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EVALUATION ON GAS SUPPLY RELIABILITY OF URBAN GAS PIPELINE NETWORK

OCENA NIEZAWODNOŚCI DOSTAW GAZU W MIEJSKIEJ SIECI GAZOWEJ

As one of the lifeline projects, an urban gas network is a complex system, as it requires maintenance of the supply capacity when any single pipeline is isolated due to failure. For such a system, its reliability needs to be evaluated. Considering that existing structural reliability and hydraulic reliability analyses reflect different aspects of the working conditions of an urban gas network, system reliability theory is employed to explain that only the gas supply reliability can achieve a comprehensive evaluation of the work capacity of the entire urban gas network, as it takes into account the combined influence of the structural reliability and hydraulic reliability. To calculate the parameters in the gas supply reliability evaluation, such as pipeline failure rate, flow reduction in the gas network under different failure conditions, etc., some research achievements in the field of structural reliability and hydraulic reliability are fully utilized. Then, the detailed calculation procedures of these parameters are given to evaluate the gas supply reliability in terms of operational and practical considerations. Finally, using an example of a simple double-loop gas network, the detailed process of the gas supply reliability evaluation of an urban gas network is described, and the feasibility of this evaluation method is also illustrated.

Keywords: urban gas network; gas supply reliability; failure condition; flow reduction; pipeline failure; failure rate.

Miejska sieć gazowa – jeden z kluczowych elementów infrastruktury miasta – stanowi złożony system, ponieważ wymaga utrzymania zdolności przesyłowej gdy przepływ gazu w jednym z rurociągów zostaje zamknięty w wyniku awarii. W przypadku tego rodzaju systemów, konieczna jest ocena niezawodności. Biorąc pod uwagę, iż dostępne w literaturze analizy niezawodności konstrukcyjnej i niezawodności hydraulicznej odzwierciedlają różne aspekty warunków pracy miejskiej sieci gazowej, nie dają one pełnego obrazu niezawodności systemu jako całości. W artykule wykorzystano teorię niezawodności systemów, która pokazuje, że jedynie ocena niezawodności dostaw gazu stanowić może kompleksową ocenę wydajności pracy całej miejskiej sieci gazowej, ponieważ uwzględnia ona zarówno wpływ niezawodności konstrukcji jak i niezawodności hydraulicznej sieci. W pracy wykorzystano dotychczasowe obserwacje badawcze dotyczące oceny niezawodności konstrukcyjnej i niezawodności hydraulicznej sieci gazowej do obliczenia parametrów oceny niezawodności dostaw gazu, takich jak intensywność uszkodzeń rurociągu, redukcja przepływu gazu w sieci gazowej w różnych warunkach uszkodzeń, itp. Następnie, podano szczegółowe procedury obliczania tych parametrów w celu oceny niezawodności przesyłowej sieci gazowej pod kątem eksploatacyjnym i praktycznym. Na koniec, na przykładzie prostej sieci gazowej składającej się z dwóch pętli, opisano szczegółowy proces oceny niezawodności dostaw gazu w miejskiej sieci gazowej i zilustrowano możliwość wykorzystania proponowanej metody.

Słowa kluczowe: miejska sieć gazowa; niezawodność dostaw gazu; warunki uszkodzenia; ograniczenie przepływu; uszkodzenie gazociągu; intensywność uszkodzeń.

1. Introduction

As one of the lifeline projects of an urban area, an urban gas network is a form of a municipal utilities infrastructure. The main function of urban gas networks is to transmit qualified natural gas and distribute it to the residential, commercial and industrial gas users for satisfying their gas demands. An urban gas network is a complex system and is often configured as multiple loops to ensure stability in maintaining a certain supply capacity when any single pipeline is isolated due to failure. For such a system, its reliability needs to be studied [1-3].

Existing reliability analyses of urban gas networks mainly include the structural reliability and hydraulic reliability of two branches. The former, from a mechanics point of view, focuses on the research of the probability of structural integrity of each pipeline unit and a whole network, without considering the influence of hydraulic conditions [4-7]. On the contrary, the latter, from a hydraulics point of view, focuses on whether the network hydraulic regime can satisfy the design requirements for pressure and flow under all possible

conditions, especially when any single pipeline is isolated for repair due to failure [8,9]. In fact, the failure of any pipeline is a random probability event, that is, the hydraulic reliability analysis of urban gas networks also ignores the influence of the failure probability of any pipeline.

