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DEVELOPMENT OF TRENCHLESS TECHNOLOGY OF RECONSTRUCTION OF «PULLING PIG P» PIPELINE COMMUNICATIONS

Ya. Doroshenko
PhD, Associate Professor*
V. Zapukhliak
PhD, Associate Professor*
E-mail: vasyazb@gmail.com
K. Poliarush
Master of the emergency-recovery section
RTM «Pechersk», PJSC «Kyivenergo»,
SSS «Kyiv Heat Distribution Networks»
Tovarna str., 1, Kyiv, Ukraine, 01103
R. Stasiuk
PhD*
S. Bagriy
PhD, Associate Professor
Department of Geotechnogenic Safety
and Geoinformatics**
*Department of Oil and Gas Pipelines
and Storage Facilities**
**Ivano-Frankivsk National Technical
University of Oil and Gas
Karpatska str., 15,
Ivano-Frankivsk, Ukraine, 76019

Розроблено технологію безтраншейної реконструкції трубопровідних комунікацій протягуванням поршнем нового поліетиленового трубопроводу в зношений сталевий – «Тяговий поршень Т». Поршень рухається під тиском повітря, яке подається в запоршневий простір компресором.

Виконано математичне та CFD моделювання процесу протягування трубопроводу поршнем. Виведено формули для розрахунку сил опору, які діють на рухому систему, та тиску на виході компресора, при якому поршень протягне новий поліетиленовий трубопровід усією довжиною реконструйованого зношеного сталевого трубопроводу. Силами опору, які діють на рухому систему на горизонтальних ділянках траси, є: сила механічного тертя манжет поршня до стінок сталевого трубопроводу; сила тертя поліетиленової труби до сталевої; сила тертя поліетиленової труби в кільцевих манжетах ущільнювальної системи.

Результати CFD моделювання були візуалізовані в постпроцесорі програмного комплексу Ansys Fluent побудовою ліній течії, векторів швидкості, полів тиску на контурах і в повздовжньому перерізі міжтрубного та запоршневого простору. Визначались точні значення швидкості, тиску в різних точках міжтрубного та запоршневого простору. Досліджено структуру потоку повітря у запоршевому та міжтрубному просторі. Виявлено місця сповільнення та пришвидшення потоку повітря, падіння та зростання тиску. Визначено втрати тиску в міжтрубному просторі.

Виконавши експериментальні випробування, встановлено, що розроблена технологія «Тяговий поршень Т» може застосовуватись для реконструкції трубопровідних комунікацій. За результатами експериментальних вимірювань побудовано графіки зміни тиску повітря на початку трубопроводу в часі під час протягування поршнем поліетиленової труби зношеною сталевою. Тиск на початку трубопроводу до початку протягування збільшується, що обумовлено силою тертя спокою. Після початку протягування тиск зменшується на незначну величину, а під час протягування відбувається незначне його збільшення. Побудовано графіки залежності швидкості протягування від об'ємної витрати повітря та від довжини протягнутої ділянки поліетиленової труби. На початковому етапі швидкість протягування різко зростає і після такого зростання стабілізується

Ключові слова: втрати тиску, об'ємна витрата, сила тертя, тягове зусилля, швидкість протягування

1. Introduction

The large volumes of construction of steel pipelines (gas, heat and water networks) in the middle and the end of the last century caused considerable difficulties in maintaining them in proper condition today, when most of them are 60–90 % worn-out out. There are many sections of pipelines that have spent their life in two, three times and their volume is constantly growing. Water losses from the networks of heat and water can cause a rise in the level of groundwater, which leads to a displacement of the soil, the destruction of buildings and structures. Quite often, the soil is eroded under the roads, which leads to falling cars in the washed cavity. Often the result of accidents networks of water and heat are fountains of water in cities. Especially dangerous are leaks of natural gas from the gas networks of cities, which can lead to explosions. In fact, old city communications are a constant threat to the life and health of city residents. The second negative point is the annual large losses of water from heat supply systems, water supply, which from year to year increase due to the emergency condition of underground utilities.

