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Numerical and laboratory experimental analysis of the movement of silicone cleaning pigs through 90-degree bends pipe

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ABSTRACT

Purpose: Analysis of the stress-strain state of cylindrical cleaning pigs manufactured of hyperelastic material during their movement through the pipe bends of the pipelines, identification of maximum contact forces' points, and places of their separation from the inner wall. The effect of the dynamic friction coefficient between the pig's lateral surface and the pipeline's inner wall on the value of the maximum equivalent von Mises stresses in the pig is investigated – determination of the required pressure for the passage of the pig through pipeline bends.

Design/methodology/approach: The finite element method performs numerical modelling of the pigs' movement through pipeline bends is performed. The non-linear properties of a hyperelastic pig material (a silicone compound with a hardness of 30 units on the Shore scale) are described by the potential Yeoh strain energy model. The contact interaction of the pig with the inner wall of the pipe bend is modelled by a surface-to-surface contact with dynamic friction coefficients of 0.1, 0.2, and 0.3 between them. For research, pigs with a length of 60 mm, 75 mm and 90 mm with a convex front and a concave rear end were manufactured and modelled. The experimental unit was designed and mounted from metal and glass pipes, between which pipe bends were placed with a bending angle of 90° and a bending radius of 1.5 DN. The metal pipeline has an internal diameter of 49 mm and a total length of 5.3 m, and the glass pipeline is 54 mm and 5 m, respectively. The experimental installation made of glass pipes was designed for visual observation of the dynamics of the pig movement through the glass pipeline bend and from metal – for measuring the pressure during the pig movement along the straight sections and the pipeline bend. To verify the correctness of the numerical modelling, the fully calculated deformations of the cleaning pigs in the bends of the pipeline were visualized and compared with photographs of the deformations of the pigs during their movement through the glass bends of the pipelines.

Findings: The bending of the pig in the pipe bend and contact forces increase equivalent von Mises stresses in the pig. Moreover, during the movement of the pig in a pipe bend, the distribution of equivalent von Mises stresses in it, as well as its deformations, changes continuously. It depends on the stage at which it is located. Numerical modelling and experiments have established that when the pig is at the stage of movement in the middle part of the pipe bend, due to bending, its lateral surface is partially separated from the inner wall of the pipe bend. With this, on the convex side of the pipe bend, the pig is separated from the wall in the front and rear parts and on the concave side – in the middle part. This separation of the lateral surface of the pig from the inner wall of the pipe bend results in the formation of a gap and cross-flows through the pig, reducing the pressure drop on it, which can lead to its sticking. For pigs made of silicone compound with a hardness of 30 units on the Shore scale to pass pipeline bends with a bending angle of 90° and a bending radius of 1.5 DN, the pressure in the pig space shall be at least twice as high as the pressure required for the pig to move along a straight section of the pipeline.

Research limitations/implications: Modelling and experimental studies were performed for pigs made of silicone compound. Therefore, subsequent studies will establish the influence of other hyperelastic materials' physical and mechanical properties on the pig movement along the pipeline bends.

Practical implications: The results obtained in this study allow for determining the possibility of pigs passing through the pipeline bends of gas gathering systems at gas fields and gas networks, determining the necessary pressure for this and, if necessary, optimising the geometric shape and dimensions of the pigs passing through the pipe bends.

Originality/value: The influence of the location of a solid pig made of hyperelastic material in the pipeline bend and the coefficient of dynamic friction on the stress-strain state of the pig is studied. The article contains original experimental units designed and installed to study the movement of pigs through pipeline bends.

Keywords: Numerical methods, Pig, Bend, Silicone compound

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

To ensure the efficiency and safety of energy carriers' transportation (gas, oil, and hot water) through pipelines, it is necessary to clean their internal cavity of various contaminants regularly. It is especially true for pipeline systems for gas gathering from depleted gas fields and low-pressure gas networks. The reason for this is the recovery of a large volume of liquid pollutants from wells and the low gas flow rates in such pipeline systems, contributing to the build-up of water and condensate in the internal cavity of lowered pipe sections [1-4].

The build-up of liquid contaminants in pipelines is a hydraulic resistance. It leads to a decrease in their hydraulic efficiency, resulting in a drop in throughput capacity, increased pressure losses, and decreased gas production volumes [5-7]. They also lead to the enhancement of intra-pipe corrosion processes, leading to defects in the pipe wall. In the case of such defects, methane leaks from the pipeline, and an explosion and contamination of the environment with greenhouse gas are possible. Wiener entropy is proposed in [8] to detect pipeline pipe wall defects in a timely manner and prevent accidents.

Under certain thermobaric conditions, liquid contamination in gas pipelines can lead to the formation of solid crystalline compounds (hydrates) and partial or complete blockage of the pipeline [9].

Another problem is that during the transfer of various contaminants by the gas stream, they hit the inner wall of pipe bends and tees, which leads to erosion defects that affect the stress state of the pipeline [10]. Pipe bends with a bending angle of 30°, 45°, 60° and 90°are used. The greatest risk of the pig-sticking in the pipe bend occurs when its bending angle is 90°.

2. Literature review

To effectively clean the interior of pipelines from accumulated pollutants by pigs. Also, the advantage of the method is minimal losses of the product transported by the pipeline. However, when the pigs move through the pipeline, they may get stuck, leading to partial or complete blocking of the flow. Installed pipe bends, tees, and adapters are local resistances of the pigs' movement [11,12]. Many such elements are installed on modern pipeline systems for various purposes [13], particularly pipelines of the gas gathering systems at depleted gas fields and low-pressure gas networks. Therefore, it is important to understand the dynamics of the pig movement in the pipe bend to prevent them from getting stuck.

The main cause of pigs' sticking in the pipe bends is their curvature, which leads to a strong bending of the pigs, resulting in a significant increase in contact forces and, accordingly, friction forces. In turn, an increase in friction forces the pig to brake, and it could temporarily stop or get stuck in case of insufficient action due to the outside pressure (pressure drop on the pig). Such cases can occur when the pig cleans the pipelines of gas gathering systems of depleted gas fields and gas networks that operate under low pressure.

Therefore, before the first (test) cleaning of the pipeline using a pig and in case of replacing the pig with another one (made of a different material, having a different geometric shape or size), it is necessary to determine the possibility of its passage through the pipeline bends, and pressure needed for this. To do this, it is necessary to understand the dynamics of the pig movement by pipeline bends and experimentally determine its flow capacity.

The movement of pigs through pipe bends is a complex process in which dynamics are influenced by various factors, including the geometric shape and dimensions of the pig, the characteristics of the material from which it is made, the radius and angle of bending of the pipe bend, and the friction coefficient. A complication is that pipeline gas gathering systems from gas fields, gas pipelines, and heat supply networks contain pipe bends of a small bending radius (steeply curved). Therefore, for pigs to pass such pipe bends, they must be solid and made from hyperelastic materials that can undergo ultra-large deformations under the influence of loads and, at the same time, quickly restore their geometric shape.

Thus, the movement of the pig through the pipeline bends is a complex non-linear problem containing geometric non-linearity, non-linear hyperelastic properties of its material, and contact non-linearity. The combination of such non-linearities significantly complicates the description of the dynamics of movement of the pigs made of hyperelastic materials by mathematical models since many uncertainties arise. To investigate the dynamics of pig movement through pipeline bends, considering the non-linear properties of its material and frictional forces that can be numerically modelled. Experimental studies make it possible to verify the modelling and determine the pressure at which the pig can pass pipe bends.