Structural reliability and hydraulic reliability analyses offer different perspectives and reflect different aspects of the working conditions of an urban gas network; furthermore, both of their research routes and conclusions are independent of each other, although there may be some intrinsic linkages between the two. Based on the above considerations, the system reliability theory is employed to explain that only the gas supply reliability can achieve a comprehensive evaluation of the working capacity of an urban gas network [10]. Furthermore, some research achievements in the field of structural reliability and hydraulic reliability are fully utilized to calculate the parameters in the gas supply reliability evaluation of urban gas networks.

2. Gas supply reliability of urban gas networks

According to the code of GB 50153-2008 "Unified standard for reliability design of engineering structures" in China, the reliability is defined as a type of "capacity" that the product completes the required functions in the specified condition and time interval. The product here refers to any system, equipment or component.

An urban gas network consists of numerous pipelines, valves, and other non-pipe elements. The "capacity" of an urban gas network to complete the "required functions" mainly refers to its supply natural gas capacity. The ideal service life and supply capacity of each urban gas network have been determined in the network planning and design stage. Thus, the gas supply reliability of urban gas networks can be defined as within the design service life, the capacity to transmit qualified natural gas and safely distribute it to the residential, commercial and industrial gas users [3, 10, 11]. The qualified natural gas here means that the pressure and flow of the natural gas supplied by urban gas networks should satisfy the user demands in the given design conditions.

For any urban gas network, only through strict design, construction, acceptance and other necessary procedures can it be implemented and placed into operation. An operating urban gas network can be considered as having strong network integrity (referred to as the "normal condition"), and consequently, it can complete the "required functions", i.e., it has the capacity to supply qualified natural gas to customers in accordance with the design requirements. With increasing service time, any pipeline in the urban gas network may fail, and the failed pipeline should be isolated from the network for repair or replacement. In this case, the integrity of the urban gas network will be disrupted (referred to as the "failure condition"), and consequently, the supply capacity will be influenced to some extent. After repairing or replacing the failed pipeline, the urban gas network will resume its normal condition and regain the designed supply capacity. Therefore, the urban gas network belongs to a type of repairable system, and its supply capacity relates to its integrity.

During the service time of an urban gas network, all of the pipelines undergo mutual conversions between the normal state and the failure state. Due to corrosion, aging, third-party damage or other reasons, some pipelines in the normal state will be converted to the failure state with a certain probability; in contrast, through repair or replacement, other pipelines in the failure state will be converted to the normal state with another certain probability. These mutual conversions of all of the pipelines will lead to the diversity of the integrity state of the urban gas network.

Considering an urban gas network consisting of N pipelines, for any pipeline j ($j=1, 2, \dots, N$), a two-valued function $x_j(t)$ is employed to represent the state of the pipeline j at a certain time t , that is, if the pipeline j is in normal state at the certain time t , $x_j(t)=1$; otherwise $x_j(t)=0$, representing the failure state. Consequently, all of the state functions of N pipelines constitute the integrity state vector of the urban gas network, as expressed by equation (1):

$$X(t)=[x_1(t), x_2(t), \dots, x_j(t), \dots, x_N(t)] \quad (1)$$

Here, t is the service time after the urban gas network is put into operation; $X(t)$ is the integrity state vector of the urban gas network at time t ; $x_j(t)$ is the state function of any pipeline j ($j=1, 2, \dots, N$) at time t ; and N is the number of pipelines in the urban gas network.

It is assumed that only a single pipeline failure per unit time will occur, and consequently, an urban gas network with N pipelines will have $(N+1)$ conditions, including a normal condition and N failure conditions.

The required functions of urban gas networks are to supply qualified natural gas in accordance with the design requirements of customers. The failure of any single pipeline may influence the supply capacity of an urban gas network, whereas different pipelines have different influences, due to their different positions within the network. During the service time, the integrity of an urban gas network always changes with the state changes of each pipeline, so the supply capacity of the urban gas network is a dynamic process with the change in the service time, as described by equation (2):

$$Q(t) = \phi[X(t)] \quad (2)$$

Here, $Q(t)$ is the supply capacity of an urban gas network at service time t .

According to the system reliability theory, the gas supply reliability of an urban gas network at service time t can be defined as the ratio of the supply capacity at time t to the designed supply capacity of the urban gas network, as is shown in equation (3) [2, 3, 12]:

$$R_{\text{net}}(t) = \frac{Q(t)}{Q_0} \quad (3)$$

Here, $R_{\text{net}}(t)$ is the supply reliability of an urban gas network at service time t and Q_0 is the designed capacity supply of the urban gas network.

