Investigation of the Performance of the Interval Radial-Stop In-Line Device Under Conditions of Increased Pressure

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Abstract. The article reflects the results of a study to determine the operability of an interval radial-thrust in-line device, intended for use in the repair of the linear part of main gas pipelines. The paper contains information characterizing the stress-strain state of the most wear-out elements of the inline shell. The problem is reduced to finding the equivalent stresses for the initially selected material. The results of the study indicate that under the conditions of a one-sided force factor (pressure) of the gas pipeline medium, the limiting state of the material of the end element is not reached. As a methodological basis for the study, the use of finite element analysis is assumed. The result of the study is a picture of the distribution of equivalent stresses in the plane of the end element.

1. Introduction

The modern system of the main transport of natural gas in the Russian Federation and the CIS countries is characterized by a stage of structural transformations. This is due, to a greater extent, to the arrival of the time for the commissioning of facilities in this area in the second half of the last century. In such conditions, the increasing physical and obsolescence of gas pipeline systems requires either the construction of additional gas transmission facilities with the decommissioning of existing ones, or the continuation of the use of existing systems after measures to restore operability. The last case, which consists in operating the technical condition of main gas pipelines, has an advantageous side from the point of view of the economy: the construction of new gas transportation facilities is associated with the need for significant investments and is characterized by a relatively long payback period. In turn, the world practice in the operation of gas transmission facilities indicates a change in the policy of the relevant companies: the development of requirements for the mandatory improvement of operating methods (including repairs) using resource-saving means and tools.

The measures used in practice to maintain a given level of the technical condition of main gas pipelines are focused on restoring the operability of their subsystems. It should be emphasized that these operations are based on work on bringing gas transport facilities into a defect-free state.

Work on the restoration of the operational state of the main gas pipelines themselves requires a preliminary stop of the pumping of the product and its removal from the allocated area. The released natural gas is discharged into the atmosphere in order to ensure safe conditions for the repair. However, the growing trend towards the introduction of resource conservation measures in the...
medium term will require a systematic reduction in the amount of bleed off, in the long term - to rejection of the free emission of the transported product.

2. Relevance
The value of irrecoverable losses of natural gas that occur during repair and restoration work at the facilities of the main pipeline transport reaches the value of 7 million cubic meters of gas per year per 1000 km of the route [1]. Considering the growth of the market price for commercial gas, the feasibility of introducing fundamentally new resource-saving methods is beyond doubt. Thus, against the background of the above, the need to develop means to prevent negative factors of repairs of gas pipelines is increasing. At the same time, the appropriate tools should ensure a decrease in the amount of natural gas losses and not require significant changes in the design of the operating systems.

3. Literature review
Among the domestic researchers who studied the problem of resource conservation in the repair of main pipelines, it is necessary to highlight Tkachev G.E., Shoter P.I., Ulikanov R.R., Ramazanov R.F., Kantyukov R.A., Boev I.V., Ryabinin V.P. The proposed solutions are based on the idea of selective overlapping of the repaired area with plugging elements. Foreign scientists also noted the need to introduce into the practice of repairing main pipelines tools to save the transported product. Some of these are Freyer Rune, Saltel Jean-Louis, Le Thi Thu Thui, Josten Alexandersen, Edd Tweet. The concepts considered in the works of the above authors are also based on the effect of sealing the in-pipe space. A review of the work of the above researchers indicates that the greatest effect on preserving the product during repair work on main pipelines can be achieved with selective blocking of the route.

4. Formulation of the problem
The purpose of the work is to substantiate the holding capacity of the interval radial-stop in-line device [2]. The task of the work is reduced to an analytical study of the contained pressure with subsequent modeling of the process of applying the found value of excess pressure to analyze the stress-strain state of the main units. Methods for solving the problem are reduced to the use of a mathematical apparatus and programs of finite element analysis.

5. Analytical study of holding capacity
The holding capacity of the interval radial-stop in-line device is provided due to the interaction of the contacting elements of the shell with the inner wall of the gas pipeline. Those, it is assumed that tangential stresses arise, which cause the emergence of a static friction force when a displacement force is applied to a stopped projectile from the product under excess pressure. Thus, the analytical study is based on the Coulomb-Amonton law, which implies the dependence of the magnitude of the static friction force on the value of the perpendicular reaction of the support and the coefficient of friction. The final value of the friction force is determined by the sum of the following force factors: friction forces in the contact zone of the support elements of the device $F_1$ and friction forces along the line of contact between the swelling element and the pipe wall $F_2$. The first of the above quantities is defined as

$$F_1 = 4\mu N$$

where $N$ is the reaction force of the support surface, $N$, $\mu$ is the coefficient of friction of polyurethane on steel.

The second quantity is defined as

$$F_2 = \tau S_1$$

where $\tau$ - shear stresses, Pa, $S_1$ - contact area of the swelling element, m².