Through pipelines, the pigs move under a force caused by the pressure difference between the front P_1 and the rear parts of the pig P_2. Then, if the pig diameter is equal to the inner diameter of the pipeline and the pig moves in a horizontal rectilinear section, the balance of forces on the pig can be defined as follows

$$m_p \frac{dV_p}{dt} = (P_1 - P_2)A_p - F_f \tag{1}$$

where: m_p – pig weight; V_p – pig speed; t – time; A_p – the cross-sectional area of the pig; F_f – friction force between the pig and the inner wall of the pipe [14].

A. Nieckele [15] and V. Grudz [16,17] combined the force balance equations acting on the pig with the gas flow equations in the pipeline. The combination made it possible to develop the basics of modelling gas-dynamic processes in gas pipelines during the movement of pigs, an algorithm for controlling the gas pipeline's operating mode during its cleaning by the pigs.

L. Chen [18] performed numerical modelling of the pig movement along a linear section of the pipeline using the finite element method in the ANSYS software package. It was established that the cause of damage to the rubber seals of the pig is the occurrence of stresses at its ends in the upper and lower parts, which are significantly greater than the tensile strength of the material. Experimental studies confirm the reliability of numerical modelling.

In contrast to the rectilinear section in the pipe bend, additional forces act on the pig due to its circular movement and bending. S. Shengtao [19] analysed the forces that occur during the movement of the disc pig through the pipe bend and recorded the rotation to determine the friction force between the pig and the inner wall of the pipe bend

$$F_f = \mu(F_N + N_1 + N_2 + \Delta F) \tag{2}$$

where: μ – a friction coefficient; F_N – the centrifugal force that acts on the pig during its movement through the pipeline; N_1, N_2 – contact forces that occur as a result of pressing the pig against the inner wall of the pipe bend from its convex side; ΔF – the force caused by the pressure drop acting on the pig.

M. Borregales [20] investigated through 2D CFD modelling the movement of pigs of various geometric shapes in rectilinear sections and pipeline bends. As a result, the pressure and flow rate distribution in the pipeline was obtained, which allows an understanding of the patterns of pig movement in pipelines. It is established that the pressure field is asymmetric during the movement of the pig along the pipeline bend.

Y. Cao [21], using three-dimensional modelling and the finite element method, investigated the deformations and stress states of the pigs during their movement along straight sections and pipeline bends. It is established that when the pig moves along a straight section of the pipeline, the radial stresses on the outer end of the four cups are evenly distributed and identical. If the pig moves along the pipeline bend, the distribution of radial stresses in each cup is different and similar to the distribution of cardioids.

3. Methods and materials

3.1. Numerical model

To clean pigs to pass pipe bends of a small bending radius, they must be able to bend in pipe strongly under the action of a force caused by a pressure drop and not collapse. Therefore, they must be made of materials that can undergo significant deformations, minimally change their volume, and quickly restore their shape after loads are removed. Such materials are called hyperelastic. During the movement of a pig made of hyperelastic material, the pipeline bends it. The movement dynamics significantly depend on the physical and mechanical characteristics of the material and the geometric parameters of the pig and the pipe bend. Therefore, it is advisable to solve the problem where geometric non-linearity, non-linearity of the pig material properties, and contact non-linearity are combined in a three-dimensional formulation using numerical modelling by the finite element method in the corresponding software. The method allows an understanding of the regularities of the deformation process of the pig in the pipeline and bends the distribution of stresses during its movement.

Numerical modelling of the dynamics of the movement of a pig made of various hyperelastic materials through pipeline bends is performed in the ANSYS software package, which is now widely used to solve complex, linear and non-linear problems.

An extremely important role in modelling is played by the model of the material from which the pig is made. In creating a material model, it is necessary to consider the non-linearity of the properties of the hyperelastic pig material since they strongly affect the deformation process.

The library of materials in the software package allows for simulating most hyperelastic materials, including the materials from which pigs are made.

The non-linear behaviour of hyperelastic materials in numerical modelling can be described by models of the potential strain energy developed by Mooney-Rivlin, Yeoh, and Ogden [22]. The models are based on the strain energy density function, which determines the amount of strain energy accumulated in a material per unit volume. The stress-strain state of the material determines the function of the strain energy density.

For an isotropic material, the energy density function can be expressed as a function of tensor strain invariants

$$W = W(\bar{I}_1, \bar{I}_2, \bar{I}_3) = W(\lambda_1, \lambda_2, \lambda_3) \tag{3}$$

where: $\bar{I}_1, \bar{I}_2, \bar{I}_3$ – three invariants of Green's strain tensor, determined by the principle of expansion coefficients λ_1, λ_2 and λ_3 by equations;

$$\bar{I}_1 = {\lambda_1}^2 + {\lambda_2}^2 + {\lambda_3}^2, \tag{4}$$

$$\bar{I}_2 = {\lambda_1}^2 \cdot {\lambda_2}^2 + {\lambda_2}^2 \cdot {\lambda_3}^2 + {\lambda_3}^2 \cdot {\lambda_1}^2, \tag{5}$$

$$\bar{I}_3 = {\lambda_1}^2 \cdot {\lambda_2}^2 \cdot {\lambda_3}^2. \tag{6}$$

The strain energy density function of any hyperelastic material can be decomposed as an infinite series of first and second principal invariants $\bar{I}_1$ and $\bar{I}_2$. The polynomial form of the strain energy function is a phenomenological model and can be represented as follows

$$W = \sum_{i+j=1}^{N} C_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{D_k} (J - 1)^{2k} \tag{7}$$

where: C_{ij} – material constants for N quantity terms; J – total volume coefficient; D_k – a coefficient that considers the parameters of material incompressibility.

The higher the N value is, the more accurate the solution will be. However, with N value increase, the difficulty of determining material constants increases due to insufficient data to cover all deformations. Therefore, the very high N values are not recommended.

Initial shift modulus μ_0 and volume modulus K_0 can be determined by the formulas

$$\mu_0 = 2(C_{10} + C_{01}), \tag{8}$$

$$K_0 = \frac{2}{D_1}. \tag{9}$$

If the nominal deformations are small or moderately large, the first term in the polynomial usually provides a fairly accurate model [22].

For an accurate numerical value modelling of large deformations with Coulomb friction between a solid and a hyperelastic body). Yeoh [23] is the best constitutive model for modelling the movement of pigs made of silicone compound through pipeline bends.

Density energy deformations for the Yeoh model [22] are as follows

$$W = \sum_{i=1}^{3} C_{i0} (\bar{I}_1 - 3)^i \tag{10}$$

where: $\bar{I}_1$ – Green's first invariant.

According to [23], it is most appropriate to use the Yeoh model of the 3rd order for silicone, which can be written as the following equation

$$W = C_{10}(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3) + C_{20}(\lambda_1^4 + \lambda_2^4 + \lambda_3^4 - 3) + \\ +C_{30}(\lambda_1^6 + \lambda_2^6 + \lambda_3^6 - 3) \quad (11)$$

where: C_{10}, C_{20} and C_{30} – material constants.

Experimentally determined values for material constant for silicone compounds [24] are given in Table 1.

