Influence of Hydraulic Modes in the Gas Pipelines on the Amount of the Gas Leaks

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Abstract. Today urgent task of reliable operation of the gas distribution systems is assessment the emergency damage danger to aboveground and underground gas pipelines, depending on various influencing factors. This study represents the issues of technological and functional reliability of the gas distribution systems. There are presented quantitative indicators, characterizing the influence of dangerous factors on the occurrence of emergency situations in the gas supply systems. Methodological principles have been developed to improve the efficiency and reliability of the gas supply systems by establishing a link between reliability indicators and design features of the gas supply systems.

1. Introduction

In most regions of the country gas networks have reached their limits and require continuous monitoring of their technical condition. In this regard, assessment of emergency danger of various damage to the gas fittings and gas pipelines, depending on conditions of their installation, the nature of damage, gas pressure, diameters, atmospheric effects, as well as the assessment of the environmental impacts of the gas leaks from damaged gas pipelines is an important task. Despite the improvement of equipment and technology, safety factor of the gas supply systems remains a priority [1].

As practice shows, in case of high-quality implementation of scheduled preventive work, strict compliance with the regulations, continuous monitoring, rapid response and accurate interaction of all services of the gas distribution organization (GDO), an uninterrupted and accident-free gas supply is ensured [2]. In addition, the forecast of the main value parameters of the gas distribution networks is an important part in maintaining the system in operation condition.

Reduction of reliability level of the gas distribution networks leads to a large range of loads and impacts, combined with a long period of operation. The material on accident condition in the gas sector makes it possible to identify weaknesses in the security system, to develop a program of measures, both an organizational plan, and for conducting analytical, experimental studies and design developments. Replacing and reconstructing obsolete and physically outdated gas pipelines and valves is one of the most effective ways to increase reliability, but it requires significant capital investments. Thus, ensuring reliable operation of the gas supply system is reduced to the solution of two main tasks: timely detection of defects and forecasting conditions of their development right up to the moment of destruction.
All emergency situations can be divided into the following groups: natural phenomena; design errors; mechanical damage; violation of the technology of construction and installation works. In addition, sources of increased danger and the cause of emergency situations can be gas-using equipment and valves with an expired service life [3, 4]. In 2013, the Gas Use Regulations (Decree of the Government of the Russian Federation №410 of May 14, 2013) came into effect, according to which technical diagnostics of instruments and equipment to ensure safety when using gas fuel is mandatory. At the same time, it is much more efficient and economical to carry out timely replacement of morally and physically obsolete equipment. Since December 2014, the “Industrial Safety Rules for Hazardous Production Facilities Using Equipment Operating Under Excessive Pressure”, approved by order of Rostecnadsor No. 116 dated March 25, 2014, establish mandatory requirements for organizations whose business includes operation of the gas supply systems not only to ensure industrial safety, but also to prevent emergencies and injuries and to prepare the “Industrial Safety Declaration of Hazardous Production Object” with analysis, risk assessment and hazard identification.

In addition to the above documents, it is necessary to rely on the regulations of the Russian State Standard (GOST) R 57193-2016 while designing process, developed taking into account the requirements of the international standard ISO/IEC/IEEE 15288:2015 “System and software engineering - Systems life cycle processes” (ISO / IEC / IEEE 15288: 2015 “Systems life cycle processes”, NEQ) [5], fundamental of which are the principles of system analysis, the principles of queuing theory and logistic approaches to flow control natural gas.

Besides establishment emergency damage danger to the gas networks, depending on the type of laying, type of damage, pumped gas pressure, diameters of the gas pipelines and other determining factors, an urgent task is to assess environmental impacts of the gas leaks from the damaged gas pipelines and gas-using equipment. The amount of leakage depends on two main factors: extent of damage (leaks), through which leakage occurs, and a category of the pipeline pressure. For example, the amount of leakage due to an accidental release of the gas due to the gas pipeline rupture varies in the range of $2.5\div3\text{ million m}^3$ [1, 8].

