Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 123 **2024**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2024.123.15

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Stetsiuk, S., Doroshenko, Y., Bondarenko, R., Filipchuk, O., Volovetskyi, V. Investigation on the dynamics of movement of cylindrical cleaning pigs through the bends of pipeline systems for fluid transportation. *Scientific Journal of Silesian University of Technology. Series Transport*. 2024, **123**, 303-317. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2024.123.15.

Serhii STETSIUK[1], Yaroslav DOROSHENKO[2], Robert BONDARENKO[3], Oleksandr FILIPCHUK[4], Volodymyr VOLOVETSKYI[5]

INVESTIGATION ON THE DYNAMICS OF MOVEMENT OF CYLINDRICAL CLEANING PIGS THROUGH THE BENDS OF PIPELINE SYSTEMS FOR FLUID TRANSPORTATION

Summary. Development and implementation of methods for cleaning the internal cavity of pipelines in the process of transporting fluids is important to ensure their energy efficiency and safe operation. The dynamics of the movement of one-piece cylindrical cleaning pistons made of various materials (silicone compound, self-destructive elastic polymer composition, polyurethane foam

[1] Institute of Petroleum Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska 15 Street, 76019 Ivano-Frankivsk, Ukraine. Email: stetsyuk.sergey@ugv.com.ua. ORCID: https://orcid.org/0009-0004-9918-7692
[2] Institute of Petroleum Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska 15 Street, 76019 Ivano-Frankivsk, Ukraine. Email: yaroslav.doroshenko@nung.edu.ua. ORCID: https://orcid.org/0000-0002-5853-3286
[3] Institute of Petroleum Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska 15 Street, 76019 Ivano-Frankivsk, Ukraine. Email: brv972@ukr.net. ORCID: https://orcid.org/0009-0000-2667-5047
[4] Hydrocarbon Collection, Preparation, and Transportation Department, Joint Stock Company "Ukrgasvydobuvannya", Kudriavska 26/28 Street, 04053 Kyiv, Ukraine. Email: oleksandr.filipchuk@ugv.com.ua. ORCID: https://orcid.org/0009-0001-4759-9378
[5] Department of Scientific and Technical Support for the Operation of Underground Gas Storage Facilities, Scientific Research Institute of Gas Transport of JSC "Ukrtransgaz", Koneva 16 Street, 61004 Kharkiv, Ukraine. Email: vvb11@ukr.net. ORCID: https://orcid.org/0000-0001-8575-5143

assembly foam) in the pipelines of pipeline systems intended for fluid transportation were studied by modelling and experimentally. The dynamics of movement of solid cylindrical cleaning pigs made from various materials (silicone compound, self-destructive elastic-polymer composition, polyurethane foam) in bends of pipeline systems intended for fluid transportation were studied through modelling and experiments. The analysis of forces acting on the pig during its movement in the pipeline bend was conducted, and the equations of pig motion based on Newton's second law were formulated. Contact forces of normal reaction, arising due to pig bending in the pipeline bend and determining the magnitude of frictional force between the pig and the inner wall of the bend, were determined based on classical bending theory. The impact of the material's modulus of elasticity, from which the pig is made, on the magnitude of contact forces of normal reaction at the pig pressing points against the inner wall of the pipeline bend was established. A method for determining the conditions under which pigs made from different materials will pass through pipeline bends without stopping and getting stuck was proposed. An equation for calculating the minimum allowable pig movement speed at the entrance to the bend to ensure its passage without stopping and getting stuck was derived.

Keywords: equations of motion, contact force, frictional forces, modulus of elasticity, minimum allowable speed, sticking, silicone compound, self-destructive elastic-polymer composition, polyurethane foam

1. INTRODUCTION

Today, pipelines are the safest and most commercially attractive way to transport gas, oil, and other substances, and one of the key components of modern energy infrastructure. However, the operation and maintenance of pipeline systems are associated with certain risks [1-3], which requires users to carefully care for such structures and monitor their technical condition [4,5].

In the process of operating pipelines for various purposes, various liquid and solid contaminants accumulate inside their internal cavities. Especially in the lower sections of industrial gas pipelines from depleted gas fields, there are many liquid contaminants (hydrocarbon condensate, formation water). Solid contaminants (products of internal corrosion, sludge deposits, sand, soil, etc.) accumulate mostly in heating and water supply pipelines.

The presence of liquid contaminants inside gas pipelines leads to numerous complications that negatively affect not only the gas transportation process but also its extraction. With the increase in the volume of liquid contaminant accumulations, the hydraulic resistance of gas pipelines increases, leading to pressure losses above the values predicted by the technological operating mode, and consequently, a decrease in the gas pipelines' throughput and hydrocarbon extraction volumes. Moreover, the contaminants present inside gas pipelines lead to the formation of solid crystalline hydrates that deposit on the inner wall (most often in places of gas flow constriction), causing intensified processes of internal corrosion. Therefore, to increase the hydraulic efficiency and residual lifespan of pipelines, their internal cavities need to be periodically cleaned.

Various methods are currently employed for cleaning pipelines from accumulated contaminants, including blowing or flushing with high-speed flows, injecting surface-active substances, passing cleaning pigs, diverting liquid into condensate collectors, etc. Each of these methods has its advantages and disadvantages, as well as its specific applications. Particularly relevant are the methods that do not involve emissions of natural gas into the environment.