Table 1.
Material constants of silicone compound of Yeoh model

C_{10}, MPa	C_{20}, MPa	C_{30}, MPa
0.196259775	0.009010431	-0.000105654

To set the characteristics of the pig material in the materials library of the ANSYS software package, Hyperelastic Materials are selected where it is set Yeoh 3rd order model and material constants C_{10}, C_{20}, and C_{30} are entered as presented in Table 1.

3.2. Geometric modelling

The pig's geometric shape significantly influences the dynamics of its movement through pipeline bends. The simpler the geometric shape of the pig, the easier it is to make it stronger and more dependable. Therefore, all pigs are modelled and manufactured in a cylindrical geometric shape for numerical modelling and experimental studies with a rounded convex spherical front part and a concave rear part (Fig. 1). Such rounding increases the passing capacity of the pig through the pipeline, which is important if they are used for cleaning pipeline gas gathering systems from gas fields and gas networks that contain various obstacles in the internal cavity. Pigs of three lengths were manufactured and modelled for research purposes – the length of the cylindrical part of the pigs – 60 mm, 75 mm and 90 mm.

Geometric parameters that characterize pipeline bends are the bending angle, radius, and diameter. The most common ones in gas-gathering pipeline systems from gas fields and gas networks are pipe bends with a bending angle of 90°. As for the bending radius of the pipe bends it can be equal to 1.5 DN, 2 DN, 3 DN, and 10 DN (where DN is the nominal diameter of the pipe). The greatest risk of pig-sticking will be when the bending radius of the pipe bend is minimal. Therefore, a pipe bend with a bending angle of 90° and a bending radius of 1.5 DN was selected for experimental studies. The pipe bend on both sides contained adjacent rectilinear pipe sections with a length of 0.15 m each. The geometric parameters of the pipe bend are given in Table 2. Based on geometric parameters, a geometric pipe bend model was created, in which a geometric pig model was placed (Fig. 1). The pipe is assigned the steel material and the pig Yeoh 3rd order model with the material constants given in Table 2.

Table 2.
Geometric parameters of the pipe bend

OD, mm	Wall thickness, mm	Bending angle, °	Bending radius, mm
57	4	90	75

3.3. Modelling of contact interaction

When the pig moves along a straight section of the pipeline and the pipe bends between its side surface and the pipe wall, surface-to-surface contact occurs, resulting in contact forces. In the pipe bend, the pig bends strongly and takes its shape, which causes a significant non-linear increase in contact forces. The magnitude of the friction forces depends on the magnitude of the contact forces.

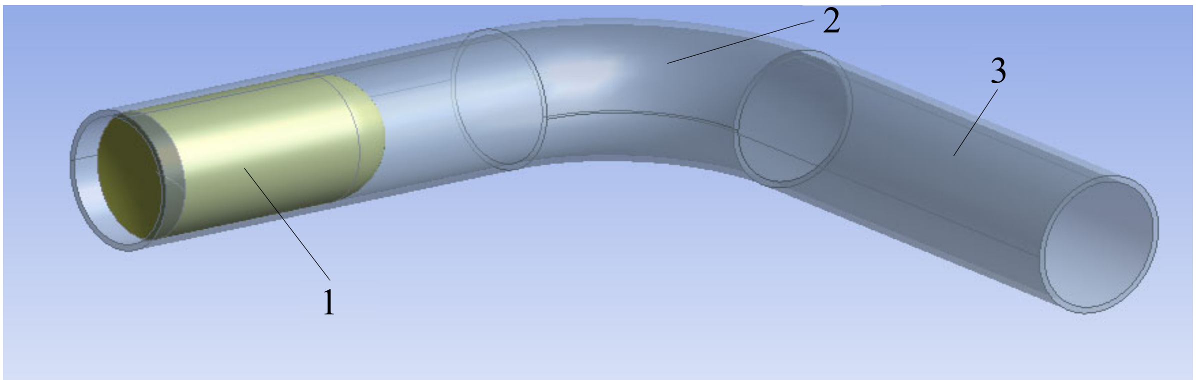


Fig. 1. Geometric model 1 – pig; 2 – pipe bend; 3 – straight pipe

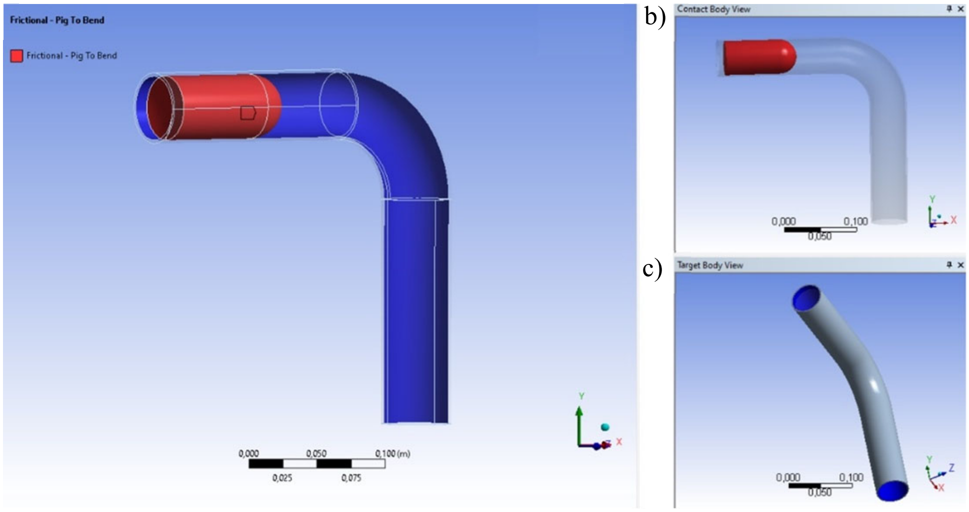


Fig. 2. Modelling of contact surfaces: a) contact interaction of the pig with the inner wall of the pipe bend; b) contact body view; c) target body view

To overcome the increased friction force, a higher locking pressure is required than for the movement of the pig in a straight section. Therefore, to determine the required outside pressure for the pig to pass through the pipe bend, it is necessary to determine the value of contact forces.

A surface-to-surface contact is modelled between them to numerically describe the processes of contact interaction of the pig with the inner wall of the pipe bend. The pipe bend surface of the pig is defined as the contact surface, and the inner wall of the pipe bend and adjacent straight sections of the pipe - as the target surface (Fig. 2).

To model the pig movement within a pipe bend, it is necessary to consider the friction coefficient. It depends on the material from which the pig is made, the condition of the pipe's inner wall (roughness, humidity), and the speed of the pig. The Coulomb friction contact model is selected to describe the interaction between the contact surface and the main guide surface, and the coefficient of dynamic friction between the pig and the pipe bend wall and adjacent pipes is set to 0.1, 0.2 and 0.3.

A body-ground contact is applied to the outer wall of the pipe bend and adjacent straight sections of pipes, which models a rigid external contact surface.

Table 3.
Variables in numerical modelling

The length of the cylindrical part of the pigs, mm	60	75	90
Coefficient of dynamic friction	0.1	0.2	0.3

To ensure the movement of the pig in straight sections and the pipe bend of the pipeline, the movement of the pig's rear end in the direction of the pipeline axis is set in ANSYS. The maximum set distance is 400 mm. The variables in the proposed numerical modelling are presented in Table 3.