One of the elements requiring modernization is the sealing surfaces of threaded and flange connections, since the energy consumption, maintenance costs and the damage from leakage during the process of reduction and accidental discharge of the gas make a significant amount [1, 9]. The actual problem of the gas distribution networks is selection of reliable valves that can ensure, besides appropriate operating conditions, operational safety and tightness of the closure during the entire service period. Despite the fact that the use of energy-saving technologies and modern non-volatile equipment is an expensive undertaking, in the future, it is possible to gain significant economic effect [2, 10].

Failures of shut-off and control valves that may occur under operating conditions include case cracks, flange separation, loss of integrity of sealing surfaces, etc. As a result, there may be dangerous emergencies connected with a gas leak.

To assess the magnitude of damage, depending on the type of through damage to valves and gas pipelines, it is convenient to use the following classification:
- maximum damage – characterized by complete rupture of the weld, which geometric area of damage coincides with the cross section of the pipeline;
- significant damage – characterized by the size of through damage $0.5\div0.75$ of the cross-sectional area of the pipeline;
- average damage – characterized by the size of the through damage $0.125\div0.5$ of the cross-sectional area of the pipeline;
- minor damage – characterized by the size of the through damage to $0.125$ of the cross-sectional area of the pipeline.

For convenience, there is a concept of damage classification criterion introduced, representing the ratio of the geometric damage area to the cross-sectional area of the gas pipeline. The area of the hole
through the gas leak occurs in case of damage or malfunction can be represented as directly proportional to the diameter of the pipeline.

In accordance with the above classification, the gradation of the gas leaks depending on the magnitude of the damage is presented in Figure 1.

The main economic consequences of accidents at the gas distribution systems is cessation of the gas supply to various categories of consumers, since the costs of restoring destroyed section of the pipeline and compensation for the accidental release of gas are small.

As a theoretical basis for the hydraulic calculations of the gas pipelines, the gas dynamics equations are used to obtain the dependencies of the geometric parameters of the gas pipeline on defining parameters of the gas flow, which characterize the physical and thermodynamic properties of the gas (viscosity, density, compressibility factor), volume flow rate and pressure loss.

To select the diameters of the gas pipelines, starting from 1960, tables and nomograms are used, constructed for various design gas pressure conditions. The basic formulas are presented as dependencies of the design pressure drops - linear (for low pressure gas pipelines) and quadratic (for high and medium pressure gas pipelines).

In order to select an adequate variant of the calculated dependence by definition of leakage from the damaged pipeline, depending on the gas pressure in front of the damage hole, a corresponding analysis of existing calculation methods was carried out. For analysis, you can use the method of capacity calculation of the pressure regulator (interpreted as the process flow through the orifice), suitable for determining large and medium gas emissions. Pressure regulators capacity is usually determined by the manufacturer's passport data, since it is rather difficult to apply theoretical methods for determining the flow rate and the correction factor to account for changes in the specific volume of the gas stream during throttling process. In the absence of data, you can use the approximate bandwidth calculation methods:

for the liquefied gas:

\[
V = \alpha \cdot f \left(\frac{2g \cdot \Delta P}{\gamma}\right)^{1/2}, \text{ (m}^3\cdot\text{s}^{-1}); \tag{1}
\]

\[
G = \alpha \cdot f \cdot \left(2g \cdot \Delta P \cdot \gamma\right)^{1/2}, \text{ (kg} \cdot \text{s}^{-1}); \tag{2}
\]

for the natural gas:
\[ V = \alpha \cdot \varepsilon \cdot f \left( \frac{2g \cdot \Delta P}{\gamma} \right)^{1/2}, \] \hspace{1cm} (3)

\[ G = \alpha \cdot \varepsilon \cdot f \left( \frac{2g \cdot \Delta P \cdot \gamma}{\gamma} \right)^{1/2}, \] \hspace{1cm} (4)

