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TECHNOLOGICAL FOUNDATIONS OF MULTILINE GAS PIPELINE RECONSTRUCTION

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Abstract- One of the important problems remains to make the operating mode of consumer enterprises independent of the operating mode of the gas distribution pipeline feeding them with gas fuel, in other words, to ensure uninterrupted gas supply to these enterprises. One of the solutions to the problem of improving the reliability of gas pipelines is the use of new effective scientifically based technologies for the reconstruction of pipeline systems. Obviously, connecting fittings, Looping's and connectors are one of the components of increasing the reliability of gas networks. To this end, a theoretically sound reporting scheme was developed for the design of gas networks, as well as for the development of new technological foundations of the gas pipeline network during its reconstruction and the prevention of possible gas losses due to modern equipment installed on these networks. This article explores the analytical expression for determining the economic length of interconnections between parallel gas pipelines and outlines a reconstruction variant for the effective methods of reconstructing multi-lines parallel gas pipelines.

Keywords: Parallel Gas Pipelines, Pipeline Reconstruction, Pipeline Interconnector, Looping's, Multi-Line Gas Pipeline Network, Uninterrupted Gas Supply, Accident Mode, Optimal Spacing of Fittings.

1. INTRODUCTION

The improvement of the technical and economic indicators of the gas industry is mainly related to two areas. Improving the equipment and technology of gas transmission and distribution networks, aimed primarily at reducing the capital intensity and operating costs of facilities. And then improving the dispatching control of gas supply, optimizing operating modes and increasing the reliability of gas supply and saving energy resources spent on their own needs.

One of the solutions to the problem of improving the reliability of gas pipelines is the use of new effective scientifically based technologies for the reconstruction of pipeline systems. Connecting fittings, Looping's and connectors are one of the components of increasing the reliability of gas networks. Loops are designed both to increase pressure at the end point of the gas pipeline or to increase throughput, and to reduce pressure at the starting point. The purpose of the calculation is to determine the length of the looping, at which the necessary effect will be provided. A Luping gas pipeline is one of the simplest types of complex gas pipelines.

Obviously, as the number of Looping's increases, the effectiveness of binders decreases. In accordance with the decrease in the diameters of the points, a decrease in the efficiency of the connections is also evident. If the diameters of the parallel spans do not change in length and there is no Looping, then using couplings as a means of increasing the capacity of the gas pipeline is useless. But the connectors allow you to reduce throughput during scheduled pipeline repairs. In other words, it is necessary to adopt such a scheme of parallel gas pipelines so that in the event of an accident, the connectors perform the Looping function.

According to the regulations, parallel gas pipelines are connected to each other through interconnectors and operate in a unified hydraulic mode (Figure 1). Parallel gas pipelines are widely used in practice due to their high reliability compared to linear pipelines and their ability to provide consumers with an uninterrupted energy carrier. When an accident occurs in one of the levels or repair work is carried out, the damaged section is isolated from the main gas pipeline using automatic valves. Subsequently, the valves on the interconnectors near the accident site are opened.

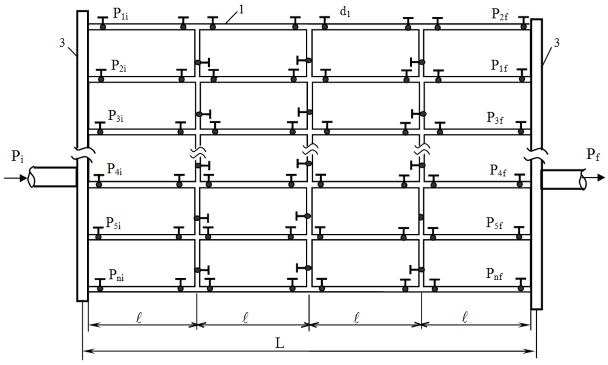

Figure 1. Schematic diagram of a multiline parallel gas pipeline:
1- Pipeline sections on the first line; 2- Interconnectors; 3- Collectors; 4- Automatic valves on pipeline sections; 5- Automatic valves on interconnectors

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In Figure 1, L is Length of the gas pipeline; ℓ is Distance between interconnectors; P_i is Initial pressure of the pipeline; P_f is Final pressure of the pipeline; d_1, d_2, d_3, ..., d_n is Diameters of the pipeline sections on each line.