The final value of the holding capacity under these assumptions can be found as
\[ p = \frac{F_1 + F_2}{S_2} \]  

(3)

where \( S_2 \) is the area of the device end surface, m².

### Table 1. Contained pressures depending on pipeline configuration.

| \( D \times \delta \), mm | 1420×16,8 | 1220×12,7 | 1020×12,5 | 820×12 | 720×10 | 630×9 | 530×8 |
|--------------------------|------------|------------|------------|--------|--------|--------|--------|
| \( p \), MPa             | 0,734      | 0,856      | 1,033      | 1,304  | 1,503  | 1,737  | 2,104  |

The results of the performed analytical calculations indicate that the value of the contained pressure varies depending on the size of the gas pipeline. Thus, as the cross-section of the pipe decreases, the retention capacity increases. This fact is due to the influence of an external force factor (excess product pressure) on the end cuffs of the device. This large-scale effect is as follows: a greater value of the shearing force falls on the corresponding interaction area.

### 6. Factor analysis of health based on temperature influence

The holding capacity as a criterion for the device's performance depends, among other things, on the temperature and slope at the point where the projectile stops. The first affects the pressure of the command environment and the coefficient of friction of polyurethane on steel, the second causes a change in the locking force depending on the inclination of the device. To analyze the performance according to the first factor (temperature), it is advisable to use Charles's law, which is allowed to be applied in relation to real gases at temperatures comparable to atmospheric. This dependence between the actual pressure of the compressed command medium \( p_1 \) on the stopping point temperature \( T \) is as follows:

\[ p_1 = \frac{p_0}{T_0} \cdot T \]  

(4)

where \( p_0 \) and \( T_0 \) are the pressure and temperature of the command environment, Pa, K.

The value of \( p_1 \) determined by the above formula (4) directly proportionally affects the value of the reaction force of the support surface \( N \) in the formula (1). Thus, if the temperature of the stop point of the projectile increases, the pressure of the command environment increases. Consequently, the parameter \( N \) will also have an increasing character, which will ultimately lead to an increase in the contained pressure. The statement in the above paragraph is explained as follows. The higher ambient temperature in the stopping zone of the device contributes to the heating of the command medium (compressed inert gas) in the projectile body. According to the molecular kinetic theory, with a similar picture, there will be more intense movement of gas particles in the body of the force cylinders and the swelling element. The total force factor from chaotic fluctuations in conditions of constant volume leads to an increase in internal pressure. Consequently, the latter contributes to an increase in the tracking force, characterized by the parameter \( N \) in the formula (1). Ultimately, the power factors \( F_1 \) and \( F_2 \), all other things being equal, will take on a greater value. It follows that the contained pressure will also increase. The results of calculating the restrained pressure, taking into account the above, are shown in Table 2.

### Table 2. Contained pressures (in MPa) versus stopping point temperature.

| \( D \times \delta \), mm | 28   | 26   | 24   | 22   | 20   | 18   |
|--------------------------|------|------|------|------|------|------|
| 1420×16,8                | 0,734| 0,731| 0,728| 0,725| 0,722| 0,719|
| 1220×12,7                | 0,856| 0,852| 0,848| 0,844| 0,840| 0,836|
| 1020×12,5                | 1,033| 1,027| 1,021| 1,015| 1,009| 1,004|
| 820×12                   | 1,304| 1,295| 1,286| 1,277| 1,268| 1,259|
| 720×10                   | 1,503| 1,491| 1,479| 1,467| 1,455| 1,444|
| 630×9                    | 1,737| 1,721| 1,706| 1,690| 1,675| 1,660|
| 530×8                    | 2,104| 2,081| 2,059| 2,037| 2,015| 1,994|
7. Health factor analysis based on the influence of slope

One of the factors that determine the capabilities of the in-line device to ensure immobility under the action of external excessive one-way pressure is the longitudinal slope of the stopping point. This affects the holding ability in the form of the effect of the gravity of the projectile on its immobility. In this case, the dead weight of the device in any of the options below contributes to its relative displacement downward in the vertical plane:
- stop of the projectile above the repair site (case No. 1);
- stop of the projectile below the repair site (case No. 2).

The effect of gravity on the holding capacity of the device in an inclined arrangement will be negative in the first case, positive in the second. This is due to the fact that when the device is located above the repair site, the action vector of the shearing force is co-directional with the component of the gravity vector and is oppositely directed. The results of calculating the restrained pressure depending on the slope of the route $\alpha$ are shown in Table 3.

| $\alpha$, ° | The $p$ value in case No. 1 | The $p$ value in case No. 2 |
|-----------|-----------------|-----------------|
| 5         | 1,990           | 1,981           |
| 10        | 1,994           | 1,976           |
| 15        | 1,998           | 1,971           |
| 20        | 2,001           | 1,966           |
| 25        | 2,004           | 1,961           |
| 30        | 2,007           | 1,956           |
| 35        | 2,009           | 1,951           |

The calculation results (Table 3) show that in areas with a large value of the longitudinal slope, the contained pressure takes the highest and lowest values depending on the orientation of the projectile in relation to the repair area. Thus, the influence of an external force factor in the form of gravity in one case plays a positive role, contributing to an increase in the holding ability, in the other - a negative one, introducing additional counterpressure.