where \( V \) is the gas volume flow rate, m\(^3\)·s\(^{-1}\); \( G \) is the weight gas flow rate, kg·s\(^{-1}\); \( \alpha \) is the discharge coefficient; \( \varepsilon \) is the coefficient taking into account the change in the specific gravity of the gas during flow through the throttle device; \( f \) is the throttle bore area, m\(^2\); \( g \) is the acceleration of gravity, m·s\(^{-2}\); \( \gamma \) is the specific gravity of the gas in front of the throttle device, kg·m\(^{-3}\); \( \Delta P \) is the pressure drop in the throttle device, kg·m\(^{-2}\) (9,806 Pa); \( \Delta P = P_1 - P_2 \); \( P_1 \) is the absolute pressure of the medium before the throttle device, kg·m\(^{-2}\); \( P_2 \) is the absolute pressure of the medium after the throttle device, kg·m\(^{-2}\).

The amount of the gas leakage from the gas pipelines (maximum gas flow rate corresponding to the critical flow rate) can also be determined by the formula proposed by “Gipronigaz” JSC (for high and medium pressure gas pipelines):

\[ V_{max} = f \cdot \left( \frac{2g \cdot K}{K + 1} \cdot (P_1 \cdot V_1) \right)^{1/2}, \] \hspace{1cm} (5)

where \( f \) is the damage hole area, m\(^2\); \( V_1 \) is the specific volume of gas, m\(^3\)·kg\(^{-1}\) (at pressure \( P_1 \)); \( K \) is the adiabatic index.

The analysis of the obtained results of the leakage value according to the existing formulas allows using a simpler version based on the laws of the continuity of the jet and the conservation of mass [1]:

\[ V = 330 \cdot 10^{-6} \cdot f \cdot P_1, \] \hspace{1cm} (6)

where 330 is the speed of sound in a stationary gas medium;

\[ V = 1.2 \cdot f \cdot P_1, \] \hspace{1cm} (7)

\[ P_1 = P_{ex} + 1, \] \hspace{1cm} (8)

where \( P_{ex} \) is the excess pressure in the gas pipeline.

Analysis of the hydraulic modes of the gas flow allows us to conclude that the volume of gas leaks from a damaged pipeline to the atmosphere depends on the magnitude of the gas pressure inside the pipeline at the point of through damage, the opening area of this through damage and on hydraulic modes. At the same time due to the absence of gas consumption due to an accident, the pressure from the damaged to the final section of the pipeline will be equal to the pressure at the site of the damage. Moreover, the hydraulic mode is completely changed with large pipeline damage and significant gas leaks.

For medium and high pressure networks, the magnitude of the gas leaks can be determined by formulas developed by Staskevich N.L. [11]:

\[ V = 0.0125 \cdot \alpha \cdot d^2 \cdot \varphi \left( \frac{P_e \cdot \gamma_g}{\gamma_d} \right)^{1/2}; \] \hspace{1cm} (9)

\[ \varphi = \left( k \cdot (k - 1)^{-1} \cdot \left( \frac{P_a}{P_g} \right)^{2k^{-1}} - \left( \frac{P_{a0}}{P_g} \right)^{(x+1)k^{-1}} \right)^{1/2}, \] \hspace{1cm} (10)
where \( P_g \) and \( P_a \) are the absolute pressure inside and outside the pipeline before damage, MPa; \( \gamma_g \) and \( \gamma_a \) are the specific gravity of the gas in front of the hole and air, respectively, kg·m\(^{-3}\).

Comparisons of calculation results using the specified formulas are presented in Table 1. It should be noted that gas losses in the amount of 250 m\(^3\)·h\(^{-1}\) (or approximately 1.5 million m\(^3\)·year\(^{-1}\)) are 2 times annual gas consumption of 100 residential buildings [1, 12].

