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Hydraulic reliability analysis of an urban loop high-pressure gas network

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ABSTRACT

Scientific analyses and the provision of practical ways of improving the hydraulic reliability of urban high-pressure gas networks are essential for the safe and stable supply of natural gas by a supplier. A reasonable estimation of the actual obtainable flow for each consumer in the event of a failure is key to the quantitative analysis of hydraulic reliability, which is not an easy task for a loop network. Based on an analysis of the hydraulic characteristics of a loop network, this paper discusses the limitations of existing methods and presents a feasible method for determining the actual nodal flow in a high-pressure gas network loop. This method adopts a process whereby the hydraulic regimes are first analysed according to the designed nodal flow. Next, the nodal pressures are checked, and the actual nodal flow is gradually rectified. Finally, the hydraulic regimes are repeatedly analysed according to the rectified flow until each nodal pressure and each nodal flow satisfy the nodal pressure equations. Moreover, a detailed procedure for a hydraulic reliability analysis of a loop network is presented, and its feasibility is confirmed with an example. The example results show that the network system hydraulic reliability is only 0.879 using the proposed method when pipe 2 fails, whereas the reliability would become 1.0 if using the existing method. The factors affecting the reliability are discussed exhaustively from the aspects of the network system and the consumer, and a number of measures are suggested for improving the hydraulic reliability.

1. Introduction

Urban high-pressure gas pipeline networks are an important part of our energy systems, and their reliability is a prerequisite for ensuring a safe and stable natural-gas supply. Reliability analyses of pipeline networks include the mechanical reliability and hydraulic reliability of two branches (LI, 2005). The former refers to the pipeline integrity and connectivity between each consumer and the natural gas supply station, which has been researched extensively and intensively by means of graph theory, neural network theory, reliability theory, etc. (Kansal and Sunita, 2007; Yeh, 2004). The use of a loop layout for a gas network pipeline is an important measure for enhancing mechanical reliability. The aim of hydraulic reliability is to ensure that the network hydraulic regime satisfies the design requirements for pressure and flow under all possible conditions (Gheisia and Naser, 2014; Liang et al., 2006). This especially applies to the failure of a single pipe and the extent to which the network can subsequently satisfy the demands of all the consumers by supplying them with sufficient natural gas, including residential, commercial, and industrial consumers.

At present, research into network hydraulic reliability is concentrated mainly on municipal water supply networks and district heating networks and somewhat less on urban gas networks (Wang, 2009; Zhuang et al., 2011). Ionin, the former Soviet Union scholar, and other pioneers performed very useful research into gas network hydraulic reliability (Ionin et al., 1986; Sukharev and Karasevich, 2010). On the basis of previous research, Yan presented a simple and approximate method for analysing gas network hydraulic reliability using homogeneous Markov chain theory (Yan, 2014). However, a loop gas network is a complex system, in that it still has to be able to supply a certain amount of natural gas in the event of the failure of some pipes. In addition, the flow direction uncertainties of some pipes give rise to their having

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ambiguous series–parallel relationships. The above factors make it difficult to quantitatively analyse hydraulic reliability when pipe failure occurs.

Considering that conventional hydraulic analysis methods are difficult for determining the actual flow when a loop network failure occurs, the available approaches mainly rely on some semi-empirical function relationships between the nodal flow and nodal pressure (Pathirana, 2010; Abdy Sayyeda, 2014; Vaabel, 2014; Zhou, 2011). However, they are just some eclectic approaches and still incapable of defining the intricate relationship (Zhou et al., 2011). Based on hydraulic reliability theory, this paper elaborates on the hydraulic characteristics of a loop gas network and analyses the hydraulic reliability of an urban loop high-pressure gas network.

2. Hydraulic reliability theory and hydraulic characteristics of a gas network

Urban high-pressure gas networks consist of numerous pipes, valves, and other non-pipe elements. Such a network is often configured as multiple loops to ensure a safe and reliable gas supply. If any single pipe (or non-pipe element) fails, it needs to be isolated from the network, and the network needs to be able to continue to at least partially satisfy all or some of the natural gas consumers. Therefore, the integrity of the network relates to the service capacity, and reliability theory can be employed to evaluate this capacity.