8. Analysis of the structural integrity of the cuffs and device supports

For an approximate assessment of the operability of the in-line device, it is advisable to consider the behavior model of the most worn out units under the influence of external excess pressure. Therefore, to obtain a contact pattern of the effect of the polyurethane plate on the pipe wall for the fixed device, the corresponding finite element analysis was carried out. In this case, the physical and mechanical properties of polyurethane according to the Blatz-Ko superelastic model [3] were taken as the initial characteristics of the materials of the analyzed units. The analysis considered a section of a gas pipeline with a cylindrical fastening along the outer surface, which implies the immobility of the object. At the same time, the moment of the impact of the compressive force developed by the force cylinder and transmitted radially through the poly-urethane support to the steel surface of the inner wall of the pipe was considered. The numerical value of the applied force factor is 19208 N, which is due to:
- the pressure of the working medium of the power cylinders of 9.8 MPa;
- the cross-sectional area of the piston of the power cylinder (0.00196 m$^2$) with its inner diameter of 0.05 m.

Numerical data on the values of equivalent stresses and displacements in the structure of the nodes indicate the preservation of the integrity of the nodes of the analyzed device. The displacements in the material of the supporting surface do not exceed 0.0049 mm, and their largest zone refers to the edging corner face. Based on this picture, it is obvious that the polyurethane surface, when exposed to radial force, does not experience significant deformations from the side of the power cylinder rod. The
occurrence of a local change in the structure is compensated by the self-healing property of the adopted material.

![Figure 1](image1.png)

**Figure 1.** Pattern of the distribution of equivalent stresses (in Pa).

Equivalent stresses along the contact area of the end element and the inner wall of the pipeline do not exceed the tensile strength of polyurethane. Deformations in the body of the analyzed element do not exceed the elastic limit value. This fact testifies to the absence of plastic deformations under the direct force action of the product with excess pressure on the device element. Under these conditions, the zone of maximum displacement of the cuff material is concentrated in the central part of the element, as evidenced by its deflection under the action of unilateral excess pressure. However, the performed strength calculation is limited by the parameters for a separate node. Obviously, in the case of analyzing the full-structure model, the stiffness due to the presence of the central body, which appears as an additional stop, will contribute to the deflection resistance of the element. The final data of the finite element analysis indicate the following: the highest value of the equivalent stress (Figure 1), according to the above loading scenario, is 237 MPa. The found value does not exceed the tensile strength parameter of the material (polyurethane). In this case, it is obvious that the areas of maximum loading refer to the extreme areas of the element and appear in the form of local stressed structures (ring-shaped nature of the location of concentration maxima). The study of the stress state arising in the course of contact interaction indicates the following: with the current quantitative and qualitative parameters of the applied force factors and forms of fastening, the structural integrity of the analyzed element is preserved, the integrity of the end cuff under conditions of excessive pressure is ensured.

The numerical value of the highest equivalent stresses occurring in the near-walled contact zone reaches 96% of the maximum permissible.

9. Conclusions

The conducted research of the contained pressure testifies to the following: the final values of the determined parameter developed when using the in-line device on gas pipelines with an outer diameter from 1420 to 530 mm, vary in the range from 0.7 to 2.1 MPa. It was found that with an increase in the diameter of the pipeline, a decrease in the holding capacity of the projectile is observed. The design substantiation of the holding capacity of the interval radial-stop in-line device was carried out taking into account the assessment of the possible temperature and slope of a particular point of the gas pipeline route. At the same time, the influence of the thermal pattern of the stopping zone on the change in the physical and mechanical characteristics of the nodes of the device and the terrain on the behavior of the contained pressure is taken into account. It was found that the value of the contained pressure varies depending on the change in the parameters of the stopping point - temperature and
slopes. The finite element analysis, carried out on the basis of the results of analytical studies on the parameter of the external overpressure of the product, testifies to the provision of the structural strength of the studied elements under the selected parameters. Checking for deformability indicates the admissibility of the resulting local displacements of the material of the end cuff, the area of variation is the zone of elasticity of polyurethane. Based on the foregoing, it is obvious that with the current initial parameters, the operability of these devices is ensured. This achieves the effect of reducing the volume of natural gas released during repair work due to the possible transfer of a part of the product from the repaired area to the value of the contained pressure.

10. References
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