3.4. Finite element meshing

In the Fluent-Meshing preprocessor, the parameters of the volumetric mesh were set. The Quadrilateral Dominant method was chosen for the pipe wall (Fig. 3). The size of the grid element is taken to be equal to 5 mm. Element order is selected Quadratic.

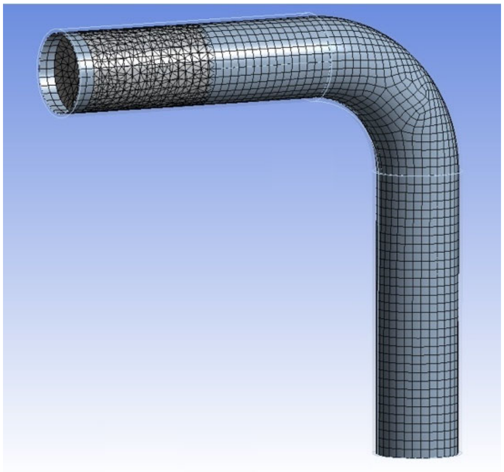


Fig. 3. FE model

The automatic method was chosen to break the cleaning pigs onto the grid. Their volume was filled with trihedral and tetrahedral prisms (Fig. 3). The size of the grid element is taken to be equal to 5 mm.

In order to better cover the areas between which there is frictional contact, a grid was set for the layers of the pig's surface and the inner wall of the pipe Face Sizing with an element size of 5 mm.

The specified grid ensures the necessary calculation accuracy, and the calculation time does not exceed 2 hours.

3.5. Manufacture of pigs and design of an experimental unit

To clean pigs to pass pipe bends of a small bending radius, they must be made of materials that can undergo significant deformations, minimally change their volume, and quickly restore their shape after loads are removed. Such materials are called hyperelastic. The pigs are made solid from a silicone compound with a hardness of 30 units on the Shore A Scale (Fig. 4). For this, 3D models of cleaning pigs and pouring moulds were developed. Then, a mixture of silicone and catalyst was poured into moulds printed on a 3D printer. The cleaning pigs were removed from the moulds after hardening the silicone compound.

The contact forces that occur between the pig and the inner wall of the pipe bend are caused by the bending of the pig, and the stress-strain state of the pig during its movement through the pipe bend significantly depends on the length of the pig. Therefore, the pigs are made of different lengths. The length of the cylindrical part of the pigs was 60 mm, 75 mm and 90 mm. The diameter of the cylindrical part of the pig is equal to the internal diameter of the pipeline bend and was 49 mm and 54 mm.

The advantages of silicone compounds are their strength, extreme elasticity, and flexibility. In addition, it is wear-resistant and durable.

For experimental studies of the dynamics of movement of the pigs made of hyperelastic materials through pipeline bends, experimental units made of metal and glass pipes and pipe bends were designed and installed.

The experimental unit made of glass pipes (Fig. 5) was designed to visually observe the dynamics of pig movement along the glass pipe bend of the pipeline. It consists of two glass pipes with a length of 2.4 m each with an internal diameter of 54 mm between which the glass pipe bend of the same internal diameter is placed. The pipe bend has a bending angle of 90° and a bending radius of 1.5 DN. Flanges connected pipes and a pipe bend. The experimental unit contains a pig launcher equipped with a pressure gauge and a gas meter.

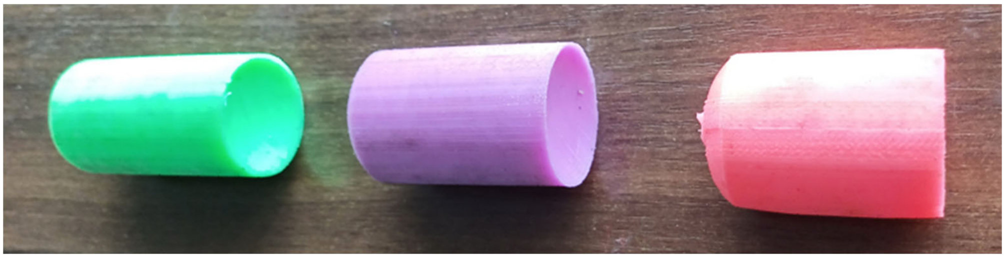


Fig. 4. Pigs

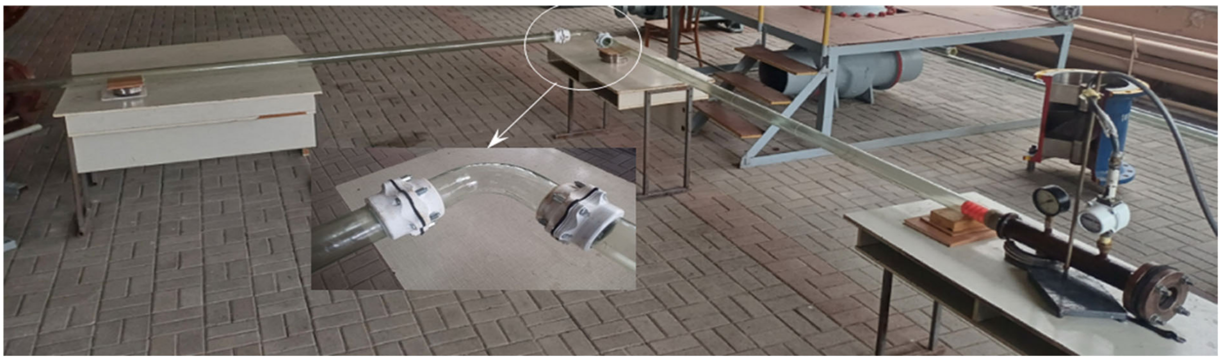


Fig. 5. Experimental unit for studying the pig movement in a glass pipe bend

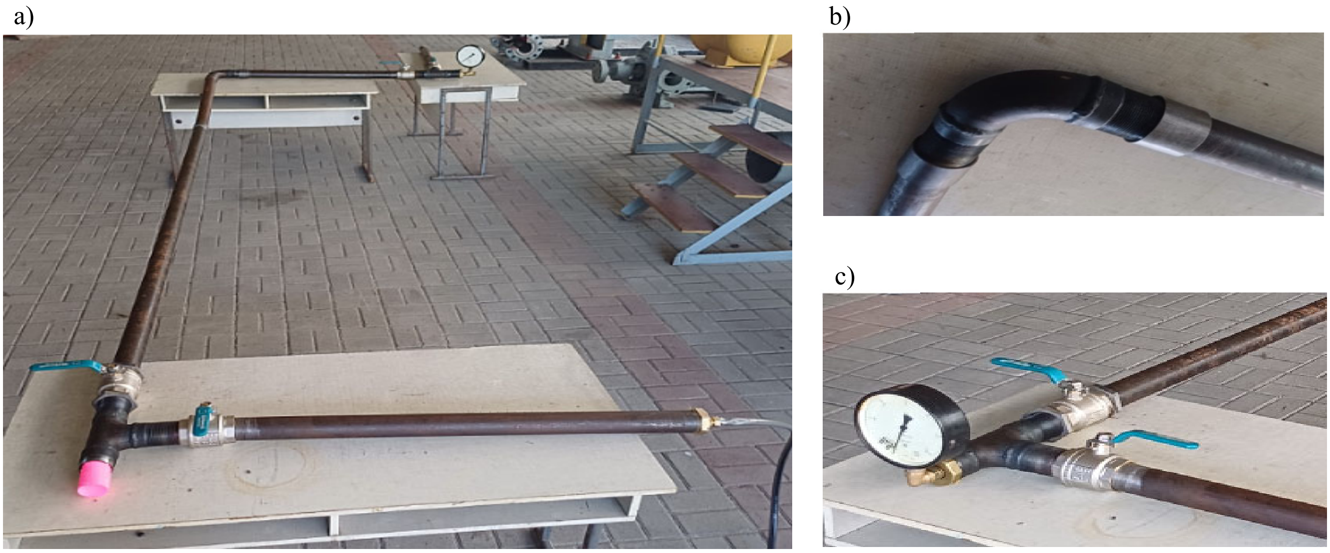


Fig. 6. Experimental unit for studying the pig movement in a metal pipe bend a) storage of the pig; b) pipe bend; c) launcher