Local repair of worn-out pipeline communications is a waste of time and money. The problem of large-scale reconstruction of pipeline communications in many large cities, where pipeline communications are extensively branched, has long been overdue. The organizations that exploit them face the need for repair and replacement of a particular section of the pipeline almost daily.

Traditional trench reconstruction of pipeline communications in large cities is low-social. The reasons for this are the long duration of work, large volumes of earthworks, blocking traffic, pedestrians, destruction of the road surface and the green zone, violation of infrastructure, improvement of cities. All this requires an increase in the cost of restoration work, complicates traffic, causes social discomfort.

Extremely difficult and in many cases such a reconstruction is impossible in hard-to-reach places, under roads, laid pavements, squares in the center of large cities where there are large concentrations of cars, people, historical infrastructure.

To avoid these difficulties and additional costs associated with the restoration work, it is possible to speed up the work with trenchless technologies. Such technologies are the most effective and cost-effective and consist in pulling a new pipe or sleeve made of polymeric materials into worn-out metal pipeline, when earthworks are minimized or not at all.

The boom of trenchless technologies for the reconstruction of pipeline communications is inevitable and the large-scale use of these technologies is a necessity for today.

All these, as well as a number of other reasons, determine the special relevance of the use, improvement, development of new trenchless technologies for the reconstruction of pipeline communications.

2. Literature review and problem statement

At present, a number of methods for the trenchless reconstruction of pipeline communications have been developed [1, 2]. However, there is no one universal that could reconstruct all pipeline communications. Each method has its own scope, advantages and disadvantages.

One of the biggest drawbacks of the method of pulling a polyethylene pipe of a smaller diameter into worn-out steel pipeline – «pipe in pipe» [3] is a reduction in the carrying capacity of the pipeline. To minimize this reduction in pulling, the worn-out steel pipeline [4–6] is destroyed, Swagelining and C-liner methods [6, 7] are applied, the hose is pulled or turned out [8, 9]. Such methods are more complex and expensive than «pipe in pipe». A way to overcome such difficulties can be to pull the latest flexible composite pipes reinforced with glass fiber, glass fiber and epoxy or steel [10, 11] into worn-out steel pipe. Such pipes can be operated under high pressure (up to 20 MPa) and they are increasingly being used for a simple pipe-to-pipe reconstruction method, but the unresolved issues for the pipe-to-pipe method are:

– large amounts of preparatory work;

– before performing the reconstruction, it is necessary to develop a receiving pit, which is not always possible when working;

– low speed of pulling new plastic pipe into worn-out steel.

The reasons for this is that pulling a new polyethylene pipe or hose into worn-out steel pipe is carried out with winches, hydro-multiple units, static hydraulic jack installation, tractors, bulldozers and other wheeled vehicles [2, 4]. This leads to objective difficulties associated with the need to develop a sufficient size of the receiving pit to accommodate the pulling means or rotary units. It is also necessary to lay in the worn-out steel pipe haul cable, clean the internal cavity of the worn-out steel pipe by pulling it cleaning pig. All this requires a lot of time and financial costs, and in complicated conditions these methods are extremely difficult to apply. All this gives grounds to assert that it is expedient to develop efficient technologies for trenchless reconstruction of pipeline communications, which accelerated the pace of work, minimized the amount of preparatory work and facilitated the work under difficult conditions.

3. The aim and objectives of research

The aim of research is development of a new technology for trenchless reconstruction of pipeline communications and to study the effectiveness of its application.

To achieve the aim, the following objectives were set:

– to investigate the possibility of pulling a new polyethylene pipeline into worn-out steel pipe;

– to perform mathematical modeling of the dynamics of pulling a new polyethylene pipe into worn-out steel by the pig;

– to investigate gas-dynamic processes in the annular space while pulling a polyethylene pipeline with worn-out steel;

– to experimentally investigate the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig.