In the case of cleaning the internal cavities of gas pipelines using cleaning pigs, it is possible to minimize the losses of the transported product (minor losses occur only during startup and pig reception) and reduce emissions of natural gas into the environment. However, complications arise as many pipeline systems are designed and constructed without provisions for pig cleaning, lacking pig launching and receiving. These systems contain numerous complex elements such as sharply bent bends, tees, reducers from larger to smaller pipe diameters, and so on. These complex elements are manufactured by various factories and possess diverse internal geometries. This primarily applies to industrial gas pipelines, gas, heating, and water supply networks.

During the initial mechano-mathematical modelling of the movement of the cleaning pig through the pipeline, we obtain the problem of the contact interaction of an elastic body with a shell with a variable topology. Contact problems about the interaction of elastic bodies form an actual section of mechanics and have applied value for the rational operation and maintenance of pipeline transport [6].

The nonlinear geometric shape of these pipeline elements results in numerous uncertainties regarding the passage of cleaning pigs and significantly increases the risk of pig getting stuck [7]. Therefore, it is crucial to determine the necessary dimensions, material, and shape of the pig to ensure it passes through all pipeline fittings effectively and efficiently cleans the pipeline.

2. MATERIAL AND RESEARCH METHODS

The internal cavities of pipelines are cleaned using pigs of various designs and materials [8,9]. Solid pigs made from diverse elastic materials distinguish themselves by their ability to pass through complex geometric pipeline elements without damage and efficiently clean the pipelines' internal cavities. It is advisable to use materials that can undergo significant deformation under load while practically maintaining their volume. However, to utilize pigs made from such materials for pipeline cleaning, accurate information about the dynamics of their movement through pipeline fittings is crucial. Different materials suitable for pig manufacturing possess varying mechanical strength, elasticity modules, and density. Therefore, pigs made from inappropriately chosen materials might get stuck, be damaged, or even break while passing through shaped elements.

To experimentally establish the impact of the physical and mechanical characteristics of materials on the dynamics of pig movement through pipeline fittings, solid cylindrical pigs were manufactured from different elastic materials. These materials include silicone compound, self-destructive elastic-polymer composition developed by the Ukrainian Scientific Research Institute of Natural Gases and mounting polyurethane foam. The diameter of all pigs is equal to the internal diameter of the pipeline.

The pigs made from silicone compound (Fig. 1a) are distinguished by their high strength, flexibility, elasticity, and wear resistance. They also have a greater mass than pigs made from other materials, making this material exceptionally suitable for manufacturing cleaning pigs. Before pouring into the mold, the silicone compound SKR-780 with a hardness of 5 on the Shore A scale was colored green, SKR-784 with a hardness of 15 was colored purple, and SKR-788 with a hardness of 30 was colored pink. The density of the silicone compound is 1100 kg/m^3.

Pigs made from elastic-polymer composition (Fig. 1b) are characterized by flexibility, elasticity, and the ability to self-destruct by dissolution upon contact with condensate or water in the pipeline. Usually, the dissolution time is longer than the duration of the pipeline cleaning operation. Therefore, when using such pigs, there is no need to create receiving chambers. The pigs are made from an elastic-polymer composition with a hardness of 4 on the Shore A scale, colored red, and a hardness of 7, colored green. The density of the elastic-polymer composition is 1040 kg/m³.

Polyurethane foam pigs are characterized by low strength and mass and are rigid. The pigs are made from mounting polyurethane foam with a density of 160 kg/m³ (Fig. 1c).

a *b* *c*

Fig. 1. Solid cylindrical pigs made from hyperplastic materials
a) silicone compound; b) elastic-polymer composition; c) mounting polyurethane foam

The force driving the pigs through the pipelines occurs when the pressure in the pig chamber P_1 exceeds the pressure in front of the pig P_2 (Fig. 2). If the pig diameter D_p is equal to the internal diameter of the pipeline, and the pig moves along a horizontal straight segment, we obtain the equation of motion:

$$m_p \frac{dV_p}{dt} = (P_1 - P_2)S_p - F_f, \qquad (1)$$

where m_p – pig's mass; V_p – pig's velocity; t – time; S_p – cross-sectional area of the pig; F_f – the sliding friction force between the pig's lateral surface and the inner wall of the pipeline.

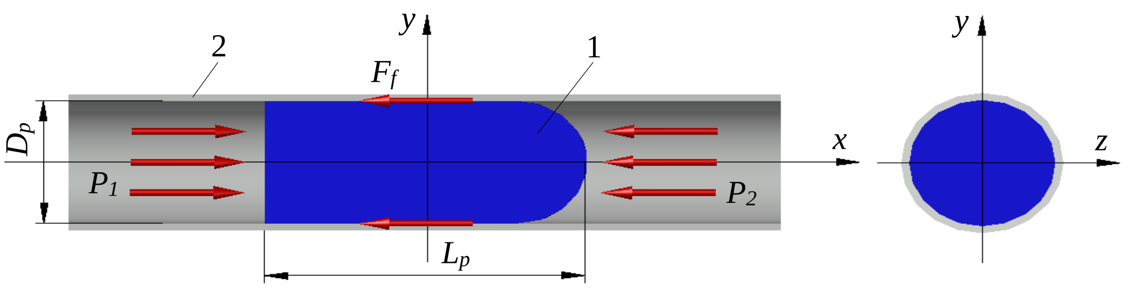


Fig. 2. Calculated schematic of the movement of a cylindrical pig along a straight section of the pipeline 1) pig; 2) pipeline

