analyzed.

5.2.1 Analysis of Pareto fronts

As mentioned earlier, pipeline network reliability and power cost need to be compromised, which is also the purpose of the multi-objective optimization and benefits pipeline management. The profiles of reliability and the total power of compressors for representative transmission coefficient are shown in Figure 5, which are Pareto fronts that reflect the relationship between the two objectives. Analyzing the Pareto fronts can evaluate the variation of pipeline network reliability along with an increased power and assist decision-making in selecting the final operation scheme.

Figure 5 shows increasing pipeline network reliability as the power is improved, which can be explained as follows. The compression ratio is larger for increased compressor power, and the pressure inside the pipeline network increases, meaning higher hydraulic availability of

consumers and better pipeline network reliability. The observations in Figure 5 are consistent with reports in previous literature [26, 28]. Su *et al.* [26] proposed that enhancing the power would reduce the interruption probability, and Shinstine *et al.* [28] confirmed larger system reliability when the pressure at consumer nodes is higher. The accordance of our present results with previous researches verifies the correctness of the model.

In Figure 5, it is also indicated that the detailed variation of pipeline network reliability against the compressor power is different under different transmission coefficients. When the transmission coefficient is small, the reliability displays a gentle increase with the increase of the compressor power. However, in the cases of large transmission coefficients, pipeline network reliability improves significantly with the increasing power. For example, for $\beta = 1.05$, increasing the power by 5.26 MW contributes to an increase in the reliability from 0.933 to 0.971, which greatly guarantees the gas supply of the pipeline network. It is inferred that improving the compressor power is a feasible way to strengthen the gas supply reliability. However, it can be noted that for cases such as $\beta = 0.80$ and 0.90 , the network reliability undergoes a fast rising stage followed by an almost unchanging stage in the process of increasing the compressor power. That is, sometimes continuing to increase the compressor power may produce little effect on improving the pipeline network reliability. Overall the