4. The study of the possibility of pulling a new polyethylene pipeline into worn-out steel by the pig

To pull a new polyethylene pipeline 1 into worn-out steel 4 with a pig 5, the «Pulling pig P» technology has been developed (Fig. 1). The pig 5 moves under the pressure of air, supplies the compressor 2 in the annular and trans-pig space. In order to maintain the necessary pressure in the trans-pig space, it is necessary to seal the space between the new polyethylene pipe and the worn-out steel one. For this purpose, a sealing system (Fig. 2) has been developed, which contains 4 annular sealing cups 3 clamped by flanges. The sealing ring 3 seals must seal the annular space and not release air from it and ensure that worn-out steel is able to pull through a new polyethylene pipe. Therefore, their inner part should be bent in the direction of pulling. Then, under the pressure of air in the annular space, they will be pressed against the wall of the new pipeline. The number of cuffs of seals 3 depends on the pressure in the annular space. Air is supplied from the compressor, which is attached to the pipe 5, and the pressure in the annular space is measured by a manometer 6.

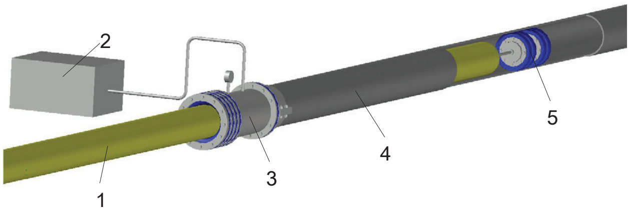

Fig. 1. Pulling of a new polyethylene pipeline into worn-out steel by the pig: 1 – polyethylene pulling pipeline; 2 – compressor; 3 – sealing system; 4 – worn-out steel pipe; 5 – pig

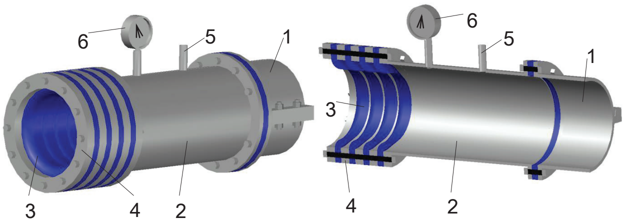

Fig. 2. Sealing system:
1 – clamp; 2 – pipe; 3 – seal cuff; 4 – flange; 5 – pipe for connecting the compressor; 6 – manometer

At the installation site near the working trench, the polyethylene pipe is pushed into the sealing system through the ring seals. Then at the beginning of the polyethylene pipe fix the pig. In the working trench, the pig is stored in a worn-out steel pipeline. Then a sealing system is attached to the end of the worn-out steel pipe with a hose clamp or flange. A compressor is attached to the sealing system, with which they begin to pump air into the space between the worn-out steel and the new polyethylene pipeline. The annular space air enters the trans-pig space. Since the sealing system does not release air from the annular space, the pressure behind the pig increases and it begins to move, pulling the new polyethylene pipe into worn-out steel pipe (Fig. 1). During pulling, the internal cavity of a worn-out steel pipeline is cleaned with a pig.

In order to investigate the process of pulling a polyethylene pipeline into worn-out steel by a pig, to determine what should be the pressure at the compressor outlet of its selection, let's consider the problem of the dynamics of the process in the complex. It is necessary to take into account the forces acting on the pig and energy losses during the movement of the annular air. Since the magnitude of the required pressure at the compressor outlet is influenced both by the resistance forces acting on the moving system, and the pressure loss in the annular space along the pipeline from the compressor to the pig, the pressure at the compressor output will be equal to:

$$P_{comp} = P_A + \Delta P_L, \tag{1}$$

where P_A – air pressure in the trans-pig space, which is determined by the resistance forces acting on the moving system; ΔP_L – pressure loss in the annular space along the pipeline from the compressor to the pig when the annular air moves.

5. Mathematical modeling of the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig

Creating and implementing a mathematical model of the movement of solids by pressure pipelines is a difficult task. The dynamics of the pig movement by pipelines was studied in [12–15]. Researchers of pipeline gas transportation have developed methods for constructing mathematical models of pig movement by pipeline and general principles for their implementation. However, studies of the dynamics of pig movement with polyethylene pipelines attached to it were not carried out.

The complex physical processes of friction of the pig cuff and of the polyethylene pipe attached to it to the walls of the worn-out steel pipe, in the cuffs of the sealing system, lead to cumbersome ratios between these parameters.

Especially complicated by the modeling is complicated for the pulling process of the pig by the pipeline in places of increase or decrease in the route. In such places, the pig and the attached polyethylene pipeline are acted upon by a variable in magnitude and direction gravity, which affects the kinematics of motion.