The force of sliding friction between the lateral surface of the pig and the inner wall of the pipeline

$$F_f = \mu_f N = \mu_f g m_p , \tag{2}$$

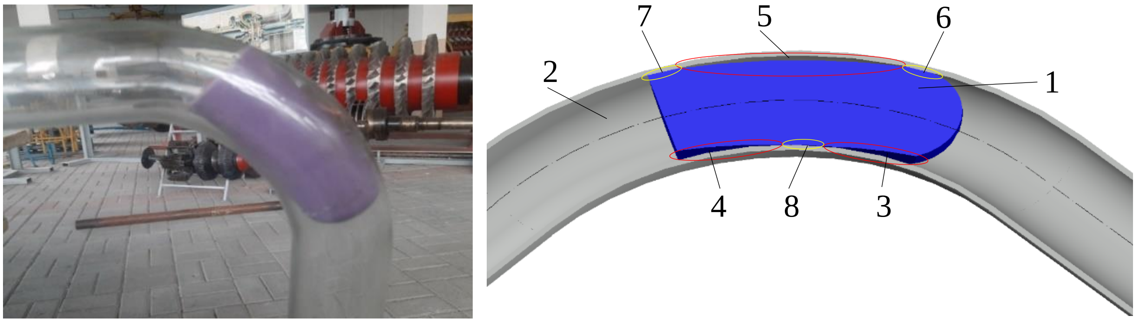
where μ_f – the coefficient of sliding friction between the lateral surface of the pig and the inner wall of the pipeline; N – normal reaction; g – gravitational acceleration. [10]

During the pig's uniform motion along the straight horizontal section with constant velocity, the pressure force and the sliding friction force between the lateral surface of the pig and the inner wall of the pipeline are balanced. Substituting (2) into (1) gives the pressure drop that occurs on the pig in this case

$$\Delta P = P_1 - P_2 = \frac{\mu_f g m_p}{S_p} . \tag{3}$$

Pipeline bends are an additional resistance to the motion of pigs [11,12], so it is important to determine how significant this impact is. During the movement of solid cylindrical pigs made of elastic materials through pipeline bends, the geometric shape of these fittings causes their deformation (bending). It has been experimentally observed that as a result of pig 1 bending in bend 2, partial separation of its lateral surface from the inner wall occurs (Fig. 3). Specifically, on the concave side of the bend, the pig separates from the wall in the front (location 3) and rear (location 4) parts, while on the convex side, it separates in the middle (location 5) (Fig. 3b). The reasons for this are that when pig 1 moves through bend 2, it is strongly pressed against the inner wall from the convex side, as it attempts to restore its shape under the action of elastic forces. As a result, the material of the pig is compressed in this area, leading to separation from the wall in the front (location 3) and rear (location 4) parts from the concave side of the bend. Similarly, strong pressing of pig 1 against the inner wall occurs in its middle part (location 8) from the concave side of bend 2. Due to this pressing, the material of pig 1 in its middle part near the concave side of bend 2 (location 8) compresses, leading to separation of the middle part of pig 1 from the wall on the convex side of bend 2 (location 5). The increase in the separation of pig 1 from the wall in this area is caused by the stretching of pig 1 material in its middle part (location 5) due to pressing against the inner wall of bend 2 from the convex side of the pipeline bend.

Bending of solid cylindrical pigs made of elastic materials in pipeline bends, uneven pressing against the inner wall, and separation of the pig's lateral surface from the inner wall bend to significant contact forces and their uneven distribution. This causes an unequal distribution of friction forces. Moreover, the separation of the pig from the inner wall can result in the leakage of the transported medium through the pig, reducing the pressure drop on it; this decrease leads to a reduction in the force caused by this pressure drop. Such changes in pig movement dynamics in bends result in a multitude of uncertainties. Experimental findings indicate that the pig can slow down, stop, resume movement, or get completely stuck. In the case of a pig getting stuck in a bend due to leakage, the transportation process will not stop, but the pig will become a significant hydraulic resistance and a threat to the system's safety.



a *b*

Fig. 3. Pig movement with a silicone compound through a pipeline bend
a) experimental setup; б) schematic; 1) pig; 2) bend; 3, 4, 5) locations where the pig separates from the wall; 6, 7, 8) locations where the pig is pressed against the wall

To avoid such situations, it is crucial to determine the conditions under which the pigs will pass through pipeline bends, which significantly depends on their physical and mechanical characteristics. To achieve this, the dynamics of pig movement in pipeline bends need to be studied. This task is complex, involving considerations of the bend's curvilinear geometric shape, uneven pressing of the pig's lateral surface against the inner wall (affecting the friction force), pig material characteristics, and gas dynamic processes.

The best methods for establishing the movement patterns of pigs in pipeline bends and determining the influence of each factor are modelling and experimental research. If the cylindrical pig is made of a rigid material, its maximum allowable length for passing through the bend can be determined using analytical geometry methods [13]. However, if the pig is made of an elastic material, it will bend in the pipeline bend, and the dynamics of its movement significantly depend on the physical and mechanical characteristics of the material as well as the geometric parameters of the pig.