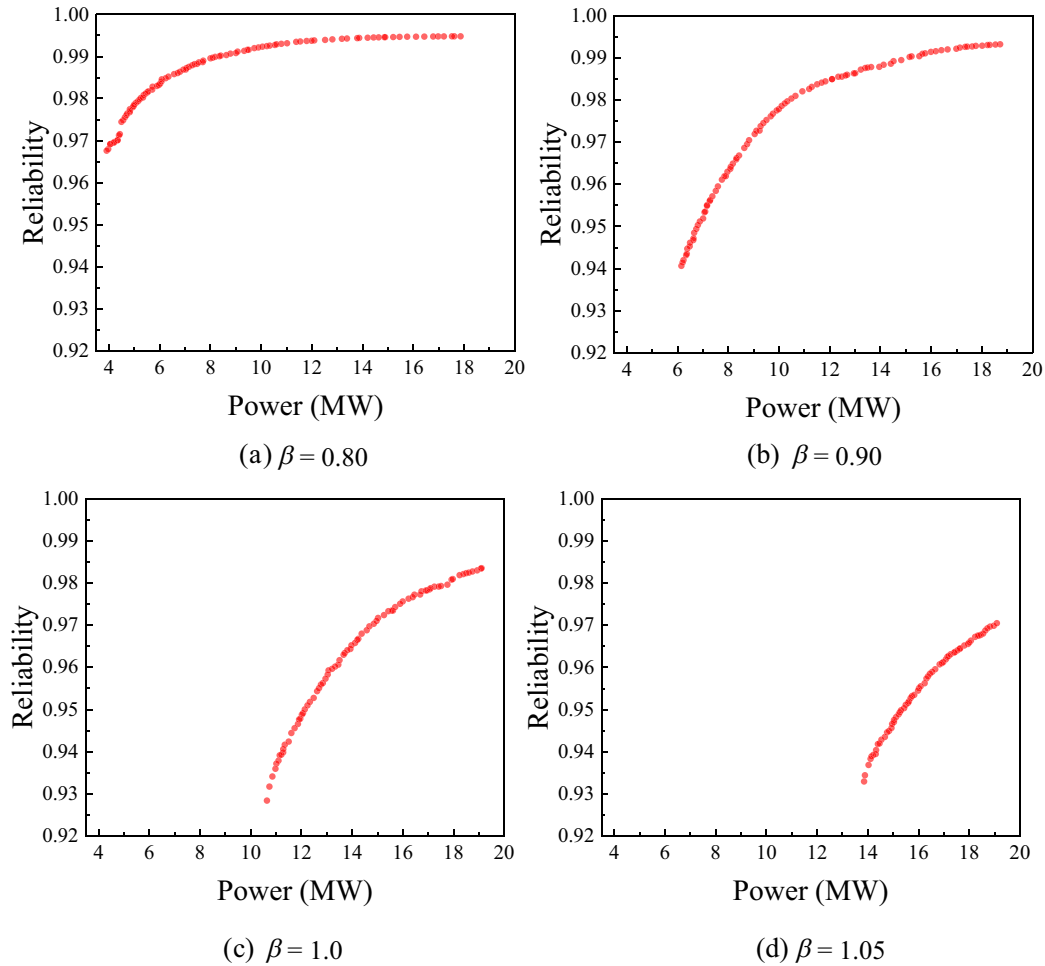


Fig. 5. Pareto fronts under different transmission coefficients.

transmission system operator can select the appropriate operation schemes in different situations through the Pareto fronts. For example, if the gas supply is significant to the regional energy supply, the operator can choose an operation scheme with high reliability, otherwise the low power consumption scheme can be adopted to save cost. By the multi-objective optimization model, a wide range of options can be provided for the operator, which are satisfactory in both reliability and economy.

5.2.2 Analysis of extreme values

The influence of throughput on the pipeline network reliability and compressor power can be analyzed from the perspective of extreme values of the objective properties. The maximum and minimum pipeline network reliability under different transmission coefficients are shown in Figure 6. Similarly, the distributions of the maximum and minimum power are presented in Figure 7.

On the whole, Figure 6 illustrates decreasing pipeline network reliability as the throughput becomes larger, which

is in accordance with the result of Shinstine *et al.* [28], that the reliability is a negative function of flow rate. Figure 7 shows that with the increase in the throughput, the power consumption increases, which is consistent with the multi-objective optimization results of Botros *et al.* [9] and Yang *et al.* [13].

For transmission coefficient varying from 1.0 to 1.10, the maximum pipeline network reliability declines sharply, as is demonstrated in Figure 6. It is illustrated that in such situations, further increasing the throughput is not beneficial to guaranteeing gas supply. While correspondingly, Figure 7 shows a rapid rise of the minimum power for β from 1.0 to 1.10, meaning that the transmission operation should be conducted under-high power schemes which naturally leads to higher reliability, explaining the rise of minimum pipeline network reliability observed in Figure 6. For the extreme throughput of this network, that is $\beta = 1.10$, the maximum and minimum power are almost the same. For transmission coefficients between 0.6 and 0.7, the reliability of the pipe network maintains at a high value of 0.995, and the variation of throughput brings insignificant

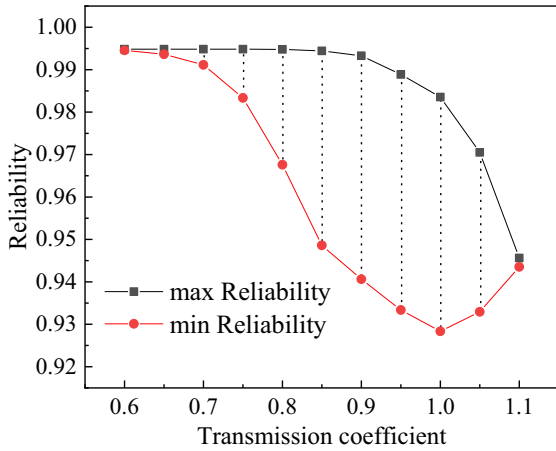


Fig. 6. The extreme values of pipeline network reliability.