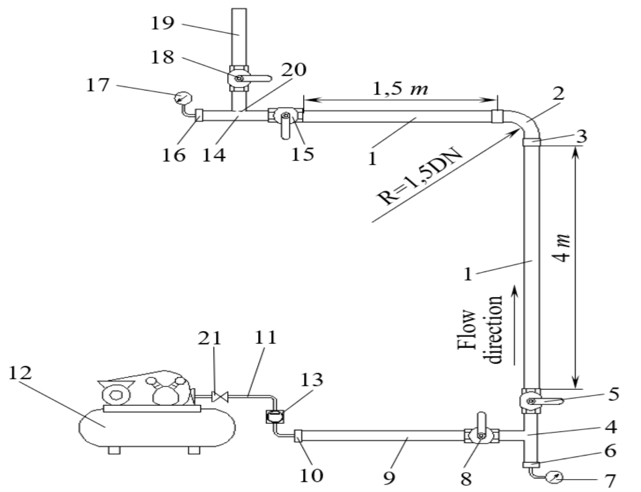


Fig. 7. Scheme of the experimental unit for studying the pig movement in a metal pipe bend: 1, 9, 19 – metal pipe 57×4; 2 – metal pipe bend 90°; 3 – coupling; 4 – pig launcher; 5, 8, 15, 18 – ball valve; 6, 10, 16 – pipe plug; 7, 17 – pressure gauge; 11 – hose; 12 – compressor; 13 – gas meter; 14 – pig receiver; 20 – lattice; 21 – valve

An experimental unit made of metal pipes (Fig. 6, Fig. 7) was designed to measure the pressure during the movement of pigs in straight sections and pipeline bends. It consists of two metal pipes 1 (Fig. 7) with a length of 4 m and 1.2 m each with an internal diameter of 49 mm, between which the metal pipe bend 2 of the same internal diameter is placed. The pipe bend 2 has a bending angle of 90° and a bending radius of 1.5 DN. The experimental unit was equipped with a pig launcher 4 made in the form of a tee to plug 6 to which a pressure gauge 7 is connected and a similar pig receiver 20 chamber. The tee branch of the pig launcher 4 was connected by hose 11 to the gas meter 13 and compressor 12, and air was freely released from the tee of the pig receiver 14. Pipes 1 with a pipe bend 2 were connected by a threaded connection using couplings 3. The advantage of an experimental unit made of metal pipes is the ability to perform studies at high pressures.

The pigs were stored in the launcher 4, after which dry compressed air was supplied from the compressor 12 receiver. A pressure gauge 7 recorded the pressure in the pig space during the movement of the pig, and a gas meter 13 recorded the airflow. The airflow was controlled by a valve 21 on the air supply line from the compressor 12.

4. Results and discussion

The modelling results are visualised by constructing three-dimensional coloured fields of equivalent von Mises stresses on the contours and in the longitudinal section of the pig. When the pig moves in a straight section of the pipeline, the pressure force and sliding friction force are balanced, and the equivalent von Mises stresses on the pig contours are evenly distributed (Fig. 8).

Making the rear end of the pig concave leads to an increase in equivalent von Mises stresses near its rear part, which indicates the occurrence of large contact forces between the pig and the pipe's inner wall in the place. Therefore, if the pig contains a concave rear part, the flow through it will be minimal, and its passage capacity will be large. As the coefficient of dynamic friction increases, the equivalent stresses at the rear of the pig increase; therefore, the contact forces increase, and the flow through the pig decreases.

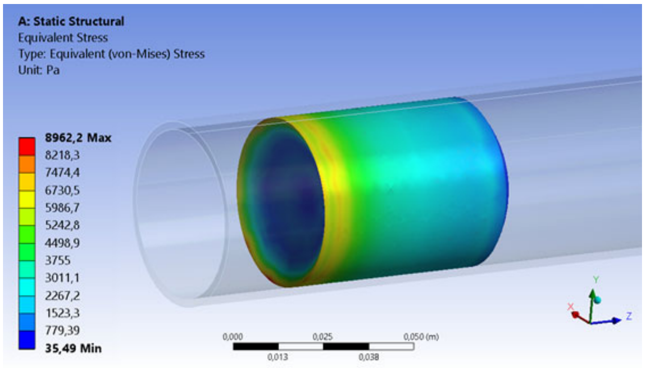


Fig. 8. Distribution of equivalent von Mises stresses on the contours of the pig during its movement along a straight section of the pipeline (dynamic friction coefficient equal to 0.2)

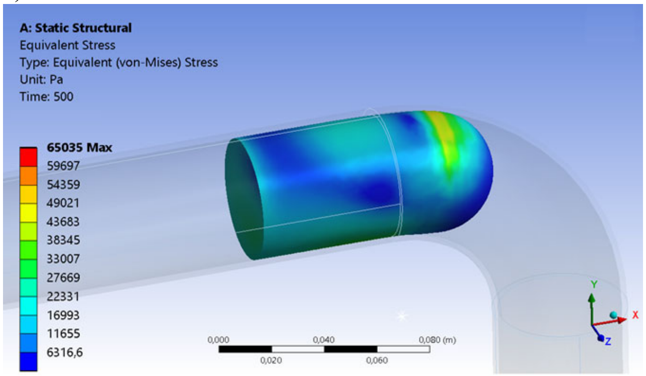
During experimental studies, it was found that pigs with a concave rear part have a large flow capacity, and the flow through them is minimal.

The movement of the pig through the pipeline pipe bend is divided into three stages:

- pig enters the pipe bend;
- the movement of the pig in the middle part of the pipe bend;
- exit of the pig from the pipe bend.