To determine the movement patterns of a cylindrical pig made of an elastic material in pipeline bends, it is necessary to identify the forces acting on it during movement. The pig's movement in the bend is slowed down and even stopped by significant friction forces caused by its deformation (bending) to a magnitude ε_y (Fig. 4a). As a result of the bending of the pig 1 made of elastic material in the bend 2 of the pipeline and its strong pressing against the inner wall in the front (location 6) and rear (location 7) parts on the convex side of the bend (Fig. 3b), significant contact forces of normal reaction N_{w1} and N_{w2} arise in these areas (Fig. 4a). Even stronger pressing of the pig against the inner wall of the bend occurs in its middle part on the concave side (location 8) (Fig. 3b), leading to the emergence of the contact force of normal reaction N_{w3} (Fig. 4a). These contact forces of normal reaction result in significant friction forces between the outer surface of the pig and the inner wall of the bend in the pressing areas F_{f1}, F_{f2}, and F_{f3}, respectively (Fig. 4a).

Similarly, during the movement through the bend, the pig is subjected to a centrifugal force, leading to a slight increase in its pressure against the inner wall in the front (location 6) and rear (location 7) parts of the bend from the convex side (Fig. 3b). This results in a minor increase in friction forces F_{f1} and F_{f2}. From the concave side of the bend, the centrifugal force leads to a slight reduction in pressure against the inner wall in the middle section (position 8) (Fig. 3b), causing a corresponding minor decrease in friction force F_{f3}. Therefore, we will not consider the influence of the centrifugal force on the pig's dynamics in the bend of the pipeline.

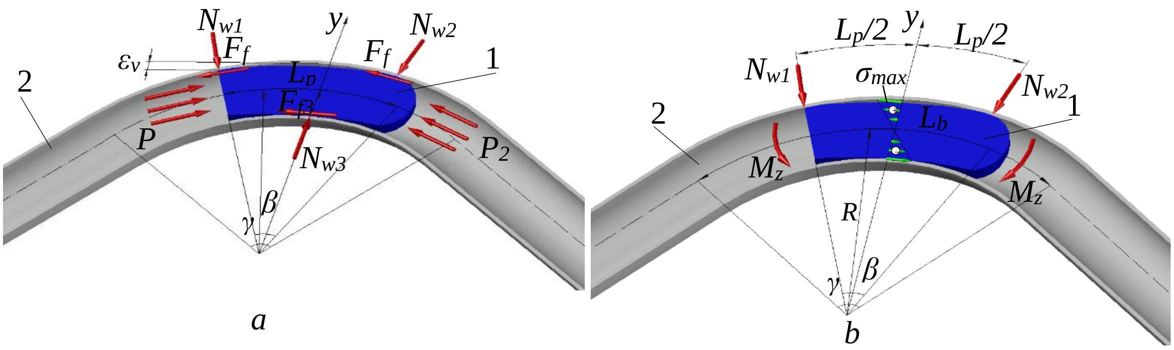


Fig. 4. Computational diagram of the movement of a cylindrical pig made of a hyperplastic material in a pipeline bend a) force action scheme; b) pig bending scheme; 1) pig; 2) bend

The gravitational force, depending on the spatial position of the bend and the pig's location inside the bend, can either slightly accelerate or decelerate the pig. Compared to the influence of friction forces, the effect of the gravitational force is negligible. Hence, we will also neglect the impact of the gravitational force.

Based on the analysis of the forces acting on the pig in the tangential direction during its movement through the bend of the pipeline and Newton's second law, we obtain the equation of motion for the pig

$$(P_1 - P_2)S_p - F_{f1} - F_{f2} - F_{f3} = m_p a_t\,, \tag{4}$$

where a_t – tangential acceleration of the pig in the bend.

To determine the friction forces F_{f1}, F_{f2} and F_{f3}, acting on the cylindrical pig made of hyper elastic material during its movement through the pipeline bend, it is necessary to determine the corresponding contact forces of normal reaction N_{w1}, N_{w2}, and N_{w3} (Fig. 4a). Obviously

$$N_{w1} = N_{w2}\,. \tag{5}$$

The forces acting on the pig can be projected onto the y-axis based on Newton's second law.

$$N_{w3} - N_{w1}\cos\frac{\beta}{2} - N_{w2}\cos\frac{\beta}{2} = -m_p a_c\,, \tag{6}$$

where a_c – centripetal acceleration of pig; β – is the bending angle of the pig, which is equal to

$$\beta = \frac{L_p}{R}\,, \tag{7}$$

where R – is the bend radius, which is equal to the bend radius of the pig.

Centripetal acceleration of the pig

$$a_c = \frac{V^2}{R}, \tag{8}$$

where V – the speed of the pig in the bend.