As a result, consumers are not deprived of gas supply (Figure 2). In other words, the gas from the damaged level is transferred to the undamaged one through interconnectors, and this process continues until the damaged pipeline is repaired [1]. From this perspective, the construction and reconstruction of gas pipelines are aimed at creating a gas supply system that is independent of the pipeline's technological operating mode and various repair works.

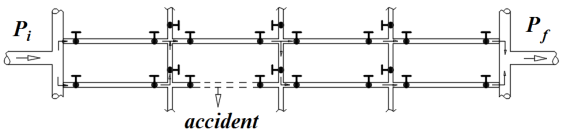

Figure 2. Schematic of interconnecting multiline gas pipelines in emergency mode

2. PROBLEM STATEMENT

During the reconstruction of parallel gas pipelines, it is necessary to select an optimal distance between interconnectors to minimize the cumulative costs while generating an alternative income from providing consumers with uninterrupted gas supply. As previously mentioned, depending on the different technological operating modes of the pipeline and the need to enhance the capacity of the system and each line, interconnectors are put into operation. It is clear that only through this process can consumers be continuously supplied with gas. This process is carried out as follows:

1. The damaged or to-be-repaired section of a parallel pipeline is identified.
2. The connecting fittings previously placed on the pipeline on either side of the identified section are activated (Figure 2). At this point, the damaged section of the pipeline is separated from the main system and prepared for repair.
3. To ensure the uninterrupted flow of gas in the damaged section, the gas valves on the connectors located on the right and left sides of the damaged section are activated (opened) [1]. This allows the gas flow to be directed to the undamaged section. As a result, consumers' gas supply remains uninterrupted (Figure 2).

3. PROBLEM SOLUTION

Assuming that the number of lines of the parallel gas pipeline shown in Figure 1 is three (n = 3), and if the last, third line is damaged, the implementation of the transition processes mentioned above will result in a three-level scheme for the pipeline.

As seen in Figure 2, after activating the connectors in the damaged section, it acts as a bypass (looping). It is known that looping is used to increase the capacity (efficiency) of gas pipelines. Research has shown that the productivity of the pipeline changes depending on the length of the installed looping. In other words, as the length of the looping increases, the productivity of the pipeline will increase accordingly [2]. On the other hand, increasing the length of the installed looping will increase the capital investment in the system.

From this perspective, it is essential to determine the optimal parameters of the installed looping (i.e., the diameter and length) to ensure that the capacity of the multiline parallel gas pipeline increases significantly while minimizing the cost of installing the looping. As shown in Figure 1, the length of the looping depends on the distance between the steps of the connectors on the parallel gas pipeline. Therefore, working to determine the optimal distance between interconnectors is one of the fundamental methods for the reconstruction of multiline parallel gas pipelines. Therefore, determining the optimal length of the looping between interconnectors during the reconstruction of parallel gas pipelines is crucial, as the income obtained as a result of increasing the pipeline's productivity allows for the cost of the system's reconstruction to be covered. We can represent this relationship in the following analytical form:

$$Z = \varphi(\ell) \tag{1}$$

To determine this function, we must first define the productivity (throughput capacity) of the multiline parallel line gas pipelines as a function of the distances between interconnectors. Our goal is to analyze the efficiency of gas supply to consumers based on distances between interconnectors, gas flow modes, and repair processes. First, we establish the existing productivity of the multiline parallel gas pipeline before any damage occurs. Using Figure 1, we describe the steady-state behavior of gas flow for each line of the gas pipeline:

For the 1st line: $$P_{1i}^2 - P_{1f}^2 = c^2 \frac{\lambda L}{d} Q_1^2 \tag{2}$$

