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# An Evaluation Method of Natural Gas Pipeline Network Complexity Based on Complex Network Theory

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## ABSTRACT

Natural gas pipeline networks gradually show a trend of system complexity. The complicated topological structure of natural gas pipeline network is likely to cause inherent structural defects, which has critical impacts on the safe operation of natural gas pipeline network. In order to understand the complexity of natural gas pipeline network and its behaviors when facing structural changes, this paper studies the complexity of natural gas pipeline network based on complex network theory. The complexity analysis results in this paper show that when the gate station is used as the expression scale, natural gas pipeline network has the small-world characteristics. This paper also creatively studied the structural characteristics of natural gas pipeline network, and defined the expression of natural gas pipeline network structure. The research results show that the 3-3 structure and the 3-4 structure are the main structures of natural gas pipeline network, which is of great significance to the future research of natural gas pipeline network.

**Keywords:** natural gas pipeline network; complex networks theory; network structure

## 1. INTRODUCTION

With the development of natural gas pipeline network, its topological structure is becoming increasingly complex. Natural gas pipeline networks gradually show a trend of system complexity. The complicated topological structure of natural gas pipeline network is likely to cause inherent structural defects, which has critical impacts on the safe operation of natural gas pipeline network.

Current researches mainly aimed at ensuring the safe and reliable operation of natural gas pipeline network, which has become a research hotspot[1-3]. However, the complexity trend of natural gas pipeline network and its potential impacts are rarely considered in these studies. Therefore, current researches on the complexity of natural gas pipeline network are not in depth. The accidents that have occurred over the past years have also highlighted the fragile side of the modern large-scale natural gas pipeline network system structure. And it objectively shows that the complexity research of natural gas pipeline network is imperative. Complexity is an inherent property of a large-scale network topology. Understanding this property not only helps to better grasp the controllability of the network system, but also helps to understand the dynamic behaviors that occur on the network, such as cascade effects, network robustness, network reliability, etc.

As a combination of statistical physics and graph theory, complex network theory is an important method for studying complex systems[4-6]. It focuses on the topological structure formed by the interaction of all units in the system and dynamic behaviors that occur in the system. The view that structure determines function is the basis for understanding the research of complex systems. At the beginning of the 21st century, the development of complex network theory has reached its own golden age. In recent years, complex network theory has been effectively applied in the fields of

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sociology, biology, engineering and so on. These studies provide theoretical bases for the complexity analysis of natural gas pipeline network system.

This research is an exploration of applying the emerging complex network science to the complexity research of natural gas pipeline networks. This paper draws on the method experience of network complexity researches in other research fields, and analyses the complexity of natural gas pipeline network and its structural characteristics in detail. Complexity analysis is helpful to increase the understanding of the network topology and analyze the reasons for the complexity of natural gas pipeline network from a microscopic point of view. The complexity evaluation method of natural gas pipeline network proposed in this paper can provide a basis for the evolutionary mechanism of natural gas pipeline network. By analyzing the dynamic behaviors of natural gas pipeline network in the face of different accident disturbances, the reliability and resilience of natural gas pipeline network can be evaluated.

## 2. MATERIALS AND METHODS

### *2.1 The modelling of natural gas pipeline networks*

This paper establishes two undirected and unweighted graphs, starting from the most basic topological structure graph to analyze the complexity of natural gas pipeline network. The expression scale is the gate station, and the modelling size is 44 in case 1 and 92 in case 2, that is, there are 44 nodes in case1 and 92 nodes in case 2, irrespectively. The edge is the pipeline between gate station and substation. This model is simplified as follows: the units that do not affect the flow of the pipeline, such as the pressure regulating station and the valve chamber, are regarded as part of the pipeline, and together with the pipeline are regarded as the edges in the model. Since the statistical description value has nothing to do with the direction and weight value, two undirected weightless graphs are established, and different node types have no effect on the statistical description value, and the node can be regarded as an indifference node. The established network model diagrams are shown in Fig. 1 and Fig. 2.