When the pig enters the pipeline bend, its front part begins to undergo extensive bending deformations, leading to uneven distribution of the equivalent von Mises stresses (Fig. 9). The stress distribution is uniform in the middle and rear parts of the pig. The maximum values of the concentration area equivalent to von Mises stresses are a circular arc in the front part of the pig on the convex side of the pipe bend. The maximum value of the equivalent von Mises stresses with a dynamic friction coefficient 0.2 is 65.035 Pa. The largest equivalent von Mises stresses at the point indicates an increase in contact forces between the pig's side surface and the pipe's inner wall and, accordingly, an increase in friction forces during the pig's entry into the outlet. In such a case, the higher the coefficient of dynamic friction, the greater the maximum stresses in the place and, accordingly, the frictional forces. Also, as the coefficient of friction increases, the maximum stress zone shifts increasingly to the outer contact surface of the pig. The maximum equivalent von Mises stress with a dynamic friction coefficient of 0.1 is 61.823 Pa, with a dynamic friction coefficient of 0.3 – 105.660 Pa. The reliability of the simulation is confirmed by the fact that during experimental studies, at a low speed of movement, the pigs stuck at the point of their entrance to the pipe bend.

a)



b)

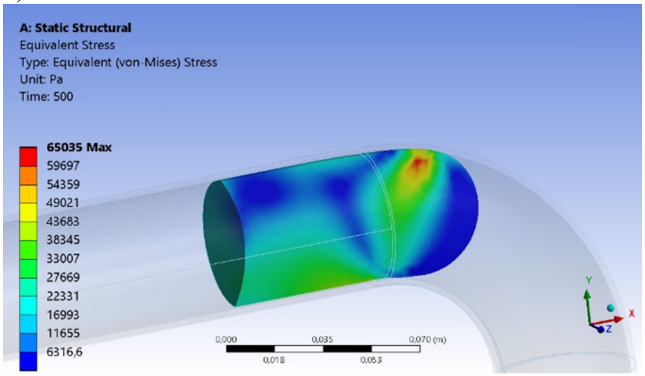
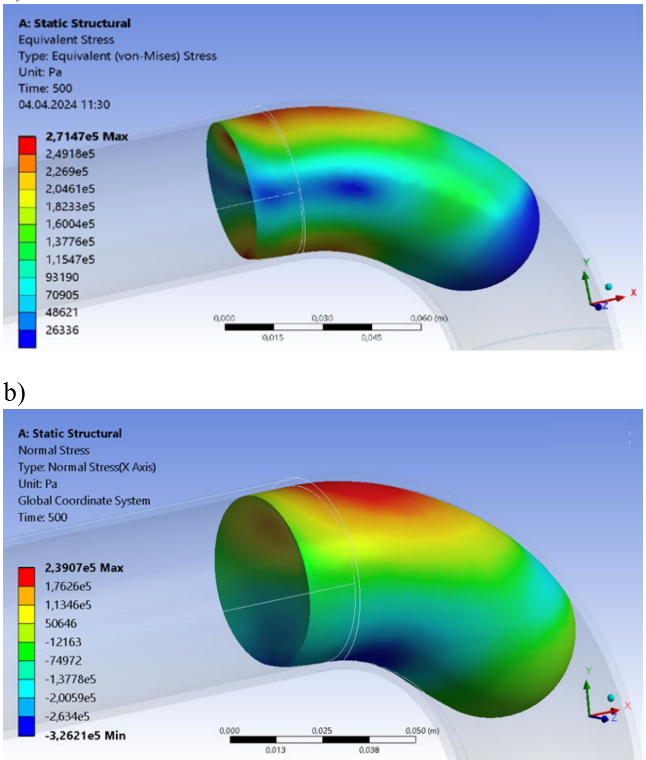


Fig. 9. Distribution of equivalent von Mises stresses in the pig during its entry into the pipeline bend (dynamic friction coefficient equal to 0.2) a) on contours; b) in the longitudinal section

When the pig moves to the middle part of the pipeline bend, it is strongly bent and takes the form of a bend. Its bending radius is equal to the bending radius of the pipe bend. As a result of this bending, the concentration area of the maximum equivalent von Mises stresses is circular. It is concentrated in the middle part of the pig (with some displacement towards the rear end) on the convex and concave sides of the pipe bend (Fig. 10a). The value of the maximum equivalent von Mises stresses with a dynamic friction coefficient of 0.2 is 271.470 Pa. In such a case, the distribution of normal stresses on the contours of the pig indicates that on the convex side of the pipe bend, the pig has tensile stresses of 239.070 Pa, and on the concave side, compressive stresses that are equal to 326.210 Pa (Fig. 10b).

The coefficient of dynamic friction by the value of the maximum equivalent von Mises stresses during the movement of the pig does not have a strong effect on the middle part of the pipeline bend.

a)

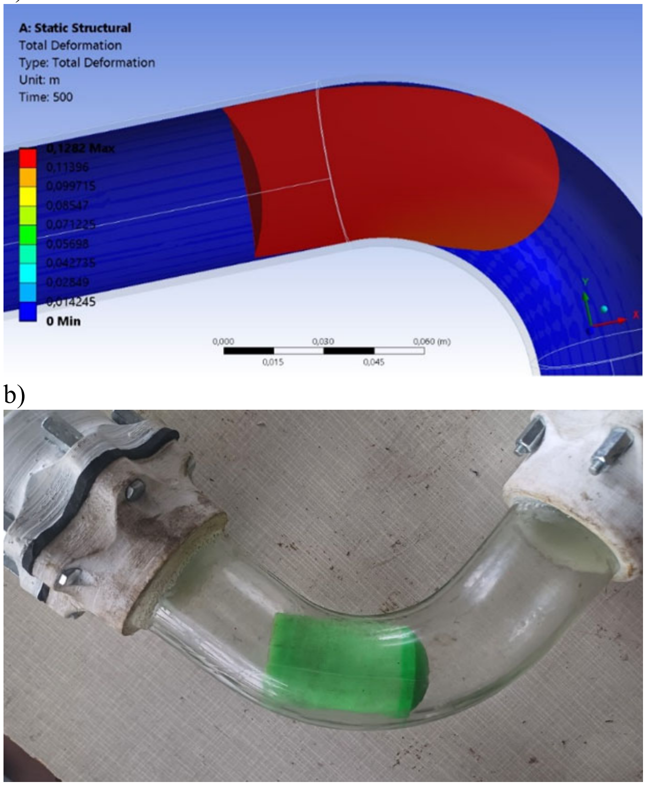


b)

Fig. 10. Stress distribution on contours of the pig during its movement in the middle part of the pipeline branch (dynamic friction coefficient equal to 0.2) a) equivalent von Mises stresses; b) normal stresses

Visualisation of complete deformations (Fig. 11a) and experimental (Fig. 11b) revealed that during the movement of the pig in the middle part of the pipeline bend, due to bending, its side surface is partially separated from the inner wall of the pipe bend. On the concave side of the pipe bend, the pig is separated from the wall in the front and rear parts and on the convex side – in the middle part. The separation of the pig's lateral surface from the pipe bend's inner wall results in the formation of a gap and cross-flows through the pig, reducing the pressure drop on it, which can lead to its sticking. It has been experimentally established that during the movement in the middle part of the pipe bend, the pig slows down or stops and resumes movement after increased pressure outside the pig or stops and gets stuck in the presence of a strong flow through the pig.

a)



b)

Fig. 11. Comparison of deformations of the pig during its movement in the middle part of the pipeline bend: a) modelling; b) experimental studies

When the pig exits in the pipeline bend, its rear part undergoes bending deformations. Therefore, the region of concentration of the maximum equivalent von Mises stresses is located in the rear part of the pig on the convex side of the pipe bend. At this point, the contact forces and frictional forces are greatest. The value of the maximum equivalent von Mises stresses at a dynamic friction coefficient of 0.2 is 65.635 Pa. Moreover, the higher the coefficient of dynamic friction, the greater the maximum stresses in this place and accordingly the friction forces. The maximum equivalent von Mises stress at a dynamic friction coefficient of 0.1 is 62.263 Pa, and at a dynamic friction coefficient of 0.3 – 131.870 Pa (Fig. 12).