For the 2nd line: $$P_{2i}^2 - P_{2f}^2 = c^2 \frac{\lambda L}{d} Q_2^2 \tag{3}$$

For the 3rd line: $$P_{3i}^2 - P_{3f}^2 = c^2 \frac{\lambda L}{d} Q_3^2 \tag{4}$$

And so on, with a similar equation applicable to the n-th line:

$$P_{ni}^2 - P_{nf}^2 = c^2 \frac{\lambda L}{d} Q_n^2 \tag{5}$$

These equations assume that the pipeline consists of pipes with the same diameter. Here, the variables λ and d represent the hydraulic resistance factor and diameter of the pipes in the existing gas pipeline lines respectively, Variable. Where, c is the speed of sound in the gas [13].

$$c = \sqrt{zRT}$$

where, R is represents the universal gas constant; T is denoting the absolute temperature; Z is representing the gas compressibility factor.

The P_{1i}, P_{2i}, P_{3i}, …, P_{ni} are initial pressures at the respective lines of the parallel gas pipeline and P_{1f}, P_{2f}, P_{3f}, …, P_{nf} are the pressures at the end of the lines of the parallel gas pipeline. Since these multiline parallel gas pipelines operate in hydraulic mode, their pressures are equal:

$P_{1i} = P_{2i} = P_{3i} = \ldots = P_{ni} = P_i$
$P_{1f} = P_{2f} = P_{3f} = \ldots = P_{nf} = P_f$

where, P_i and P_f represent the initial and final pressures of the multiline parallel gas pipeline, as shown in Figure 1. To determine the total productivity of the multiline parallel gas pipeline, we sum Equations (2)-(5). We get:

$$\Pi\left(P_i^2 - P_f^2\right) = c^2 L\left(\frac{Q_1^2 + Q_2^2 + Q_3^2 + \ldots + Q_n^2}{d}\right)\lambda \quad (6)$$

It is important to note that for a steady-state mode, the sum of losses in the lines is equal to the total pipeline losses (Q_0). So:

$$Q_1^2 + Q_2^2 + Q_3^2 + \ldots + Q_n^2 = Q_0^2 \quad (7)$$

Now, using Equation (7) in Equation (6), we can calculate the required flow rate as follows:

$$Q_0 = \sqrt{\frac{\left(P_i^2 - P_f^2\right) n \times d}{c^2 \lambda}} \times \frac{1}{\sqrt{L}} \quad (8)$$

Next, when one line of the parallel gas pipeline is damaged, that is, when gas is redirected from the damaged section to the undamaged section using connectors, we can determine the total productivity (efficiency) of the pipeline for the transition process. For research purposes, we divide the damaged section into three parts (Figure 2):

- The distance from the start of the pipeline to the first connector (looping system) $0 \le x \le \ell$
- The damaged section between two connectors $x \le \ell \le (L - x - \ell)$
- The distance from the last connector to the end of the $\ell \le (L - x - \ell) \le L$

Then, we define the following variables:

$\tilde{Q}$ is the changed productivity of the pipeline due to gas flow redirection from the damaged section to the undamaged section (looping system), ℓ is the unknown distance between connectors, P_1 and P_2 are the pressures at the start and end of the damaged section. Using these variables, we can write the equations for the steady-state gas flow in each of these sections:

For the looping system $0 \le x \le \ell$:

$$P_i^2 - P_1^2 = \lambda c^2 \frac{Q_\ell^2}{2d} x \quad (9)$$

For the damaged section $x \le \ell \le (L - x - \ell)$:

$$P_1^2 - P_2^2 = \lambda c^2 \frac{Q_\ell^2}{d} \ell \quad (10)$$

For the looping system at the end: $\ell \le (L - x - \ell) \le L$:

$$P_2^2 - P_f^2 = \lambda c^2 \frac{Q_\ell^2}{2d} (L - x - \ell) \quad (11)$$

Combining Equations (9)-(11), we can determine the efficiency (consumption) of the second and third lines (branch system) of a three-line parallel chamber. For the second and third lines of the three-line parallel chamber, based on the power formula:

$$Q_\ell = \sqrt{\frac{\left(P_i^2 - P_f^2\right)}{\lambda c^2}} \times \frac{\sqrt{2}}{\sqrt{\ell + L}} \quad (12)$$