As stated previously, during the service time, all of the pipelines in an urban gas network undergo mutual conversions between the normal state and the failure state. At time t , if the urban gas network has high integrity, it can complete the required functions and consequently has the designed supply capacity Q_0 ; on the contrary, if any pipeline j is isolated for repair due to failure, the urban gas network will be converted into the fault condition j and will lose a certain amount of supply capacity ΔQ_j , with the supply capacity decreased to Q_j .

As previously mentioned, an urban gas network with N pipelines has $(N+1)$ conditions, including one normal condition and N failure conditions. It is obvious that the condition of an urban gas network at time t is associated with the structure reliability of each pipeline; nevertheless, the supply capacity in each specific condition of the urban gas network is associated with the hydraulic reliability. The change in the integrity state of an urban gas network can be regarded as a homogeneous Markov process; thus, according to formula (3), the supply reliability of the urban gas network at time t can be derived as follows [2, 11]:

$$R_{\text{net}}(t) = 1 - \sum_{j=1}^N \frac{\Delta Q_j}{Q_0} \frac{\lambda_j l_j}{\sum (\lambda_j + \mu_j) l_j} [1 - e^{-(\sum \lambda_j + \mu_j) l_j t}] \quad (4)$$

Here, ΔQ_j is the lost supply capacity of an urban gas network under failure condition j , compared to the capacity under the normal condition, referred as to the flow reduction, in Nm^3/h ; λ_j is the failure rate of pipeline j , in $\text{times}/(\text{km}\cdot\text{a})$; l_j is the length of pipeline j , in km ; and μ_j is the repair rate of pipeline j , in $\text{times}/(\text{km}\cdot\text{a})$.

As shown in equation (4), the supply reliability of an urban gas network changes with the service time t . Under a given service time, the supply reliability of an urban gas network is not only related to the flow reduction under each failure condition but is also closely related to the repair rate and failure rate of each pipeline.

Equation (4) also shows that the supply reliability of an urban gas network can achieve a comprehensive evaluation of the work capacity of the entire urban gas network, as it takes into account the combined influence of the structural reliability and hydraulic reliability.

To make the evaluation of gas supply reliability more operational and practical, the following will make full use of some research achievements in the field of structural reliability and hydraulic reliability to calculate the parameters in the gas supply reliability evaluation, such as the pipeline failure rate, pipeline repair rate, and flow reduction of the urban gas network under different failure conditions.

3. Calculation of the gas supply reliability parameters

3.1. Pipeline failure rate

The scientific determination of the pipeline failure rate requires a complete and detailed failure statistics database. The European Gas Pipeline Incident Data Group (EGIG), with abundant gas pipeline failure data from 15 countries, including France, Germany, Denmark, etc., is useful in determining the pipeline failure rate and improving the failure level [13-15]. Unfortunately, the construction of urban gas pipeline failure databases has not attracted adequate attention and is therefore relatively less advanced in China; moreover, the abundance and validity of the collected data are also limited. At present, the determination of the urban gas pipeline failure rate in China is mainly based on expert knowledge, such as the Kent method, fault tree analysis, analytic hierarchy process (AHP), the fuzzy comprehensive evaluation method, etc. [16-18]. However, methods based on expert knowledge can only obtain the relative values of pipeline failure rate rather than absolute values, not to mention these methods are very subjective.

At present, there has been considerable research into the reliability of pipeline structures, and its main purpose has been to obtain the failure probability of pipelines [19-21]. Moreover, according to system reliability theory, the failure rate is defined as failure probability in unit time [22, 23]. That is, for a properly functioning pipeline that has not failed until time t , the failure rate is the probability of the pipeline failure occurring in the next unit time dt . The relationship between the two is as follows:

$$\lambda(t) = -\frac{1}{1 - P_f(t)} \frac{d[1 - P_f(t)]}{dt} = \frac{dP_f(t)/dt}{1 - P_f(t)} \quad (5)$$

Here, $\lambda(t)$ is the pipeline failure rate, in times/(km·a); $P_f(t)$ is the failure probability of the pipeline; and t is the service time of the operating pipeline, in a.

When there is no sufficient pipeline failure database, it is feasible to adopt the method based on structural reliability analysis to determine the pipeline failure rate [24-26]. The main calculation processes of the method are as follows:

① The parameters affecting the pipeline failure are regarded as random variables. According to related information for a given pipeline, the probability distribution types and statistical features such as the mean and variance of the random parameters are reasonably determined.

② The possible failure model for the pipeline is analyzed. According to the stress-strength interference theory, the limit state equation of pipeline failure is established.

③ Using the Monte Carlo method, or Linear Second Order Moment Method or any other related algorithm, the pipeline structural reliability is analyzed, and consequently, the failure probability of the pipeline can be obtained.