Substitute (5), (7) and (8) into (6). We obtain the contact force of the normal reaction at the place where the pig is pressed against the inner wall of the bend in its middle part from the concave side (location 8) (Fig. 3b)

$$N_{w3} = 2N_{w1} \cos\frac{L_p}{2R} - m_p \frac{V^2}{R}. \tag{9}$$

To determine the contact forces of the normal reaction N_{w1}, consider the bending of a cylindrical pig made of elastic material in the pipeline bend (Fig. 4b). Since bending occurs relative to the z axis, which is perpendicular to the plane of the figure, the bending moment is equal to

$$M_z = \frac{EI_z}{R}, \tag{10}$$

where E – modulus of elasticity of the material from which the pig is made; I_z – moment of inertia of the pig relative to the z axis. [14]

The moment of inertia of the pig relative to the z axis

$$I_z = \frac{\pi D_p^4}{64}. \tag{11}$$

The bending moment can also be determined according to the calculation scheme (Fig. 4b)

$$M_z = N_{w1} \frac{L_p}{2}. \tag{12}$$

We substitute (12) in (10) and, considering (11), we obtain the equation for determining the contact forces of the normal reaction in the places where the pig is pressed against the inner wall in the front (location 6) and rear (location 7) parts on the convex side of the bend (Fig. 3b)

$$N_{w1} = N_{w2} = \frac{\pi D_p^4 E}{32RL_p}. \tag{13}$$

Equation (13) is substituted into (9) and we get the equation for determining the contact force of the normal reaction in the places where the pig is pressed against the inner wall in its middle part (location 8) on the concave side of the bend (Fig. 3b)

$$N_{w3} = \frac{\pi D_p^4 E}{16RL_p} cos\frac{L_p}{2R} - m_p\frac{V^2}{R}. \tag{14}$$

Based on the contact forces of the normal reaction N_{w1} and N_{w2}, we determine the force of friction in the places of their occurrence

$$F_{f1} = F_{f2} = \mu_f N_{w1} = \mu_f \frac{\pi D_p^4 E}{32RL_p}. \tag{15}$$

The force of friction at the point of occurrence of the contact force of the normal reaction N_{w3}

$$F_{f3} = \mu_f N_{w3} = \mu_f\left(\frac{\pi D_p^4 E}{16RL_p} cos\frac{L_p}{2R} - m_p\frac{V^2}{R}\right). \tag{16}$$

Substitute (15) and (16) into the pig motion equation (4) and determine the tangential acceleration of the pig in the bend

$$a_t = \frac{\pi D_p^2 (P_1 - P_2)}{4m_p} - \mu_f\left(\frac{\pi D_p^4 E}{16m_p RL_p}\left(1 + cos\frac{L_p}{2R}\right) - \frac{V^2}{R}\right). \tag{17}$$

3. RESULTS AND DISCUSSION

The contact forces of the normal reaction occur in the places where the pig is pressed against the inner wall in the bend. Accordingly, the frictional forces significantly depend on the characteristics of the material from which the pig is made, namely the modulus of elasticity. Thus, for pigs made of an elastic polymer composition, the modulus of elasticity is 0.2 MPa, the contact forces of normal reaction N_{w1} and N_{w2} are equal to 19.8 N. On the other hand, for pigs made of silicone compound, the modulus of elasticity is 0.6 MPa, the contact forces of the normal reaction N_{w1} and N_{w2} are 3 times larger and amount to 59.3 N, and for pigs made of polyurethane foam, the modulus of elasticity is 4 MPa, 20 times larger and amount to 395.7 N (calculation performed according to equation (13) for a pipeline bend with an internal diameter of 54 mm, a bending radius of 80 mm and a bending angle of 90°, which moves pigs made of the investigated materials with a diameter of 54 mm and a length of 110 mm). Such large contact forces of the normal reaction can lead to a rapid deceleration of the pig, made of polyurethane foam installed in the bend, to a stop. And in case of a significant flow of the transported medium through it, it will get stuck. Therefore, it is necessary to determine under what conditions the pig will stop in the pipeline bend.

How quickly the pig decelerates in the pipeline bend (the change in the speed of the pig in the bend) determines its tangential acceleration. Equations that determine the uniformly decelerated movement of the pig by the bend

$$L = V_p t + \frac{a_t t^2}{2}, \tag{18}$$

$$V_f = V_p + a_t t, \tag{19}$$

where L – length; t – time; V_p – the speed of the pig at the entrance to the bend; V_f – is the final speed of pig movement.

From (19) we get

$$t = \frac{V_f - V_p}{a_t}. \tag{20}$$

Substitute (20) into (18) and get

$$L = \frac{V_f^2 - V_p^2}{2a_t}. \tag{21}$$

If the final speed of the pig is set to zero ($V_f = 0$), then the distance travelled by the pig to a complete stop

$$L = -\frac{V_p^2}{2a_t}. \tag{22}$$

In turn, the length of the segment built along the axis of the bend L_b (Fig. 4b) depends on the angle of bend γ and its radius R. There is the following relationship between these values

$$\gamma = \frac{L_b}{R}. \tag{23}$$

Then

$$L_b = \gamma R. \tag{24}$$

Therefore, if the results of the calculation establish that the condition

$$L \geq L_b \tag{25}$$

If this is performed, then the pig will pass through the pipeline and its getting stuck will not occur. If condition (25) is not fulfilled, then the pig will stop in the bends and get stuck, which is possible if condition (25) is not fulfilled.