For the first line of the three-line parallel chamber ($n = 1$), according to Equation (8), we have:

$$Q_\ell = \sqrt{\frac{\left(P_i^2 - P_f^2\right)}{\lambda c^2}} \times \frac{1}{\sqrt{L}} \quad (13)$$

It is clear that, for the transition process of a three-line parallel chamber, we can calculate the total efficiency (consumption) by summing Equations (12) and (13):

$$\tilde{Q} = \sqrt{\frac{\left(P_i^2 - P_f^2\right)}{\lambda c^2}} \times \left[\frac{\sqrt{2}}{\ell + L} + \frac{1}{\sqrt{L}}\right] \quad (14)$$

where, $\tilde{Q} = Q_\ell + Q_1$.

So, when the connectors are located at the beginning and end of the gas pipeline, the efficiency increases. However, for the other sections of the pipeline, the length ℓ between the connectors is essential. Therefore, we need to determine the optimal length of ℓ so that the productivity remains close to its original line before any damage to the gas pipeline (until the repair period). To find the required expression for point (1), we assume n=3 in Equation (8) (for a three-line parallel pipeline) and determine the ratios of Equation (8) with Equation (14):

$$\varphi(\ell) = \frac{\tilde{Q}}{Q_0} = \left[\frac{\sqrt{\frac{2L}{\ell + L}} + 1}{\sqrt{3}}\right] \quad (15)$$

From Equation (15), it is clear that to find the optimal distance between the connectors in a multiline parallel gas pipeline, you need to find the value of l that makes $\varphi(\ell)$ approach unity $\left[\varphi(\ell) \to 1\right]$. However, under this condition, it is possible to provide consumers with a continuous supply of gas, regardless of damage to the pipeline and its repair. In other words, the majority of consumers can use gas normally, and the system's reliability will be high. On the other hand, as previously mentioned, it is necessary to determine the value of ℓ in such a way that the cost of the system's reconstruction is not significantly higher than the revenue obtained from the uninterrupted supply of gas to consumers. In other words:

$$\varphi(\ell) \times S_g \ge S_{rec} \quad (16)$$

If we replace the "≥" symbol with "=" in Equation (16), we get the Equation (17):

$$\frac{2L}{\ell + L} + 2\sqrt{\frac{2L}{\ell + L}} + 1 - \frac{\sqrt{3} \times S_{rec}}{S_g} = 0 \quad (17)$$

where, S_{rec} is the total incurred cost of the reconstruction of the multi-layer parallel gas pipeline, and S_g is the profit obtained as a result of optimal placement of the connectors. By solving Equation (17), you can determine the optimal length of the step between connectors in the reconstruction of multiline parallel gas pipelines.

$$\ell = L\left[1 - \frac{2}{\left(\sqrt{\beta}-1\right)^2}\right] \tag{18}$$

where, $\beta = \frac{\sqrt{3}\times S_{rec}}{S_g}$.

However, determining the optimal length of connectors leads to the need to consider many reconstruction variants, as the value of β ($\beta \in [0:\infty]$) can be infinite. As a result, Equation (18) can take an infinite number of values. Thus, the number of reconstruction variants according to Equation (18) will be sufficiently large. To avoid the complexity mentioned above, the issue of determining the lengths of connectors based on the complex nature of the system can be considered. As shown in Figure 1, if we assume the length between connectors as ℓ, then the number of steps (number of connectors) m will be $m = \frac{L}{\ell}$.