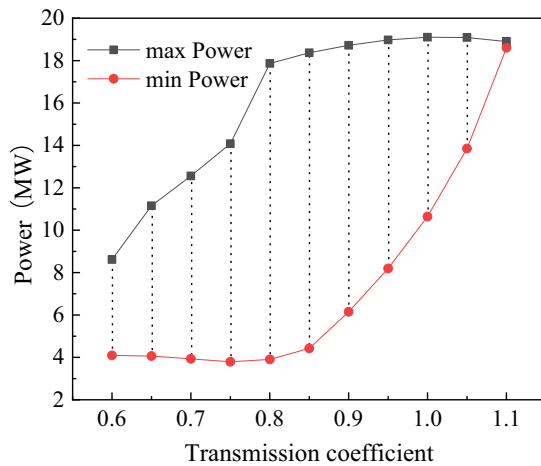


Fig. 7. The extreme values of compressor power.

change of the reliability. From the above analysis it is known that the multi-objective optimization model can evaluate the relationship between pipeline network reliability and throughput.

5.2.3 Analysis of consumer reliability

Consumer reliability can quantitatively reflect the probability that a consumer obtains the demanded flow rate. Consumer nodes that are susceptible to fault state can be identified by analyzing the consumer reliability of each consumer node based on the optimization results. For each transmission coefficient, the consumer reliability of each consumer node is averaged, and the results are shown in Figure 8.

Observing Figure 8, one can notice that the consumer reliability depends greatly on the transmission coefficient. The larger transmission coefficient is, on the whole the

lower the consumer reliability becomes. Consumer nodes with low consumer reliability have lower probability of receiving the required flow rate. Significantly, for large transmission coefficients, consumers No. 13, No. 24, and No. 25 show low reliability than others. The system operator should give prior monitoring to the three consumers, and gas supply can be guaranteed by other ways such as compressed natural gas vehicles. Comparatively, consumers No. 4, No. 7 and No. 10 always have high consumer reliability, indicating strong resistance to the failure situations of the pipeline network. In short summary, the multi-objective optimization model can analyze the ability of a pipeline network to deliver required flow rate to individual consumers.

5.2.4 Analysis of the impact of pipeline failure

The impact of failure of a pipeline on the overall transmission of the pipeline network can be investigated from the perspective of the minimum cut set. The minimum cut set of a consumer node refers to a set of pipelines that once encounter failure status leads to inability of satisfying the consumer's demand. In the optimization process, the iteration results approach the Pareto front gradually. The results of the last several iterations can be seen as operation schemes balancing the pipeline network reliability and power, which are the possible operating status of the pipeline network. The minimum cut sets appearing in the last three iterations are selected, and the percentage of consumers in failure caused by the break of each pipeline is calculated respectively, as presented in Figure 9.

It can be observed from Figure 9 that when the transmission coefficient increases, the consumers in failure account for a larger percentage, which causes lower pipeline network reliability. Also the percentage of consumers in failure caused by the pipe can reflect to what extent the failure of this pipeline disturbs gas supply of the pipeline network. For instance, when pipe No. 15 is in failure for $\beta = 1.1$, 88% of the consumers cannot reach the required flow rate. So the system operator should place more sensors to strengthen the monitoring and enhance the maintenance for this pipeline to reduce its failure possibility. However, the failure of pipe No. 37 only gives rise to 10% consumer failure, indicating that the failure of this pipeline produces little impact on the gas supply system. Thus the multi-objective optimization model can judge the influence of a single pipeline on the whole pipeline network, and provide valuable guidance in taking proper measures.