To calculate using equation (22) the distance that the pig will travel until it comes to a complete stop, it is necessary to first determine the tangential acceleration of the pig in the bend using equation (17). However, in equation (17), the pressure drop $P_1 - P_2$ across the pig during its movement through the bend is unknown. Since the time of movement of the pig through the pipeline bend is insignificant, in the case of a short-term slowdown of the pig movement, the pressure drops on it during movement through the bend $P_1 - P_2$ is approximately equal to the pressure drop on the pig during its movement at a constant speed through a straight section of the pipeline adjacent to the bend. Therefore, we should substitute (3) for (17) Then the tangential acceleration of the pig in the bend is equal to

$$a_t = \mu_f \left(g + \frac{V^2}{R} - \frac{\pi D_p^4 E}{16 m_p R L_p} \left(1 + cos \frac{L_p}{2R} \right) \right). \tag{26}$$

Before using pigs, it is necessary to determine under what conditions they will pass through all elements of the pipeline, including bends. For this purpose, based on the obtained mathematical model of the movement of a cylindrical pig made of hyper elastic material through a pipeline bend, it is advisable to determine the minimum permissible speed of the pig at the entrance to the bend, so that it passes through it without stopping and getting stuck. For this, it is necessary to equalize the length L_b and distance L. We equate (24) and (22)

$$\gamma R = -\frac{V_p^2}{2a_t}. \tag{27}$$

From (27), we determine the tangential acceleration of the pig in the bend

$$a_t = -\frac{V_p^2}{2\gamma R}. \tag{28}$$

We equate (26) and (28) and express the pig speed. Then the minimum allowable speed of the pig at the entrance to the bend

$$V_{p\ min} = \sqrt{\frac{2\mu_f \gamma R}{1 + 2\mu_f \gamma} \left(\frac{\pi D_p^4 E}{16 m_p R L_p} \left(1 + cos \frac{L_p}{2R} \right) - g \right)}. \tag{29}$$

Therefore, if the speed of movement of the pig at the entrance to the bend is lower $V_{p\ min}$, then the pig will stop in the bend of the pipeline The pig may get stuck in the event of a significant flow of the transported medium through it.

For the experimental study of the movement of cylindrical pigs made of elastic materials by pipelines by dynes, verification of the obtained mathematical models, a labouratory experimental installation was developed and assembled. It consists of a pig launch chamber 4 equipped with a manometer and a counter, and a pipeline of two pipes between which a bend is placed (Fig. 5). Three different pipelines have been installed. Two of glass tubes 2.4 m long with an internal diameter of 38 mm and 3 m long with an internal diameter of 54 mm and one of steel tubes with a length of 2.4 m and an internal diameter of 47 mm. Between the pipes, glass and steel pipes with a bending angle of 60°, 90° and 120° and a bending radius equal to DN, 1.5DN and 2DN were placed bend. The inner diameter of the bends was the same as the inner diameter of the pipes between which they were mounted. Pipes with a bend connected to flanges. The advantage of the experimental pipeline made of glass pipes and a glass bend is the possibility of visual observation of the dynamics of the movement of the pigs. A pipeline made of steel pipes allows for studies to be carried out at higher pressures.

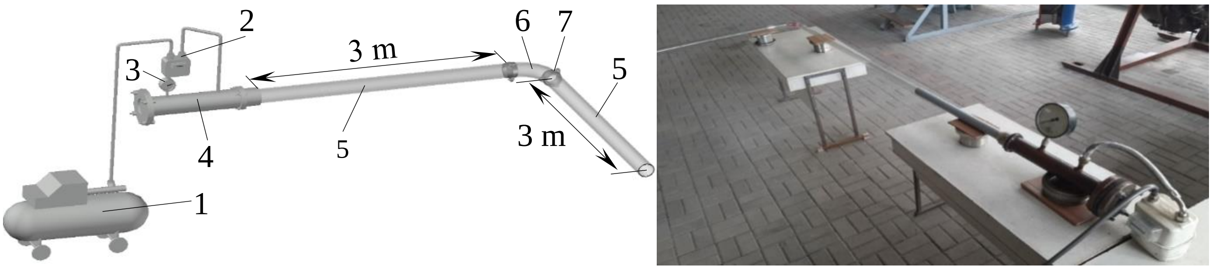


Fig. 5. Experimental setup for researching the movement of pigs with bends
1) compressor; 2) counter; 3) manometer; 4) pig start unit; 5) pipe; 6) bend; 7) flange

The pigs were placed in the launch chamber, and they moved through the pipeline under the pressure of air, which was supplied from the compressor receiver. A tap on the air supply line from the compressor regulated the airflow and, accordingly, the speed of the pig. At the place of air release from the experimental installation, the pressure is equal to atmospheric pressure. During experimental studies, the pressure at the pipeline entrance was recorded with a manometer and the airflow rate was recorded with a meter. A video recording of the displays of the measuring devices and the movement of the pig through the glass pipeline was made, which made it possible to determine the speed of the pig's movement.