On the other hand, it is clear that for one step, there will be approximately 8 automatic valves (connector fittings) and 3 connectors installed for a three-layer parallel gas pipeline. Thus, when the number of connectors is m, the total cost of the incurred expenses for the reconstruction of gas pipelines can be determined as follows [4, 6]:

$$S_{rec} = m \times Z \tag{19}$$

where, Z is the value of expenses for each step of pipeline reconstruction, Z is given by:

$$Z = E_n\left(8\,K_{a.v} + 3\,K_{con}\right) + 8\,C_{a.v} + 3\,C_{con} \tag{20}$$

where, $K_{a.v}$, K_{con} are the capital costs for the installation of an automatic valve and connector during reconstruction, $C_{a.v}$, C_{con} are operating expenses for automatic valves and connectors, and E_n is the normative factor for the comparative efficiency of capital investment for gas pipelines. Thus, to determine the reconstruction variant, we consider Equation (19) in Equation (16). Then we have:

$$\varphi(\ell)S_g \ge mZ \quad \text{or} \quad \left[\frac{\sqrt{\frac{2L}{\ell+L}}+1}{3}\right]\times S_g \ge \frac{L}{\ell}Z \tag{21}$$

The left side of Equation (21) in the inequality represents the profit obtained by consumers during the reconstruction of the connectors, and the right side represents the expenses incurred in the reconstruction of the system. It is clear that when the condition of Equation (21) is met, the length of the specified connector ensures the economically efficient reconstruction of the system [4, 10]. When one of the layers of the parallel gas pipeline is damaged, or during the operation of the connectors for different reasons, the profit obtained for each 1 m^3 of gas supplied to consumers can be determined analytically as follows:

$$S_g = \frac{Q_0 \times t \times e}{n} \times \omega \times L \tag{22}$$

where, Q_0 is the productivity of multi-layer gas pipelines, m^3/hour, n is the number of layers in the gas pipeline, t is the period of repairing the gas pipelines or the period during which consumers are supplied with gas without interruption, ω is the gas pipeline's accident rate, 1/km×year, and L is the length of the gas pipeline, km, e is the income obtained for each 1 m^3 of gas supplied to consumers with different categories.

Thus, the analysis of inequality (21) shows that during the reconstruction of parallel gas pipelines, both the profit obtained and the cost of the connectors are dependent on the distance between the connectors. Then, if we assume that the left and right sides of inequality (21) are equal, we get:

$$\left(\sqrt{\frac{2L}{3\ell+3L}} + \frac{1}{\sqrt{3}}\right)\times \wp = \frac{L}{\ell} \tag{23}$$

where, $\wp$ is defined as follows: $\wp = \frac{S_g}{Z}$.

From Equation (23), we obtain the Equation (24).

$$Wl^3 + \left(\frac{2\sqrt{3}L}{\wp} - L\right)\times \ell^2 + \left(\frac{2\sqrt{3}L}{\wp} + \frac{3L^2}{\wp^2}\right)\times \ell + \frac{3L^3}{\wp^2} = 0 \tag{24}$$

Solving Equation (24) allows to determine unknown length of step between connectors for economically efficient reconstruction of parallel gas pipelines.

$$\ell = \frac{2L}{\sqrt{3}}\left(\mu sh\frac{4}{3} - \frac{1}{\wp} + \frac{1}{2\sqrt{3}}\right) \tag{25}$$

where, $\mu = \sqrt{\left(\frac{1}{\wp} - \frac{5}{\sqrt{3}}\right)^2 - 8}$; $\xi = \frac{\eta}{3\sqrt{3}\mu}$;

$\eta = \frac{9\sqrt{3}}{\wp}\left(\frac{3}{\wp^2}+1\right) - \left(\frac{2\sqrt{3}}{\wp} - 1\right)^3$; $\varphi = \ln\left[\xi + \sqrt{1+\xi^2}\right]$.