④ According to the relationship between failure probability and failure rate, i.e., equation (5), the pipeline failure rate can be calculated.

In the reference [27] by the authors, the failure probability of an urban gas pipeline is analyzed by using the structural reliability

theory, and the changes with service time are obtained, as shown in Figure 1.

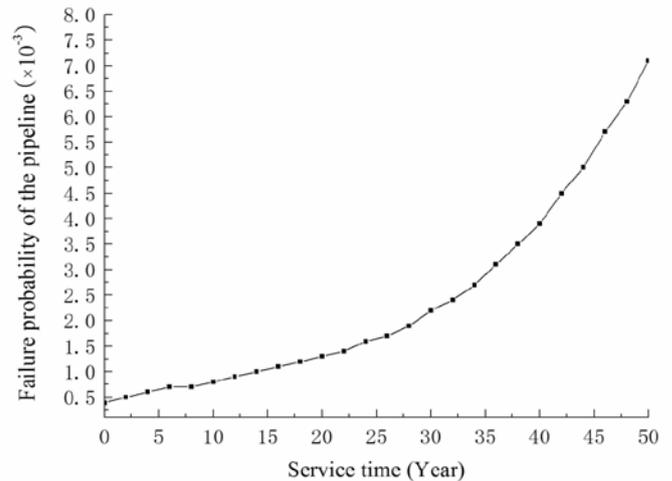


Fig. 1. Failure probability of the pipeline changes with service time [27].

Taking into account $P_f(t) = 1$ when $t=0$, the relationship between failure probability and the failure rate of the above specified pipeline can be derived from equation (5), as follows:

$$\lambda(t) = -\frac{\ln P_f(t)}{t} = -\frac{\ln(1 - P_f(t))}{t} \quad (6)$$

According to equation (6) and the change in the failure probability with service time in Figure 1, the pipeline failure rate of different service times can be determined, as shown in Figure 2.

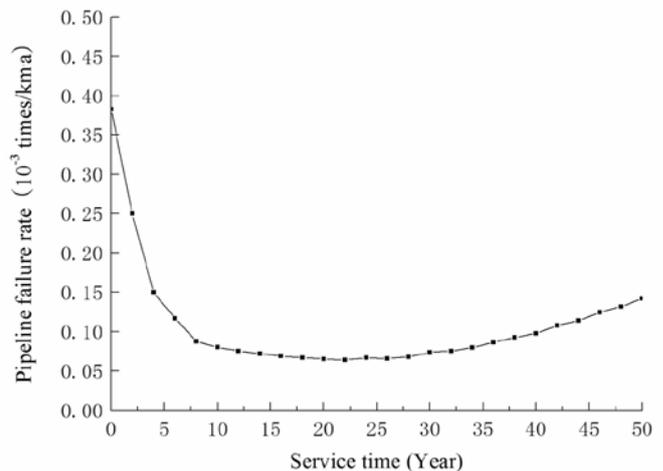


Fig. 2. Pipeline failure rate changes with service time.

As shown in Fig. 2, the pipeline failure rate curve based on the structural reliability analysis method presents all of the features of the “bathtub curve”, which is considered to be the typical failure rate curve. In the early stages of operation, the pipeline failure rate is rather high and gradually decreases with the service time. In the middle stages, the pipeline failure rate is maintained at a lower level, which can be approximated as a constant for convenience of discussion, i.e., $\lambda(t) = \lambda = \text{Constant}$. Take $t=20$ as an example; the failure rate λ is

only 0.065×10^{-3} times/(km·a). In the late stages, however, the pipeline failure rate increases annually.

3.2. Pipeline repair rate

The pipeline repair rate is the probability that a failed pipe that was not repaired during time t can be repaired in the next unit time dt .

The pipeline repair rate is associated with the maintenance time of the pipeline. The maintenance time of the pipeline is defined as the time taken from failure detection to the recovery of normal function, including the time of failure diagnosis, failure location, failure post-processing, recovery, etc. This time depends on the enterprise's management level, maintenance equipment and maintenance capability, etc., so the repair rates of all pipelines of the same enterprise have the same value.

Considering that different gas supply enterprises have different operation management levels, maintenance equipment and maintenance capacities, and the above-mentioned factors also affect the pipeline failure rate of the corresponding enterprise, the pipeline repair rate of different enterprises can be determined according to the average value of all of the pipeline failure rates of the corresponding enterprise.