Calculated according to equation (29) and determined experimentally, the minimum permissible speed of movement of the pigs from the studied materials at the entrance to the bend. The minimum permissible speed of movement of pigs increases significantly with an increase in the modulus of elasticity of the material from which the pig is made (Fig. 6) (the modulus of elasticity of the silicone compound is 0.6 MPa, the elastic-polymer composition is 0.2 MPa, and the mounting polyurethane foam is 4 MPa). If the modulus of elasticity increases from 0.2 MPa (pigs are made of elastic-polymer composition) to 4 MPa (pigs are made of polyurethane foam), then the minimum permissible movement speed of the pigs at the entrance to the outlet increases 4 times - from 1.7 m/s to 6.8 m/s (the calculation was made for a pipeline bend with an internal diameter of 54 mm, a bending radius of 80 mm, which moves pigs made of the investigated materials with a diameter of 54 mm and a length of 110 mm).

In [15], it was established that the efficiency of cleaning pipelines is best when they move at a speed of 2 m/s to 5 m/s. Since, for pigs made of polyurethane foam assembly, the minimum allowable speed of movement of the pig at the entrance to the bend is 6.7 m/s according to the results of calculations. At speeds up to 5 m/s such pigs will stop in the bends of the pipeline and may get stuck. Therefore, parametrically, by changing the length of the polyurethane foam pig, it is determined that if it surpasses 230 mm, the minimum permissible speed of the pig at the entrance to the bend will be less than 5 m/s. For such a length, the pigs made of polyurethane foam of the assembly plant will effectively clean the pipeline and pass without stopping through all bends with a bending radius of 1.5 DN and more.

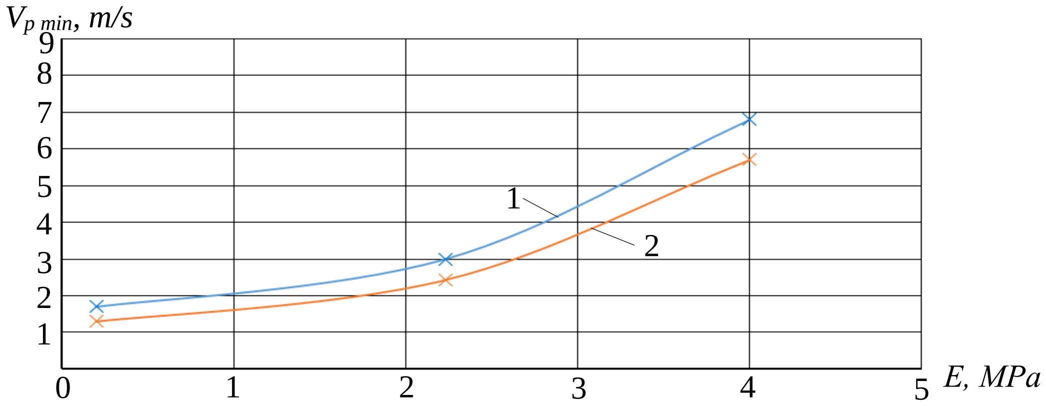


Fig. 6. Dependence of the minimum permissible speed of movement of the pig at the inlet to the bend on the modulus of elasticity of the material from which it is made
1) calculation results; 2) experimental data

4. CONCLUSION

It has been established by modelling and experiments that pistons made of elastic materials (silicone compound, self-destructive elastic-polymer composition, polyurethane foam mounting foam) can be used to clean the inner cavity of pipelines intended for the transportation of fluids. Pipelines contain branches of different radii and bending angles, including steeply curved ones. However, the bending of solid-cast cylindrical pigs made of such materials in the bends of pipelines leads to the occurrence of large contact forces of normal reaction and their uneven distribution, which significantly affects the friction forces between the side surface of the pig and the inner wall of the bend. This leads to braking of the movement of the pig, as a result of which a stop is possible and the pig get stuck.

The contact forces of the normal reaction determined by modelling, which act on the pig in the pipeline bend, are proportional to the modulus of elasticity of the material from which the pig is made. For pigs made of polyurethane foam the modulus of elasticity of which is 4 MPa when bending is 395.7 N, which is 20 times more than for pigs made of an elastic-polymer composition, the modulus of elasticity of which is equal to 0.2 MPa for bending. Therefore, pigs made of materials that have the smallest modulus of elasticity are the best for pipeline bends.

On the basis of the methodology developed based on the results of simulations for calculating the minimum permissible speed of movement of the pig at the entrance to the bend. It has been determined that the pigs are constructed from polyurethane foam and are capable of moving through the pipeline at the recommended speed range of 2 m/s to 5 m/s, as recommended in the literature. However, it has been observed that the pigs may encounter pipeline bends and may become stuck. Therefore, according to the results of the analysis of the relationship between the length of the pig and the minimum permissible speed of its movement at the entrance to the bend. It was determined that, for the given calculation data, if the length of the pig is greater than 230 mm, then the minimum permissible speed of the pig at its entrance to the bend will be less than 5 m/s.

The results of simulation are recommendations for determining what material, length, and speed of movement of the cylindrical pig should be so that it passes through all pipeline bends without stopping, which can be the cause of getting stuck.