4. CASE STUDY

Thus, for engineering calculations in the reconstruction of parallel gas pipelines, you can confidently use the formula (25). To do this, we accept the following initial data of a three-line parallel gas pipeline:

The initial pressure of the gas pipeline is $P_i = 2$ MPa;
The final pressure of the gas pipeline is $P_f = 0.85$ MPa;
The length of the gas pipeline is $L = 40$ km;
The diameter of the gas pipeline threads is $D = 0.5$ m;
The speed of sound sliding in the gas is $c = 383.3$ m/sec^2;
The number of lines is $n = 3$.

For gas pipelines, fracture intensity value $\lambda = 2.5\times10^3$ MPa 1/km×year is assumed, and value of coefficient of friction $\lambda = 0.03$. To begin with, let's determine output of the parallel gas pipeline using Equation (8).

$Q_0 = 0.17\times10^{-3}$ MPa×sec/m = 161028 m^3/h

The amount of damage for each 1 m^3 of gas that is not presented to various categories of consumers, based on statistical data studied by Professor O.M. Ivanchov, we take $e = 1.2$ €/m^3. The repair period of gas pipelines according to building standards $T = 6\div24$ hours, based on which we assume $T = 6$ hours. Then according to Equation (22) $S_g = 618348$ €/year, it will be.

To determine the value (Z) of the total reduced costs incurred in the system during the reconstruction of the gas pipeline, we take the following initial data. On the website of the agrochemiyainvest society on the internet (http://zadvizhki.narod.ru/) it is indicated that the cost of an automatic crane (electric drive) $K_{a.k}$ = 1500 €. Accordingly, the operating costs of the crane will amount to $C_{a.k}$ = 145.5 €/year. If the cost of installing one contactor is K_{con} = 103 €, then its operating costs will amount to 10 €/year.

First, using Equation (23), we find the value of Z (we take E_n = 0.12).

Z = 2659 €/year

So, $\wp = 232.55$; μ = 0.555; η = 1.023; ξ = 0.355 taking into account the calculated prices of the coefficients in Equation (25),

$\ell = 0.39 \times L = 0.39 \times 40 = 15.6$ km

Thus, for this particular example, the most convenient length for the reconstruction option is the placement of $\ell = 15.6$ km distance between connectors that will be installed on a three-circuit gas pipeline with a length of L = 40 km. But if the parameters of the gas flow in the pipeline differ from the example considered, then the length of the lupin that will be installed for the gas pipeline at this length may change. In other words, the length between the connectors may vary depending on the geometric and technical parameters of the parallel line's location, gas flow parameters, as well as the category of consumers. For this reason, determining the optimal distance between connectors is of great importance in the method of reconstruction of multicomponent gas pipelines.

5. CONCLUSIONS

The aim of the study is to develop a method for the reconstruction of gas transmission networks of complex design in order to save energy resources and ensure the reliability of gas supply to consumers. The advantage of this method is characterized by the practical significance of technological calculations. Timely implementation of measures makes it possible to increase the productivity of the gas pipeline and reduce energy costs for gas transportation. For this particular example, the most convenient length for the reconstruction option is the placement of $\ell = 15.6$ km distance between connectors that will be installed on a three-circuit gas pipeline with a length of L = 40 km. According to the report, the annual effect is 2650 €. Based on the results of the study, a function has been developed that characterizes the ratio of performance of parallel gas pipeline systems in stationery and emergency modes. Using this function allows you to determine and increase the throughput of the pipeline luping system, the hydraulic efficiency of which is acceptable during pipeline operation.

By using the formula, it is possible to efficiently carry out the reconstruction of currently operating multilayer parallel line gas pipelines based on economic and technical principles. The implementation of the proposed calculation scheme for the economically efficient placement of connectors in existing and newly constructed parallel gas pipelines allows for the optimal decision on the technological basis for reconstruction. Effective results have been obtained to reduce the amount of gas lost to the environment during the time preceding the closure of automatic valves. In order to ensure the safety of repair work, gas losses to the environment are completely prevented as a result of accurate calculations in order to control the process without loss of pipeline discharge between overlapping cranes.

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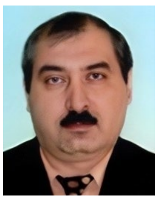

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