In general, the pipeline repair rate has an order of magnitude difference compared to the pipeline failure rate, as in the following function relation [11].

$$\mu = (10 \sim 1000)\bar{\lambda} \quad (7)$$

Here, μ is the repair rate of all pipelines of an enterprise, in times/(km·a); $\bar{\lambda}$ is the average value of all pipeline failure rates of the corresponding enterprise, in times/(km·a).

3.3. Flow reduction of an urban gas network under different failure conditions

As is known from Equation (4), the supply reliability evaluation of an urban gas network involves flow reduction of the network under each failure condition, which implies that N flow reductions require individual calculation for an urban gas network consisting of N pipelines, which can, in theory, be performed through the network hydraulic regime analysis. However, when any single pipeline fails and needs to be isolated from an urban network for repair, the flow through some pipelines will change, as will the flow directions in some other pipelines, leading to ambiguity in the series-parallel relationships between the pipelines in the network, as well as an increase in the complexity of the network hydraulic regime analysis.

Because of the above situation, the determination of the flow reduction of an urban gas network under different failure conditions has not yet been reasonably solved. In reference [11], the flow reduction is obtained from the static load diagram of the network, which is obviously impractical. In reference [2], the hydraulic regime of an urban gas network under normal conditions is analyzed, and the flow through each pipeline under normal conditions is approximately considered to be the flow reduction under the corresponding failure condition. This simple method allows for simultaneous the determination of the flow reduction under each failure condition with the hydraulic calculation of the network such that it has certain operability. However, although the actual flow reduction due to the failure of any one pipeline is positively related to the flow through the corresponding pipeline under normal conditions, it is also affected by many other factors, such as the utilization coefficient of pressure drop, the topology structure of the urban gas network, etc. The larger the scale of the urban gas network, the greater is the inaccuracy of the simple method.

It is considered that the emphasis of hydraulic reliability analysis is to study the influence of any failure pipeline on the whole gas

network by using fluid mechanics. In reference [8], the hydraulic reliability of an urban loop high-pressure gas network is analyzed, and a feasible method for determining the actual nodal flow is presented. After proper adjustments, the method can also be employed to calculate the flow reduction of an urban gas network under failure conditions. As for an urban gas network consisting of N pipelines and M consumer nodes, the steps for the flow reduction σ_{equiv} of the network under failure condition j are as follows:

① According to the known designed flow of each consumer node Q_i ($i=1, 2, \dots, M$), simulate the hydraulic regime of the urban gas network under normal conditions.

② If any single pipeline fails and needs to be isolated from the urban gas network, it is first considered that the pressure P_i ($i=1, 2, \dots, M$) of each node in the network can still meet the required minimum pressure P^{\min} of the network. That is, assume that the actual nodal flow Q_i^{avl} ($i=1, 2, \dots, M$) of each consumer node is equal to the designed nodal flow Q_i under each failure condition j .

③ According to the actual nodal flow Q_i^{avl} and the new topology of the urban gas network due to the isolation of failure pipeline j , simulate each nodal pressure P_i under failure condition j .

④ The pressures of all of the nodes in the urban gas network are checked to determine whether the inequality $P_i \geq P^{\min}$ is true. If "yes", the network pressure reserve is capable of compensating for extra pressure losses despite the occurrence of a failure. That is, the network has the ability to convey Q_i^{avl} for all of the consumer nodes in the network, such that Q_i^{avl} is a reasonable value.

Otherwise, the network is unable to convey qualified natural gas to satisfy Q_i^{avl} and then moves on to step ⑤ to adjust Q_i^{avl} .

⑤ The node with the lowest pressure in the urban gas network is identified, and the Q_i^{avl} of this node is multiplied by 0.99 to gradually reduce its actual flow. Steps ③, ④, and ⑤ are repeated until the pressures of all of the nodes satisfy the minimum required pressure P^{\min} .

⑥ The final adjusted nodal flow Q_i is the actual flow of each consumer node. It is evident that the flow reduction σ_{equiv} of the urban gas network under failure condition j is equal to

$$\left(\sum_{i=1}^M Q_i - \sum_{i=1}^M Q_i^{avl} \right).$$

According to the above steps to write the program, by adding a loop statement inside the program, the flow reductions of an urban gas network under all failure conditions can be calculated both easily and quickly.

4. Example

Using the above method, the gas supply reliability of an urban gas network can be expediently evaluated. The main purpose of the evaluation is for an overall consideration of the structural reliability of all of the pipeline units and the hydraulic regimes under all the failure conditions to have a comprehensive capacity analysis of an urban gas network.