References

1. Mohamed Azzam. 2023. Failure Analysis of Pipelines in the Oil and Gas Industry. In: *The Book of Pipeline Engineering - Design, Failure, and Management*, edited by Sayeed Rushd, Mohamed Ismail, 1-23. Saudi Arabia: IntechOpen. ISBN: 978-1-83768-000-9. DOI: https://doi.org/10.5772/intechopen.108140.
2. Ivan Shatskyi, Andrii Struk. 2009. „Stressed state of pipeline in zones of soil local fracture". *Strength of Materials* 41: 548-553. ISSN: 1573-9325. DOI: https://doi.org/10.1007/s11223-009-9165-9.
3. Evstakhii Kryzhanivs'kyi, Vasyl Rudko, Ivan Shatskyi. 2004. „Estimation of admissible loads upon a pipeline in the zone of sliding ground". *Materials Science* 40: 547-551. ISSN: 1573-885X. DOI: https://doi.org/10.1007/s11003-005-0076-z.
4. Maciej Dutkiewicz, Taras Dalyak, Ivan Shatskyi, Tetyana Venhrynyuk, Andrii Velychkovych. 2021. „Stress Analysis in Damaged Pipeline with Composite Coating". *Applied Sciences* 11(22): 10676. ISSN 2076-3417. DOI: https://doi.org/10.3390/app112210676.
5. Maciej Dutkiewicz, Andrii Velychkovych, Andriy Andrusyak, Ivan Petryk, Andrii Kychma. 2023. „Analytical Model of Interaction of an Oil Pipeline with a Support of an Overpass Built in a Mountainous Area". *Energies* 16(11): 4464. ISSN: 1996-1073. DOI: https://doi.org/10.3390/en16114464.
6. Xiao Zhu, Chun Fu, Yu Wang, Shi Zhang. 2023. „Experimental research on the contact force of the bi-directional pig in oil and gas pipeline". *Petroleum Science* 20(1): 474-481. ISSN 1995-8226. DOI: https://doi.org/10.1016/j.petsci.2022.08.021.
7. Aidan O'Donoghue. 2002. „Why Pigs get Stuck, and how to avoid it". In: *Pipeline Pigging, Integrity Assessment, and Repair Conference*: 1-16. Pipeline Research Limited. Amsterdam, Netherlands. 30 October 2002, Scientific Surveys, Beaconsfield, United Kingdom.
8. Роман Кондрат, Андрій Угриновський, Василь Петришак, Тетяна Сапожкова. 2013. „Характеристика та вибір очисних пристроїв для очищення внутрішньої порожнини трубопроводів". *Розвідка та розробка нафтових і газових родовищ* 3(48): 48-61. [In Ukrainian: Roman Kondrat, Andrii Uhrynovskyi, Vasyl Petryshak, Tetiana Sapozhkova „Characteristics and selection of cleaning devices for cleaning the internal cavity of pipelines". *Prospecting and Development of Oil and Gas Fields* 3(48): 48-61]. ISSN: 1993-9973.
9. Manuel Borregales, Ruben Ensalzado, Miguel Asuaje. 2014. „CFD Analysis of Phenomena Attributed to Pigging Run in a Straight Pipeline". In: *ASME 2014 International Mechanical Engineering Congress and Exposition*: 1-7. American Society of Mechanical Engineers. Montreal, Quebec, Canada. 14-20 November 2014, ASME, Montreal, Quebec, Canada. ISBN: 978-0-7918-4954-5. DOI: https://dx.doi.org/10.1115/imece2014-37452.
10. Tore Galta 2014. „Bypass Pigging of Subsea Pipelines Suffering Wax Deposition". *Master thesis*. Trondheim, Norway: Norwegian University of Science and Technology.
11. Chang Liu, Yungang Wei, Yuguang Cao, Shihua Zhang, Yongtai Sun. 2020. „Traveling ability of pipeline inspection gauge (PIG) in elbow under different friction coefficients by 3D FEM". *Journal of Natural Gas Science and Engineering* 75(2): 103-134. ISSN: 1875-5100. DOI: https://doi.org/10.1016/j.jngse.2019.103134.

12. Tan Nguyen, Dong Kim, Yong Rho, Sang Kim. 2001. „Dynamic modelling and its analysis for PIG flow through curved section in natural gas pipeline”. In: *IEEE International Symposium on Computational Intelligence in Robotics and Automation*: 492-497. American Society of Mechanical Engineers. Banff, Alberta, Canada. 29 July 2001 - 01 August 2001, IEEE, Banff, Alberta, Canada. ISBN: 0-7803-7203-4. DOI: https://dx.doi.org/10.1109/CIRA.2001.1013250.
13. Majid Moghaddama, Saeed Jerbanb. 2015. „On the in-pipe inspection robots traversing through elbows”. *International Journal of Robotics* 4(2): 19-27. ISSN: 2008-7144.
14. Віталій Огороднiков, Іван Сивак, Микола Бабак. 2001. *Опір матеріалів з елементами теорії пластичності. Частина 1*. Вінниця: ВДТУ. [In Ukrainian: Vitalii Ohorodnikov, Ivan Syvak, Mykola Babak. 2001. *Resistance of materials with elements of plasticity theory*. *Part 1*. Vinnitsa: VSTU].
15. Seungman Kim, Jongyeon Jeong, Kwanghyun Yoo, Huiryong Yoo, Yutaek Seo. 2022. „Experimental investigation on speed excursion of PIG due to friction variation in natural gas pipeline”. *Journal of Natural Gas Science and Engineering* 104: 104659. ISSN: 1875-5100. DOI: https://doi.org/10.1016/j.jngse.2022.104659.

Received 16.01.2024; accepted in revised form 28.04.2024