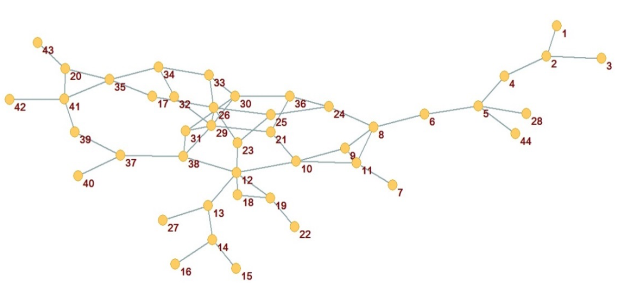

Fig. 1. The network model diagram of natural gas pipeline network, case 1

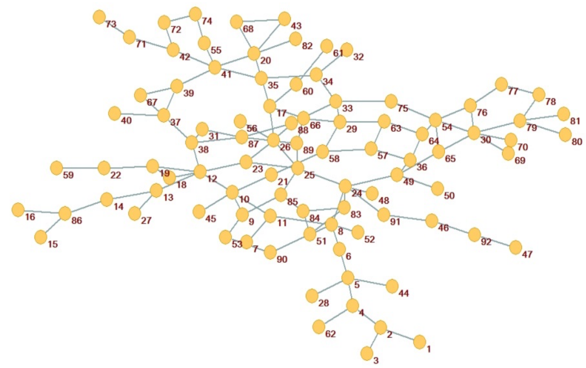

Fig. 2. The network model diagram of natural gas pipeline network, case 2

### *2.2 The structural feature analysis of natural gas pipeline network*

As shown in Fig.3, branch structures and ring structures are generally considered to be the smallest structural units of natural gas pipeline network. However, this research subdivides the smallest structural unit of pipeline network, and uses the connection edge and the node degree at the two ends of the connection edge as the standard for dividing the structure. Through the statistical subdivision of the structure, this paper explored and studied whether the natural gas pipeline network has specific structural characteristics.

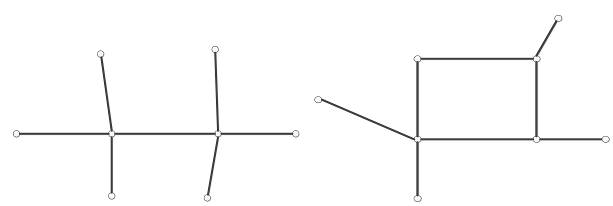

Fig. 3. Dendritic pipeline network and annular pipeline network diagram

The following uses a case to explain in detail how this paper studies the structural characteristics of natural gas pipeline network. As shown in Fig.4, the pipeline network has 11 nodes and 10 edges. By observing the structure, we can see that the nodes at both ends of edge 1 are node 1 and node 2. The node degree of node 1 is 1, and the node degree of node 2 is 3. This paper defines such a structure as 1-3, where 1-3 and 3-1 is equivalent, and the number in the front is customarily smaller than the number in the back. In the same way, the nodes at both ends of the edge 8 are node 6 and node 9. The node degree of node 6 is 4, and the node degree of node 9 is 3. Such a structure is defined as 4-3.

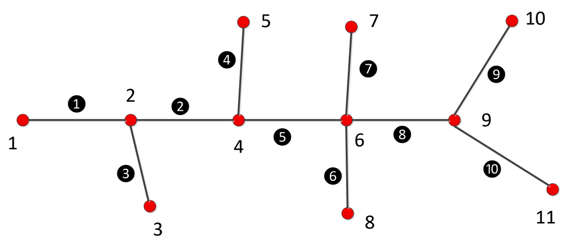


Fig. 4. A case of pipeline network

## 3. RESULTS AND DISCUSSIONS

The natural gas pipeline network is an integrated, man-made functional network, which contains many units with different functions, such as compressor stations, transmission stations, pressure regulating stations, etc. A large number of units with different functions increase the complexity of the network. Therefore, ensuring that they can work together in the same system is a difficult and complex task. Although the number of natural gas pipeline network units is relatively large, many examples show that the number of pipelines in the pipeline network is in the same order of magnitude as the number of units. If the adjacency matrix is used to represent the natural gas pipeline network, the matrix must be a sparse matrix. The above-mentioned macro characteristics of the natural gas pipeline network conform to the manifestation of a complex network, so the natural gas pipeline network is a complex network.

As a complex network, the natural gas pipeline network has its own unique complexity. Although due to the limitations of objective data, the current research cannot fully include all types of components with different functions and the actual connections between components into the network model, but research in various fields proves that complex networks have family characteristics, that is, different Networks of the same type of scale will have similar complexity and dynamic behavior, and local networks and global networks will also have similar complexity and dynamic behavior.