Considering the complexity of an urban gas network system consisting of dozens or even hundreds of pipelines, making it difficult to identify some of the most essential conclusions, this section employs the simple double-loop gas network in reference [8] to illustrate the process and the feasibility of this evaluation method. As long as this method is feasible, it can be extended to any complex urban gas network.

An urban gas network is shown in Fig. 3. Seven branches, numbered from 1 to 7 (in parentheses), represent seven high-pressure gas pipelines, with the impedance of each being 1.2. Each pipeline is equipped with two valves, one at each end (not shown in the figure), to isolate the network system when it fails. ① to ⑤ represent five consumer nodes, which can be regarded as five high-medium pressure

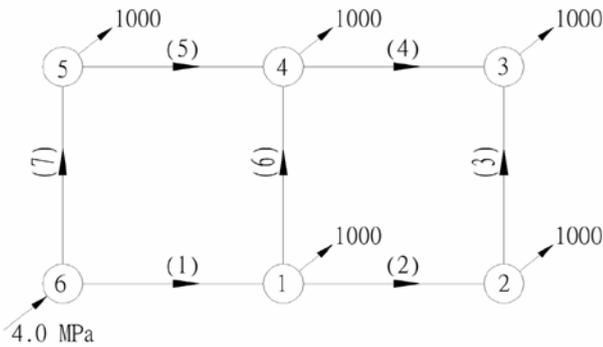


Fig. 3. Schematic of an urban gas network

regulating stations, supplying natural gas to residential, commercial or industrial areas as previously described. Node ⑥ represents the gas source station. The arrows in the figure represent the natural gas flow directions. Under normal conditions, the pressure of node ⑥ is held constant at 4.0 MPa, while the designed flow of each consumer node is 1000 Nm³/h. The minimum required pressure in the gas network is 2.5 MPa.

According to equation (1) and the network topological structure in Fig. 3, the integrity state vector of the urban gas network can be expressed as follows:

$$X(t) = [x_1(t), x_2(t), x_3(t), x_4(t), x_5(t), x_6(t), x_7(t)] \quad (8)$$

Because the failure rate and failure time of each pipeline are different, the urban gas network with 7 pipelines may have 8 conditions during the service time. They can be expressed as:

- $X_0(t) = [1, 1, 1, 1, 1, 1, 1]$,
- $X_1(t) = [0, 1, 1, 1, 1, 1, 1]$,
- $X_2(t) = [1, 0, 1, 1, 1, 1, 1]$,
- $X_3(t) = [1, 1, 0, 1, 1, 1, 1]$,
- $X_4(t) = [1, 1, 1, 0, 1, 1, 1]$,
- $X_5(t) = [1, 1, 1, 1, 0, 1, 1]$,
- $X_6(t) = [1, 1, 1, 1, 1, 0, 1]$,
- $X_7(t) = [1, 1, 1, 1, 1, 1, 0]$.

Among them, $X_0(t)$ represents the urban gas network in normal conditions and can satisfy all of the designed supply capacity. Each of the remaining seven vectors respectively represents one failure condition of the urban gas network and can only satisfy part of the designed supply capacity.

The conversion of the urban gas network from normal conditions to each failure condition is caused by the failure of any of the 7 pipelines. Each single pipeline failure corresponds to a unique failure condition. Considering that different pipelines have different design parameters, construction technology, service times, operating environments, etc., the failure rates of each pipeline are also different. Based on investigation and statistics of the actual data of each pipeline, the failure rates of pipeline (1) to (7) can be calculated according to the method introduced in Section 3.1. Provided that the service time of the urban gas network is 10 years, the failure rate of each pipeline can be calculated, and the results are shown in Table 1.

Table 1. The failure rate of each pipeline (10⁻³ times/((km·a))

Pipeline number	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Failure rate	0.122	0.162	0.340	0.213	0.331	0.216	0.113

According to the method of Section 3.3, through hydraulic reliability analysis of the urban gas network, the total network flow and the flow reductions of the network under normal and seven failure conditions can be obtained. The calculation results are shown in Table 2.

Table 2. The total network flow and the flow reductions under different conditions (Nm³/h).

Condition number	Integrity state vector	Total network flow	Flow reduction
0	[1,1,1,1,1,1,1]	5000	0
1	[0,1,1,1,1,1,1]	2476	2524
2	[1,0,1,1,1,1,1]	4393	607
3	[1,1,0,1,1,1,1]	4990	10
4	[1,1,1,0,1,1,1]	4514	486
5	[1,1,1,1,0,1,1]	3746	1254
6	[1,1,1,1,1,0,1]	4905	95
7	[1,1,1,1,1,1,0]	2746	2254

Considering the enterprise's management level, maintenance equipment and maintenance capability, etc., the pipeline repair rate is assumed as 100 times that of the average value of all pipeline failure rates, i.e., $\mu = 100\bar{\lambda} = 100 \times \sum_{j=1}^7 \lambda_j / 7 = 0.0214$ times/(km·a).