6 Conclusion

Reducing the operating cost has been the pursuit of previous optimization researches of gas pipeline networks, which however would lead to a decline in the pipeline network reliability. To achieve trade-off between reliability and operating cost, a multi-objective optimization model is developed in this study to determine optimal operation scheme for natural gas pipeline network. This model

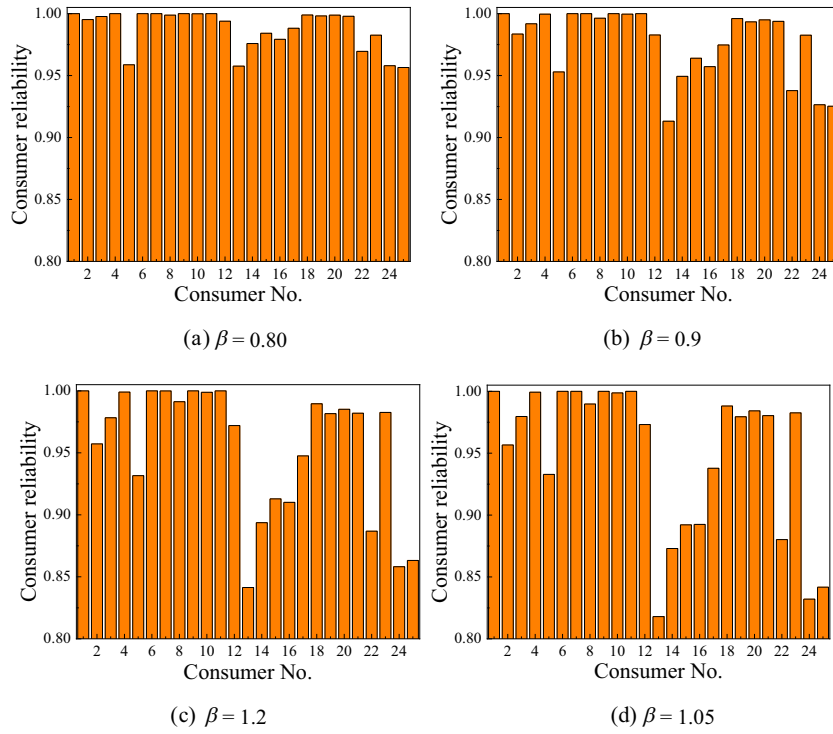


Fig. 8. Consumer reliability under different transmission coefficients.