Results of measuring the pressure outside the pig during its movement in rectilinear sections and the pipe bend of an experimental unit made of metal pipes (Fig. 6) are given in Table 4. For pigs made of silicone compound with a hardness of 30 units on the Shore scale to pass pipeline bends with a bending angle of 90° and a bending radius of 1.5 DN, the inlet pressure shall be at least twice as high as the pressure required for the pig to move along a straight section of the pipeline.

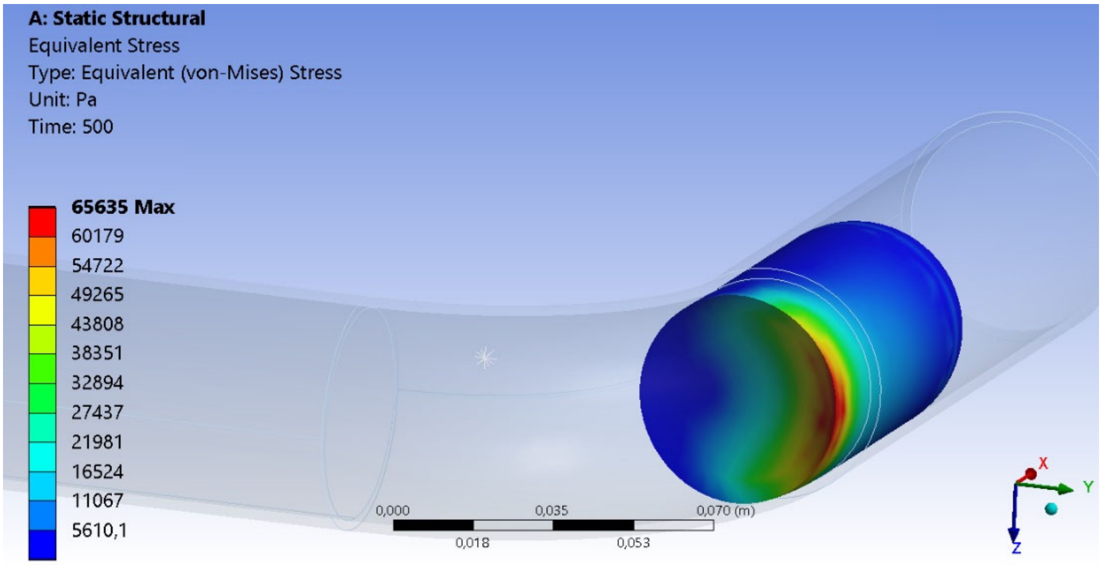


Fig. 12. Stress distribution on contours of the pig during its exit from the pipeline bend (dynamic friction coefficient equal to 0.2)

Table 4.
Results of pressure measurement during the pig movement in straight sections and the pipe bend of an experimental unit made of metal pipes

No.	Pig length, mm	Inlet pressure when the pig moves in a straight section, Pa	Inlet pressure during the pig movement through the bend, Pa
1	60	9800	21500
2	75	18600	38200
3	90	42100	76500

Prospects for further work in this direction consist of the study of the influence of the hardness of the cleaning pig's material, the angle and radius of the pipe bends on the stress-strain state of cylindrical cleaning pigs manufactured of various hyperelastic materials and the change in pressure at the inlet during their movement through the pipeline.

5. Conclusions

1. The movement of the pig in the pipeline bend slows down. It stops (at a low speed at the pipe bend inlet) with a greater friction force caused by an increase in contact forces between its lateral surface and the inner wall of the pipeline due to the deformation (bending) of the pig. The bending of the pig in the pipe bend and contact forces increase equivalent von Mises stresses in the pig. Moreover, during the movement of the pig in a pipe bend, the distribution of equivalent von Mises stresses in it, as well as its deformations, changes continuously and depends on the stage at which it is located.
2. When the pig is at the stage of entering the pipe bend, the area of concentration of maximum equivalent von Mises stresses is a circular arc in the front of the pig on the convex side of the pipe bend. Thus, when the pig enters the pipe bend, due to its bending, there is an increase in contact forces between the pig's lateral surface and the pipe's inner wall and an increase in friction forces. The simulation is confirmed by the fact that during experimental studies, at a low speed of movement, the pigs stuck at the point of their entrance to the pipe bend. When the pig is at the stage of movement of the middle part of the pipeline bend, the area of concentration of the maximum equivalent von Mises stresses is circular and concentrated in the middle part of the pig (with some displacement towards the rear end) on the convex and concave side of the pipe bend. At the stage of the pig exiting from the pipeline bend, the concentration of maximum equivalent von Mises stresses is in the rear part of the pig on the convex side of the pipe bend.
3. Additionally, the amount of equivalent von Mises stresses in the pig is affected by friction between its

lateral surface and the inner wall of the pipeline. Based on the results of numerical modelling, it was established that with an increase in dynamic friction coefficient, the equivalent von Mises stresses do not increase at the pig entry and exit to/from the pipe bend. Thus, at the stage of the pig entering into the pipe bend, when the coefficient of dynamic friction increases from 0.1 to 0.3, the maximum contact stresses increase by 1.7 times, and at the exit stage – by 2.1 times. Such results show that with an increase in the coefficient of dynamic friction, the passing capacity of the pig at the stage of its entry and exit from the pipe bend deteriorates, and the probability of sticking increases. However, during the movement of the pig in the middle part of the pipeline outlet, the coefficient of dynamic friction does not strongly affect the value of the maximum equivalent von Mises stresses.

4. Numerical modelling and experiments have established that when the pig is at the stage of movement in the middle part of the pipe bend, due to bending, its lateral surface is partially separated from the inner wall of the pipe bend. With this, on the convex side of the pipe bend, the pig is separated from the wall in the front and rear parts, and on the concave side – in the middle part. The separation of the pig's lateral surface from the pipe bend's inner wall results in the formation of a gap and cross-flows through the pig, reducing the pressure drop on it, which can lead to its sticking.
5. Experiments show that for pigs made of silicone compound with a hardness of 30 units on the Shore scale to pass pipeline bends with a bending angle of 90° and a bending radius of 1.5 DN, the pressure in the pig space shall be at least twice as high as the pressure required for the pig to move along a straight section of the pipeline.

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Authors contribution

All authors contributed equally to the article. All authors have read and agreed to the published version of the manuscript.