As shown in Table 1, although the scales of the two pipeline networks are different, the difference in average degree and clustering coefficient is small, and the change in the pipeline network scale does not affect the average degree and clustering coefficient. Although the 92-node pipeline network is twice as large as the 44-node pipeline network, the average path length does not show up the same trend of change. This also strengthen the view that natural gas pipeline networks have small-world characteristics, because from the dynamic point of view, changes in the scale of the network can be understood as the growth of the network. In the growth process of a network with small-world characteristics, the average path length increase will not be proportional to the multiple of the scale change, but will be proportional to the logarithm of the multiple of the scale change. As the scale of the network increases, by observing the change trend of structural entropy, it can be known that the network is becoming increasingly uniform, and the networks with small-world characteristics are more uniform. The distribution patterns of the degree distribution of the two pipeline networks are both high in the middle and low on both sides, which is an obvious small-world network. In the two pipeline networks, the number of nodes with a node degree of 2 is relatively low, and the proportion of nodes with a node degree of 2 is relatively small, and is less than the probability of 1 and 3. The degree distributions of the two have poor first-order fitting effect in the double logarithmic coordinate system, so none of them have scale-free characteristics. Therefore, when the gate station is used as the scale of expression, the natural gas pipeline network has the small-world characteristics but not scale-free characteristics.

Table 1 The information table of different network's statistical description

| Metrics | Case 1 | Case 2 |
|---|---|---|
| Number of nodes | 44 | 92 |
| Average degree | 2.68 | 2.58 |
| Clustering coefficient | 0.12 | 0.10 |
| Average path length | 4.79 | 5.82 |
| Structural entropy | 3.65 | 4.38 |
| Normalized structure entropy | 0.88 | 0.91 |
| Degree distribution pattern | High in the middle and low on both sides | High in the middle and low on both sides |

 

It can be seen from Table 2 that the 3-3 structure and the 3-4 structure are the main structures of the pipeline network, indicating that the pipeline network has more branched structures, reflecting the idea of satisfying both the gas supply requirements and the economy in the pipeline network design. Except for a few main structures, the proportions of other structures are roughly the same. On the one hand, the structure of the natural gas pipeline network has the characteristics of 'outstanding' (some structures account for much larger proportions than others). On the other hand, the 'outstanding' structure accounts for about 20%, while other structures are more evenly distributed.

Table 2 Different network's structure information table

| Network's structure information | Case 1 | Case 2 |
|---|---|---|
| The most structure | 3-4 | 3-4 |
| The second most structure | 3-3 | 3-3 |
| The third most structure | 1-3 | 1-3 |

## 4. CONCLUSIONS

Considering all of this, this paper firstly proposed a natural gas pipeline network modelling method based on the characteristics of natural gas pipeline network, using expression scale and modelling size as the modelling standard. Secondly, this paper put forward an analysis method for the complexity of natural gas pipeline network. Using this analysis method, this article analyzed the complexity of natural gas pipeline network. Results showed that the structure of natural gas pipeline network is relatively uniform. When the gate station is used as the expression scale, natural gas pipeline network has the small-world characteristics, but not the characteristics of scale-free. At the same time, the degree distribution of natural gas pipeline network has its own characteristics: the number of nodes with a node degree of 2 is relatively low, and the proportion of points with a node degree of 2 is relatively small, and the probability is less than 1 and 3. This paper also creatively studied the structural characteristics of natural gas pipeline network, and defined the expression of the pipeline network structure based on the joint degree distribution, which means to name a certain structure by the node degree of the nodes at both ends of the edge. Results have shown that the 3-3 structure and the 3-4 structure are the main structures of natural gas pipeline network. On the one hand, the structure of natural gas pipeline network has the characteristics of 'outstanding', which means that some structures account for more than others. And on the other hand, the number of the structure which is 'outstanding' accounts for about 20%, while other structures are more evenly distributed.

To sum up, this paper proposed an evaluation method of natural gas pipeline network complexity based on complex network theory, which can help understand the structure of natural gas pipeline network and its behaviors when facing structural changes. Changes in the topology of natural gas pipeline network will lead to changes in the complexity of the system. Through the analysis of natural gas pipeline network system complexity, it can help analyze the impact of structural changes of natural gas pipeline network on the pipeline network transmission capacity. Besides, the proposed method can help analyze the evolutionary mechanism of natural gas pipeline network in the future study.

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