The equation of pig motion with a polyethylene pipe attached to it is described by the second Newton law:

$$m_p \frac{dV_n}{dt} = \sum_{i=1}^{n} F_p, \tag{2}$$

where m_p – pig mass; V_p – pig speed; t – time; $\sum_{i=1}^{n} F_p$ – sum of the forces acting on the mobile system.

The pig with a polyethylene pipe attached to it moves under the action of a force caused by air pressure in the pig space P_P. The resistance forces acting on the mobile system on the horizontal sections of the route include:

– force of mechanical friction of the pig cuff against the walls of the steel pipeline $F_{Fp.c}$;

– friction force of polyethylene pipe to steel $F_{Fp.p}$;

– friction force of the polyethylene pipe in the annular cuffs of the sealing system $F_{Fs.s}$ (Fig. 3).

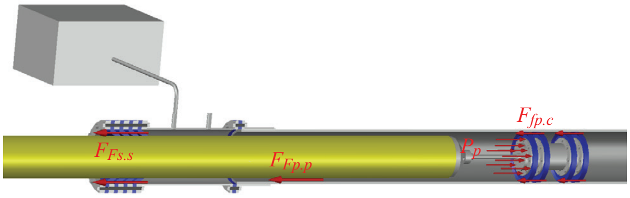

Fig. 3. The design scheme of pulling the polyethylene pipeline by the pig by the horizontal section of worn-out steel

Then the sum of the forces acting on the mobile system will be equal to:

$$\sum_{i=1}^{n} F_p = P_A \frac{\pi D_{i.s}^2}{4} - F_{Fp.c} - F_{Fp.p} - F_{Fs.s}, \tag{3}$$

where $D_{i.s}$ – internal diameter of the steel pipe.

In case of uniform pig movement:

$$\sum_{i=1}^{n} F_p = P_A \frac{\pi D_{i.s}^2}{4} - F_{Fp.c} - F_{Fp.p} - F_{Fs.s} = 0. \tag{4}$$

Mechanical friction force of the pig cuffs to the walls of the steel pipeline:

$$F_{"p.s} = n_{p.c} f_{p.c} F_p, \tag{5}$$

where $n_{p.c}$ – number of pig cuffs; $f_{p.c}$ – coefficient of sliding friction of the rubber cuffs of the pig to the walls of the steel pipeline depends on the speed of movement of the sliding pair (decreases with increasing speed), surface cleanliness, its area, the force of pressing the cuffs to the walls of the pipeline, rubber type and is in the range of 0.5…0.7; F_p – reaction force.

The reaction force F_p is the force that occurs when the rubber cuffs of the pig are pressed against the wall of the steel pipe. To calculate the reaction force, let's write Hooke's law, according to which the stresses arising in the cuffs of the pig level:

$$\sigma = \varepsilon E, \tag{6}$$

where ε – relative deformation of the pig cuffs; E – elastic modulus of rubber (E=2 MPa).

Relative deformation of the pig cuffs:

$$\varepsilon = \frac{\Delta L}{L}, \tag{7}$$

where L – radius of the pig cuffs ($L=D_{p.c}/2$, where $D_{p.c}$ – diameter of the pig cuffs to its storage in the pipeline) ΔL – absolute compression of the pig cuffs equal to:

$$\Delta L = \frac{D_{p.c} - D_{i.s}}{2}. \tag{8}$$

It is also known that the stresses that occur in the cuffs of the pig level:

$$\sigma = \frac{F_p}{S}, \tag{9}$$

where S – cross-sectional area of the pig cuff in the direction of the force:

$$S = D_{i.s} h_c, \tag{10}$$

where h_c – thickness of the pig cuff.