According to equation (4), the gas supply reliability of the urban gas network at 10 years can be calculated as follows:

$$R_{net}(10) = 0.9623$$

Similarly, the changes in the gas supply reliability of the urban gas network with the service time can be calculated, as shown in Fig. 4. With increasing service life, the gas supply reliability decreases from 1.0 at the beginning to 0.914 at 50 years.

It should be noted that the improvement of gas supply reliability of urban gas networks should be considered from aspects of network planning and design, network hydraulic regime analysis, pipeline integrity management, etc. This example is used to describe the detailed process of the gas supply reliability evaluation and to illustrate the feasibility of this method. Unfortunately, until now, the use of evaluation results to guide current gas engineering design and operation management has had no standard of reference.

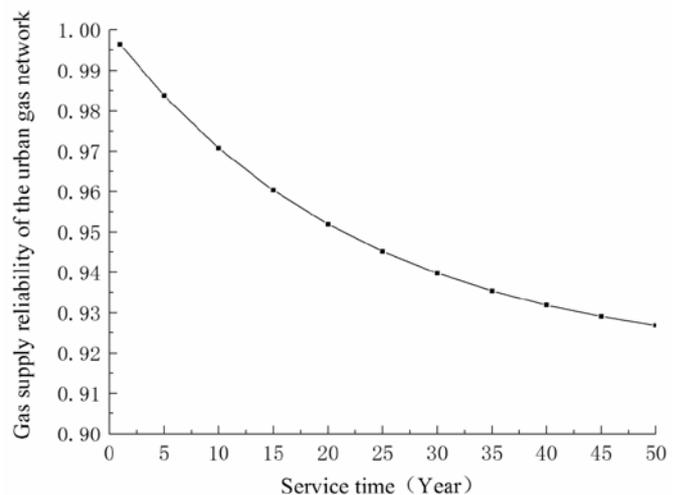


Fig. 4. Gas supply reliability changes with service time

However, from the perspective of the development of technology, the gas supply reliability evaluation of urban gas networks should be applied in practical engineering, and the requirement for gas supply reliability of each specific urban network should also be introduced in the future. Certainly, the scientific requirements of gas supply reliability should be gradually accumulated through the actual operation data of many urban networks. In addition, data for different types and scales of urban gas networks should be obtained to explore different gas supply reliability ranges, as well as to make timely adjustments according to technological and economic changes.

5. Conclusion

An urban gas network is one of the lifeline projects of urban areas, and its supply capacity is not only related to the structural reliability of each pipeline but also to the hydraulic conditions of the whole network. Structure reliability analysis and hydraulic reliability analysis offer different perspectives of an urban gas network and reflect differ-

ent aspects of the network working conditions; however, they cannot be used to make a comprehensive capacity analysis of an urban gas network.

The system reliability theory is employed in this study to examine gas supply reliability of an urban gas network. The research achievements both in the structural reliability and hydraulic reliability fields are fully utilized to calculate the parameters in the gas supply reliability evaluation, making the evaluation more operational and practical. Finally, using an example of a simple double-loop gas network, the detailed process of the gas supply reliability evaluation of an urban gas network is described, and the feasibility of this evaluation method is also illustrated.