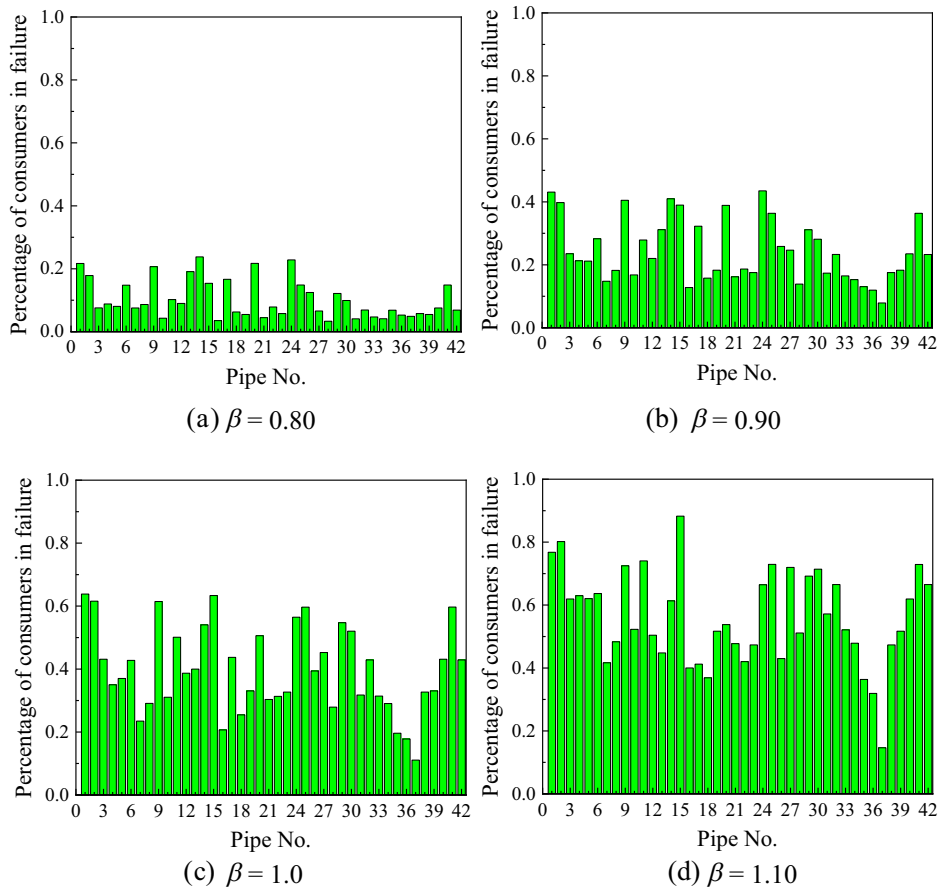


Fig. 9. Percentage of consumers in failure caused by the break of a pipe under different transmission coefficients.

considers a pipeline network with multiple components and a complicated topology. The evaluation of pipeline reliability takes the failure of each component and the hydraulic-thermal state of the fault pipeline network into consideration. The optimization variables are the rotating speed of the compressors and the opening of the valves. The established multi-objective optimization model can be solved effectively by DIMENS method and NS-saDE algorithm. Application of this proposed model is analyzed in a complicated natural gas pipeline network, by which the Pareto solution set and extreme values of the two optimal variables are discussed under different throughputs. There are the following conclusions:

1. The Pareto solution set obtained by the proposed model is able to reflect the quantitative correlations between pipeline network reliability and the total power. For different throughputs, larger total power results in higher pipeline network reliability. In cases of throughputs lower than rated load, pipeline network reliability is reduced to a small extent due to the reduced compressor power. While when the pipeline transports at a load larger than rated, a small decrease of compressor power significantly reduces the pipeline network reliability. The Pareto solution set assists to determine the operation scheme providing trade-off between pipeline network reliability and the total power.
2. The extreme values of the optimal variables stand for the maximum and minimum pipeline network reliability and operating cost under different throughputs. The limited throughput can be determined accordingly. When the network transports at a small load, the reliability is relatively high and is insensitive to the variation of compressor power. As the throughput increases, the maximum value of pipeline network reliability drops rapidly and the minimum value of compressor power rises rapidly. At the extreme throughput, high-power is required to ensure the normal operation of the pipeline network, which corresponds to the lowest reliability and the largest operating cost.
3. The probability of each consumer obtaining the demanded gas distribution can be quantitatively obtained by the model, which acts as a basis for determining the consumers for prior maintenance. At low throughput, the reliability of each customer is relatively high. With the increase in throughput, the reliability of some customers drops significantly, and these consumers are selected to give prior attention. Strengthening the minoring and maintenance of these consumers can effectively improve the pipeline network reliability.
4. When a pipeline is in failure, the percentage of consumers failing to get demanded gas supply can be calculated by the proposed model to evaluate the failure of this pipeline on the whole transmission. The pipelines, which when fail result in larger percentage of consumers in failure, should be given more attention to enhance the pipeline network reliability.

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Appendix

Table A1. Pipeline data.

Serial number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Starting node	1	1	34	4	3	2	5	22	6	4	4	4	12	12	11	13	10	14	9	15	15
Ending node	2	3	4	3	2	22	6	21	21	10	11	12	13	11	10	14	14	15	32	9	16
Length (km)	48	50	70	60	80	90	120	104	60	80	70	110	70	60	80	80	150	160	100	160	150
External diameter (mm)	406	406	406	406	508	508	406	406	406	406	406	406	406	406	508	406	406	406	406	406	406
Serial number	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Starting node	16	10	9	9	8	9	8	7	6	18	7	20	20	6	14	17	31	33	1	37	39
Ending node	17	30	17	36	17	7	18	18	7	19	38	19	21	23	24	25	6	10	35	8	20
Length (km)	160	100	130	80	110	90	60	84	40	60	80	64	90	40	40	40	60	100	70	80	80
External diameter (mm)	406	406	406	406	406	406	406	406	406	406	406	406	406	406	508	406	508	406	406	406	406

Table A2. Compressor data.

Serial number	1	2	3	4
Starting node	26	27	28	29
Ending node	1	6	9	11

Table A3. Performance data of compressor.