**Table 1.** Gas leakage, m\(^3\)·h\(^{-1}\), through an opening in the gas pipeline with an area of 1 cm\(^2\).

| Gas pressure in the pipeline                  | According to the formula (9) | According to the formula (5) | According to the formula (6) |
|----------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Average – 0.1 MPa (1 kg·cm\(^{-2}\))         | 92                           | 280                           | 252                           |
| Average – 0.3 MPa (3 kg·cm\(^{-2}\))         | 183                          | 560                           | 504                           |
| High II category – 0.6 MPa (6 kg·cm\(^{-2}\))| 356                          | 980                           | 854                           |
| High I category – 1.2 MPa (12 kg·cm\(^{-2}\))| 646                          | 1830                          | 1686                          |

As the analysis of the obtained values shows, using formula (9) we get an underestimated leakage value, and the results of calculations using formula (5) are 10% higher than the values obtained using formula (6). At the same time, it should be noted that in the formulas (5) and (6), flow coefficient is not taken into account when the gas flows out of the hole \( \alpha \) (for the considered case of an ideal nozzle \( \alpha = 1 \)). To assess the environmental damage from the maximum possible leakage on the gas pipelines located on a flat territory, from a worn-out linear shut-off valves and microdamages, m\(^3\)·year\(^{-1}\), can be estimated by the formula:

\[
Q_{leak} = 1113.5 \cdot \frac{D \cdot \ell \cdot P_{aw} \cdot t}{T_{av} \cdot m \cdot Z_{av}},
\]

where 1113.5 - conversion factor, degrees·(kg·day\(^{-1}\)); \( D \) is the size of the outer diameter of the pipeline, m; \( \ell \) is the total length of the pipeline, km; \( P_{aw} \) is the operational gas pressure, kg·cm\(^{-2}\); \( t \) is the duration of operation of the pipeline, days; \( T_{av} \) is the average gas temperature, K; \( m \) is the value of the initial tightness; \( Z_{av} \) is the average compressibility factor.

Release condition of the minimum gas amount from the hole of damage on the pipeline at known values of the final pressure is expressed by the following equation:

\[
\frac{\partial V_{aw}}{\partial P_n} = 0,
\]

where \( P_n \) is the gas pressure in the absence of gas consumption at any point in the gas network; \( V_{aw} \) is the amount of gas leakage from the hole damage.

2. Conclusions

Currently used formulas to determine volume of the leaks are rather complicated to conduct a rapid assessment of the consequences of an accident [1, 13 ÷17]. In case of small leaks, which practically do not affect the hydraulic mode, the formula (6) can be used. In case of major damage, mode of the gas pressure changes depending on the amount of leakage, which may cause a decrease or cessation of the gas supply to consumers [18, 19]. In case of damage at the beginning of the pipeline when the pressure at the site of leakage \( P_{aw} = P_n \) is used, the following formula is used:

\[
V_{aw,b} = 45 \cdot \frac{Q^{0.762} \cdot \ell^{0.38}}{(P_n^{0.38} - P_{fa}^{0.38})} \cdot P_n.
\]
For damage cases at the end point of the pipeline, the formula is clarified as follows:

\[
V_{am,b} = 45 \cdot \frac{Q^{0.762} \cdot \epsilon^{0.38}}{(P_n^2 - P_{fin}^2)^{0.38}} \left( P_n^2 - V_{am}^2 \right) \left( P_n^2 - P_{fin}^2 \right) Q^{-2} \left( P_n^2 - P_{fin}^2 \right)^{1/2}.
\] (14)

Based on the analysis, it can be concluded - to prevent emergencies, as well as reduce their consequences, it is necessary:

- strict compliance with the requirements of regulatory documents and orders of Rostechnadzor, monitoring compliance with the rules of technical operation, strict compliance with safety requirements;
- high-quality construction of facilities according to project documentation;
- use of resource and energy saving technologies and materials to ensure uninterrupted operation and reliable operation of the gas complex;
- timely work on the identification of defects in equipment and materials, their repair or replacement; high-quality performance of emergency repair and restoration works [1, 11, 20].

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