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References

1. Sukharev M G, Karasevich A M. Reliability models for gas supply systems. *Automation and Remote Control* 2010; 71(7): 1415–1424, <https://doi.org/10.1134/S0005117910070155>.
2. Yan M Q. Reliability assessment on gas supply of gas transmission and distribution network. *Gas & Heat* 2014; 34(1): 01–05.
3. Su H, Zhang J J, Zio E, et al. An integrated systemic method for supply reliability assessment of natural gas pipeline networks. *Applied Energy* 2018; 209: 489–501, <https://doi.org/10.1016/j.apenergy.2017.10.108>.
4. Kucheryavyi V I, Milkov S N. Strength reliability of gas-supply pipes of large diameter. *Journal of Machinery Manufacture and Reliability* 2014; 43(5): 448–452, <https://doi.org/10.3103/S1052618814050094>.
5. Kong F T, Pesimis K. Reliability prediction for corroding natural gas pipelines. *Tunnelling and Underground Space Technology* 2017; 65: 91–105, <https://doi.org/10.1016/j.tust.2017.02.009>.
6. Szybka J, Boniec Z, Pilch R. Forecasting the failure of a thermal pipeline on the basis of risk assessment and exploitation analysis. *Eksploracja i Niezawodność - Maintenance and Reliability* 2011; 4: 5–10.
7. Tchórzewska-Cieślak B, Pietrucha-Urbanik K, Urbanik M. Analysis of the gas network failure and failure prediction using the Monte Carlo simulation method. *Eksploracja i Niezawodność - Maintenance and Reliability* 2016; 18(2): 254–259, <https://doi.org/10.17531/ein.2016.2.13>.
8. Li J, Qin C K, Yan M Q, et al. Hydraulic reliability analysis of an urban loop high-pressure gas network. *Journal of Natural Gas Science and Engineering* 2016; 28: 372–378, <https://doi.org/10.1016/j.jngse.2015.12.010>.
9. Gheisia A, Naser G. Simultaneous multi-pipe failure impact on reliability of water distribution systems. *Procedia Engineering* 2014; 89: 326–332, <https://doi.org/10.1016/j.proeng.2014.11.195>.
10. Myers A. *Complex system reliability*. Berlin: Springer Publishers, 2010, <https://doi.org/10.1007/978-1-84996-414-2>.
11. Ionin, Li Y, Wang M. *Gas Supply*. Beijing: China Building Industry Press, 1986.
12. Marvin R, Arnljot H. *System reliability theory: models, statistical methods, and applications*, 2nd Edition. Wiley Online Library, 2003.
13. EGIG- European Gas Pipeline Incident Report Group. *Report of the European Gas Pipeline Incident Group* 2015.
14. Mather J, Blackmore C, Petrie A, et al. An assessment of measures in use for gas pipelines to mitigate against damage caused by third party activity. *HSE Contract Research Report* 2001.
15. Vianello C, Maschio G. Quantitative risk assessment of the Italian gas distribution network. *Journal of Loss Prevention in The Process Industries* 2014; 32(1): 5–17, <https://doi.org/10.1016/j.jlp.2014.07.004>.
16. Dong Y, Yu D. Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis. *Journal of Loss Prevention in The Process Industries* 2005; 18(2): 83–88, <https://doi.org/10.1016/j.jlp.2004.12.003>.
17. Guo Y B, Meng X L, Meng T, et al. A novel method of risk assessment based on cloud inference for natural gas pipelines. *Journal of Natural Gas Science and Engineering* 2016; 30: 421–429, <https://doi.org/10.1016/j.jngse.2016.02.051>.
18. Liang W, Hu J, Zhang L, et al. Assessing and classifying risk of pipeline third-party interference based on fault tree and SOM. *Engineering Applications of Artificial Intelligence* 2012; 25(3): 594–608, <https://doi.org/10.1016/j.engappai.2011.08.010>.
19. Dundulis G, Žutautaitė I, Janulioni R, et al. Integrated failure probability estimation based on structural integrity analysis and failure data: natural gas pipeline case. *Reliability Engineering & System Safety* 2016; 156: 195–202, <https://doi.org/10.1016/j.res.2016.08.003>.
20. Qian G, Niffenegger M, Zhou W, et al. Effect of correlated input parameters on the failure probability of pipelines with corrosion defects by using FITNET FFS procedure. *International Journal of Pressure Vessels and Piping* 2013; 105(4): 19–27, <https://doi.org/10.1016/j.ijvp.2013.02.004>.
21. Zhao Y F, Song M D. Failure analysis of a natural gas pipeline. *Engineering Failure Analysis* 2016; 63(5): 61–71, <https://doi.org/10.1016/j.engfailanal.2016.02.023>.
22. Gertsbakh I B. *Statistical reliability theory*. Wiley Online Library, 1989.
23. Elsayed A. *Reliability Engineering*, 2nd Edition. Wiley Online Library, 2012.
24. Robert E M, Andre T B. *Structural reliability analysis and prediction*, 3rd Edition. New Jersey: Wiley-Blackwell, 2018.
25. Bisaggio H C, Netto T A. Predictive analyses of the integrity of corroded pipelines based on concepts of structural reliability and Bayesian inference. *Marine Structures* 2015; 41: 180–199, <https://doi.org/10.1016/j.marstruc.2015.02.003>

26. Huang X M, Li M Z, Peng S N, et al. Assessment methods of failure probability on gas pipelines. *Acta Petrolei Sinica* 2010; 31(4): 664-667.
27. Qin C K, Li J, Yan M Q, et al. Analysis of failure probability of urban underground gas pipelines under corrosion effect. *Natural Gas Industry* 2015; 35(5): 85-89.

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