H (m)	η	Q_{in} (am ³ /h)	ε	n (r/min)	H (m)	η	Q_{in} (am ³ /h)	ε	n (r/min)
2080	0.87	3741	1.15	4412	4039	0.88	5369	1.3	6109
2024	0.87	4026	1.14	4412	3876	0.88	6000	1.29	6109
1927	0.88	4534	1.14	4412	3744	0.88	6495	1.28	6109
1802	0.88	5029	1.13	4412	3600	0.88	6978	1.26	6109
1691	0.88	5536	1.12	4412	3243	0.87	7981	1.24	6109
1559	0.87	6006	1.11	4412	3054	0.86	8513	1.22	6109
1484	0.86	6279	1.1	4412	2874	0.86	8959	1.21	6109
1372	0.84	6650	1.1	4412	2677	0.84	9442	1.19	6109
1269	0.82	7008	1.09	4412	2451	0.82	9975	1.17	6109
1130	0.8	7441	1.08	4412	2146	0.79	10 619	1.15	6109
2425	0.87	4044	1.17	4751	4963	0.88	6235	1.37	6788
2304	0.88	4589	1.17	4751	4757	0.88	6988	1.36	6788
2202	0.88	5035	1.16	4751	4420	0.88	8000	1.33	6788
2081	0.88	5542	1.15	4751	4230	0.88	8531	1.31	6788
1955	0.88	6025	1.14	4751	4055	0.87	8988	1.3	6788
1844	0.87	6420	1.13	4751	3801	0.87	9568	1.28	6788
1656	0.85	7014	1.12	4751	3618	0.86	9988	1.26	6788
1569	0.84	7298	1.11	4751	3152	0.83	10 988	1.22	6788
1429	0.82	7682	1.1	4751	2858	0.8	11 580	1.2	6788
1313	0.79	8065	1.09	4751	2646	0.78	12 000	1.18	6788
3172	0.88	4648	1.23	5430	5449	0.88	6719	1.41	7127
3115	0.88	4994	1.23	5430	5365	0.88	7037	1.41	7127
2980	0.88	5501	1.22	5430	5038	0.88	8016	1.38	7127
2858	0.88	5984	1.21	5430	4671	0.88	9006	1.35	7127
2566	0.87	6986	1.18	5430	4516	0.87	9459	1.33	7127
2413	0.86	7407	1.17	5430	4329	0.87	9997	1.31	7127
2219	0.85	7976	1.16	5430	3828	0.85	10 987	1.28	7127
2024	0.83	8497	1.14	5430	3480	0.83	11 500	1.25	7127
1838	0.81	8979	1.13	5430	3310	0.82	11 976	1.23	7127
1716	0.79	9314	1.12	5430	2977	0.78	12 685	1.2	7127

Table A4. Valve data.

Serial number	1	2	3	4	5
Starting node	31	32	35	36	38
Ending node	30	33	34	37	39

Table A5. Boundary data.

Serial number	1	2	3	4	5	6	7	8	9	10	11	12	13
Adjacent node	26*	2	3	4	5	27*	7	8	28*	10	29*	12	13
Serial number	14	15	16	17	18	19	20	21	22	23	24	25	
Adjacent node	14	15	16	17	18	19	20	21	22	23	24	25	

* The node connected with source, the others are connected with consumer.

Table A6. Components of natural gas.

Component	Volume fraction (%)
CH ₄	96.07
C ₂ H ₆	1.17
C ₃ H ₈	0.02
N ₂	0.71
CO ₂	2.03

Table A7. The design flow rate of consumers.

Serial number	2	3	4	5	7	8	10	12	13	14	15
Volume flow rate (10 ⁵ Nm ³ /h)	1.5	2.0	1.5	1.1	0.3	0.36	2	1.28	1.2	0.4	0.8
Serial number	16	17	18	19	20	21	22	23	24	25	
Volume flow rate (10 ⁵ Nm ³ /h)	0.4	0.32	0.8	0.5	0.6	0.8	1.5	1.8	0.4	1.2	