The consumer nodal hydraulic reliability and network system hydraulic reliability are the two most conventional indexes for measuring the network service capacity (Abunadaa, 2014; Liang, 2006).

$$R_{\mathrm{j}} = \frac{Q_{\mathrm{j}}^{\mathrm{avl}}}{Q_{\mathrm{j}}} \tag{1}$$

$$R_{\mathrm{net}} = \frac{\sum_{n} Q_{\mathrm{j}}^{\mathrm{avl}}}{\sum_{n} Q_{\mathrm{j}}} \tag{2}$$

Here, j is any consumer node in the network; R_{j} is the consumer nodal hydraulic reliability of node j; $Q_{\mathrm{j}}^{\mathrm{avl}}$ is the actual gas consumption of node j, i.e., the actual nodal flow, in Nm^3/h; Q_{j} is the required gas consumption of node j, i.e., the designed nodal flow, in Nm^3/h; R_{net} is the network system hydraulic reliability; and n is the total number of nodes in the network.

Generally, the designed nodal flow is known when analysing the hydraulic reliability. Supposing that a network has no pipe failures (referred to as the “normal condition”), it should have sufficient capacity to satisfy all of the nodal consumptions under the designed pressures and flow, i.e., the actual flow of each node equals the designed flow. According to equations (1) and (2), both R_{j} and R_{net} are equal to 1 under normal conditions.

Nevertheless, each pipe has its own failure rate curve (called the “bathtub curve”), which may fail at any stage during its service time (Ahammed and Melchers, 1997; Majid et al., 2012). Calculating the probability of failure of a pipe belongs to the category of mechanical reliability. The following analysis will exclude the failure rate curve's influence on hydraulic reliability. Supposing a single pipe failure has happened as a result of corrosion, aging, third-party damage or any other reason, it would be isolated from the network for repair. In this state (referred to as the “failure condition”), the incomplete system would influence the network service capacity, resulting in not all of the nodes being able to receive their designed flow, i.e., the actual flow of some nodes may be less than the designed flow. However, the complexity of a loop network makes it difficult to identify which nodes will be influenced and the extent of the influence. Consequently, when analysing a network's hydraulic reliability, it is essential to determine the actual flow of each node that is in the failure condition. However, this is not an easy task for a loop gas network.

The existing gas network hydraulic calculation process is as follows: first, each nodal pressure is calculated under a range of conditions according to the designed nodal flow by means of the node equations method, loop equations method, or some other method. Then, the network layout and pipe diameters are gradually adjusted until all of the nodal pressures satisfy the design requirement (Luis et al., 2013; Vasconcelos et al., 2013; Wagner et al., 1988). The premise of this adjustment is that the flow of all the nodes should remain constant, regardless of how the pressure changes. In other words, the current hydraulic calculation for a gas network is based upon the hypothesis that the actual nodal flow always equals the designed flow and does not change with the nodal pressure. Under normal conditions, this hypothesis is feasible. Consequently, the existing calculation method is also appropriate and could produce a desirable result. Furthermore, existing methods are still feasible even under the majority of failure conditions, as gas networks are often endowed with high reserves of pressure during the planning and design stages such that there is enough pressure to compensate for pressure losses under accidental fault conditions.

In fact, most existing research into gas hydraulic reliability has adopted the above hypothesis, therefore reaching reasonable conclusions (Peng, 1998; Yan, 2014).

However, once the network is put into operation, there will be very few opportunities to change the pipe diameters or the network layout. As a result of the gas supply pressure being insufficient due to a low-pressure reserve, a main pipeline fracture, gas consumption beyond the designed flow, or some other reason, some nodal pressures will be reduced. Each node in an urban high-pressure gas network is connected to a high- or medium-pressure regulating station, which is used to supply natural gas to a residential, commercial or industrial area. Hence, each regulating station can be treated as a consumer node in the network, and the high-pressure gas network can be simplified to a system with only concentration nodal flow, and no distribution flow. The reductions in some nodal pressures will affect the flow capacities of the regulating stations. In extreme cases, when the nodal pressure is too low to satisfy the minimum inlet pressure of the regulating station, the regulator will fail to operate properly and will not provide sufficient natural gas to satisfy the design requirement, causing both R_{j} and R_{net} to be less than 1.

That is, a single pipe failure in the network would result in some nodal pressures failing to satisfy the minimum required pressure, resulting in some nodal flows being lower than their design values. If we were to continue to employ the conventional hydraulic analysis method after a failure had occurred, it would be difficult to obtain a reasonable simulation result. Furthermore, it would be possible for some nodal pressures to fall to a value lower than the minimum required pressure while their actual flows continue to satisfy the design flow. Obviously, this analysis result will not correctly reflect the network's actual operating conditions given that, when there is a fault in the network, the hypothesis of the nodal flow being independent of the pressure may no longer be valid. Therefore, the relationship between the nodal flow and its pressure should be taken into account when analysing the network's hydraulic reliability.