References

[1] V.B. Volovetskyi, Ya.V. Doroshenko, G.M. Kogut, A.P. Dzhus, I.V. Rybitskyi, J.I. Doroshenko, O.M. Shchyrba, Investigation of gas gathering pipelines operation efficiency and selection of improvement methods, Journal of Achievements in Materials and Manufacturing Engineering 107/2 (2021) 59-74. DOI: https://doi.org/10.5604/01.3001.0015.3585

[2] S.V. Matkivskyi, O.V. Burachok, L.I. Matiishyn, Evaluation of the gas recycling duration on the hydrocarbon recovery from gas condensate fields, Archives of Materials Science and Engineering 117/2 (2022) 57-69. DOI: https://doi.org/10.5604/01.3001.0016.1776

[3] R. Kondrat, L. Matiishyn, Improving the efficiency of production wells at the final stage of gas field development, Mining of Mineral Deposits 16/2 (2022) 1-6. DOI: https://doi.org/10.33271/mining16.02.001

[4] V.B. Volovetskyi, Ya.V. Doroshenko, G.M. Kogut, I.V. Rybitskyi, J.I. Doroshenko, O.M. Shchyrba, Developing a complex of measures for liquid removal from gas condensate wells and flowlines using surfactants, Archives of Materials Science and Engineering 108/1 (2021) 24-41. DOI: https://doi.org/10.5604/01.3001.0015.0250

[5] V.B. Volovetskyi, Ya.V. Doroshenko, S.M. Stetsiuk, S.V. Matkivskyi, O.M. Shchyrba, Y.M. Femiak, G.M. Kogut, Development of foam-breaking measures after removing liquid contamination from wells and flowlines by using surface-active substances, Journal of Achievements of Materials and Manufacturing Engineering 114/2 (2022) 67-80. DOI: https://doi.org/10.5604/01.3001.0016.2157

[6] V.B. Volovetskyi, Y.L. Romanyshyn, S.O. Altukhov, A.O. Bugai, Ya.V. Doroshenko, O.M. Shchyrba, Developing an electronic archive of geophysical survey results from underground gas storage wells, Journal of Achievements in Materials and Manufacturing Engineering 122/1 (2024) 14-30. DOI: https://doi.org/10.5604/01.3001.0054.4826

[7] V.B. Volovetskyi, Y.L. Romanyshyn, P.M. Raiter, M.D. Serediuk, O.M. Shchyrba, S.V. Matkivskyi, O.O. Filipchuk, Study of gas gathering pipelines hydraulic efficiency in gathering facilities of depleted fields, Journal of Achievements in Materials and Manufacturing Engineering 122/2 (2024) 69-85. DOI: https://doi.org/10.5604/01.3001.0054.4833

[8] R. Ceravolo, M. Civera, E. Lenticchia, G. Miraglia, C. Surace, Detection and Localization of Multiple Damages through Entropy in Information Theory, Applied Sciences 11/13 (2021) 5773. DOI: https://doi.org/10.3390/app11135773

[9] V.B. Volovetskyi, Ya.V. Doroshenko, A.O. Bugai, G.M. Kogut, P.M. Raiter, Y.M. Femiak, R.V. Bondarenko, Developing measures to eliminate of hydrate formation in underground gas storages, Journal of Achievements in Materials and Manufacturing Engineering 111/2 (2022) 64-77. DOI: https://doi.org/10.5604/01.3001.0015.9996
[10] Y.V. Doroshenko, G.M. Kogut, I.V. Rybitskyi, O.S. Tarayevs'kyy, T.Yu. Pyrig, Numerical investigation on erosion wear and strength of main gas pipelines bends, Physics and Chemistry of Solid State 22/3 (2021) 551-560. DOI: https://doi.org/10.15330/pcss.22.3.551-560
[11] P. Ward, D. Cockfield, Development of the pathfinder foam caliper pig, Proceedings of the Pigging Products and Services Association Seminar "PPSA 2018", Aberdeen, 2018, 1-1–1-10.
[12] A. O'Donoghue, Why Pigs get Stuck, and how to avoid it, Proceedings of the Pipeline Pigging, Integrity Assessment, and Repair Conference, Pipeline Research Limited, Amsterdam, Netherlands, 2002, 1-16.
[13] Y. Doroshenko, I. Rybitskyi, Investigation of the influence of the gas pipeline tee geometry on hydraulic energy loss of gas pipeline systems, Eastern-European Journal of Enterprise Technologies 1/8(103) (2020) 28-34. DOI: https://doi.org/10.15587/1729-4061.2020.192828
[14] M. Durali, A. Fazeli, A. Nabi, Investigation of dynamics and vibration of pig in oil and gas pipelines, Proceedings of the ASME 2007 International Mechanical Engineering Congress and Exposition, Vol. 9: Mechanical Systems and Control, Parts A, B, and C, Seattle, Washington, USA, 2007, 2015-2024. DOI: https://doi.org/10.1115/IMECE2007-43301
[15] A.O. Nieckele, A.M. Braga, L.F. Azevedo, Transient pig motion through non-isothermal gas and liquid pipelines, Proceedings of the 2000 3rd International Pipeline Conference, Vol. 1: Codes, Standards and Regulations; Design and Constructions; Environmental; GIS/ Database Development; Innovative Projects and Emerging Issues, Calgary, Alberta, Canada, 2000, V001T05A018. DOI: https://doi.org/10.1115/IPC2000-175
[16] V.Ya Grudz, V.V. Bakaiev, Ya.V. Grudz, H. Rosen, Mathematical modeling of the process of movement of an intelligent pig by gas pipeline, Oil and Gas Industry 1 (2000) 46-47 (in Ukrainian).
[17] V.Ya. Grudz, V.B. Mykhalkiv, V.V. Rozghoniuk, V.P. Rudko, Management of the gas pipeline operation mode during preventive cleaning, Oil and Gas Industry 6 (1998) 37-38 (in Ukrainian).
[18] L. Chen, Y. Li, X. Chen, Y. Zhan, M. Dang, Numerical Study of Being Forced Leather Cap Type Pig in Straight Gas Pipeline, Open Civil Engineering Journal 10/Suppl-1,M3 (2016) 141-148. DOI: https://doi.org/10.2174/1874149501610010141
[19] S. Chen, L. Xia, X. Wang, K. Teng, Y. Zhang, M. Zhang, Y. Gong, Motion Law and Mechanical Properties of PIGs When Passing through a Pipe Bend, Machines 10/10 (2022) 963. DOI: https://doi.org/10.3390/machines10100963
[20] M. Borregales, R. Ensalzado, M. Asuaje, CFD analysis of phenomena attributed to pigging run in a pipeline, Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition, Vol. 7: Fluids Engineering Systems and Technologies, Montreal, Quebec, Canada, 2014, V007T09A082. DOI: https://doi.org/10.1115/IMECE2014-37452
[21] Y.-G. Cao, Y. Zhen, Y.-J. Shi, S.-H. Zhang, Y.-T. Sun, W.-J. Nie, Stress Distribution of the Power Section Cup of Pipeline Inspection Gauges by Finite Element Method, Journal of Pipeline Systems Engineering and Practice 9/2 (2018) 04017039. DOI: https://doi.org/10.1061/(ASCE)PS.1949-1204.0000308
[22] F. Lalo, M. Greco, Rubber bushing hyperelastic behavior based on shore hardness and uniaxial extension, Proceedings of the 24th ABCM International Congress of Mechanical Engineering, Curitiba, PR, Brazil, 2018, 1-10. DOI: https://doi.org/10.26678/ABCM.COBEM2017.COB17-5280
[23] C. Renaud, J.-M. Cros, Z.-Q. Feng, B. Yang, The Yeoh model applied to the modeling of large deformation contact/impact problems, International Journal of Impact Engineering 36/5 (2009) 659-666. DOI: https://doi.org/10.1016/j.ijimpeng.2008.09.008
[24] M. Elsamanty, M. Hassaan, M. Orban, K. Guo, H. Yang, S. Abdrabbo, M. Selmy, Soft Pneumatic Muscles: Revolutionizing Human Assistive Devices with Geometric Design and Intelligent Control, Micromachines 14/7 (2023) 1431. DOI: https://doi.org/10.3390/mi14071431