Then substituting (6)–(8), (10) in (9):

$$F_p = E h_c D_{i.s} \frac{D_{p.c} - D_{i.s}}{D_{p.c}}. \tag{11}$$

Substituting (11) into (5) let's obtain the formula for calculating the mechanical friction force of the pig cuffs against the walls of the steel pipeline:

$$F_{''p.c} = n_{p.c} f_{p.c} E h_c D_{i.s} \frac{D_{p.c} - D_{i.s}}{D_{p.c}}. \tag{12}$$

Friction force of polyethylene pipe to steel:

$$F_{Fp.p} = f_{p.p} q_{p.p} L_{p.p}, \tag{13}$$

where $f_{p.p}$ – coefficient of sliding friction of polyethylene in steel (is in the range of 0.1…0.2); $q_{p.p}$ – uniformly distributed load of its own weight of the polyethylene pipeline; $L_{p.p}$ – length of the polyethylene pipe.

Uniformly distributed load from the own weight of the polyethylene pipeline:

$$q_{p.p} = g \rho_p \frac{\pi\left(D_{o.p}^2 - D_{i.d}^2\right)}{4}, \tag{14}$$

where ρ_p – polyethylene density; $D_{o.p}$ – outer diameter of the polyethylene pipe; $D_{i.p}$ – internal diameter of the polyethylene pipe.

Polyethylene pipe friction force in sealing system cuffs:

$$F_{Fs.s} = n_{c.s.s} \pi D_{o.p} B P_c f_{f.r}, \tag{15}$$

where $n_{c.s.s}$ – number of cuffs in the sealing system; B – width of the contact of the cuff with the polyethylene pipe; P_c – contact pressure arising during the installation of the cuffs (in the range of 0.5…0.9 MPa); $f_{f.r}$ – coefficient of friction of polyethylene to rubber (is in the range of 0.1…0.13).

The total resistance force acting on a moving system:

$$F = F_{Fp.p} + F_{F\,s.s} + F_{f.f.r}. \tag{16}$$

The results of calculations of the resistance forces acting on the moving system when the pig pulls through a new polyethylene pipeline into worn-out steel are given in Table 1. Calculations were performed for the steel pipeline with an outer diameter of 49 mm and through pulling of polyethylene pipelines with an outer diameter of 32 mm and 40 mm.

Table 1

The calculated values of the resistance forces acting on the moving system when pulling a new polyethylene pipeline into worn-out steel pipe

$D_{o.p}$, mm	$F_{Fp.p}$, N/m	$F_{Fp.c}$, N	$F_{Fs.s}$, N	F, N
32	1.0	46.1	86.8	136.9
40	1.2	46.1	98.5	155.8

As it is possible to see, the friction force of the pig cuffs to the walls of the worn-out steel pipeline and the friction force of the polyethylene pipe in the cuffs of the sealing system are insignificant and do not have a significant effect on the pulling process. The friction force of one meter of a polyethylene pipe to a steel pipe is scanty and ranges from 1 to 2 N.

Substituting (12), (13), (15) into (4):

$$\begin{aligned} &P_A \frac{\pi D_{i.s}^2}{4} - n_{p.c} f_{p.c} E h_c D_{i.s} \frac{D_{p.c} - D_{i.s}}{D_{p.c}} - \\ &- f_{p.p} q_{p.p} L_{p.p} - n_{c.s.s} \pi D_{o.p} B P_c f_{s.s} = 0. \end{aligned} \tag{17}$$

Then the required air pressure in the trans-pig space, so that the pig with a polyethylene pipe attached to it moved horizontal pipe:

$$P_A = \frac{4\left(n_{p.c} f_{p.c} E h_c D_{i.s} \frac{D_{p.c} - D_{i.s}}{D_{p.c}} + f_{p.p} q_{p.p} L_{p.p} + n_{c.s.s} \pi D_{o.p} B P_c f_{s.s}\right)}{\pi D_{i.s}^2}. \tag{18}$$

On inclined sections of the route, significant gravitational forces act on the pig and the polyethylene pipe attached to it (Fig. 4).

On inclined sections of the path of equation (4) will be:

$$\begin{aligned} &\sum_{i=1}^{n} F_p = P_A \frac{\pi D_{i.s}^2}{4} - F_{''p.c} - F_{Tp.p} - F_{Ts.s} - \\ &- G_p \sin\varphi - G_{p.p} \sin\varphi = 0, \end{aligned} \tag{19}$$

where G_p – pig gravity; $G_{p.p}$ – polyethylene pipeline gravity; φ – angle of inclination of the steel pipeline to the horizon.

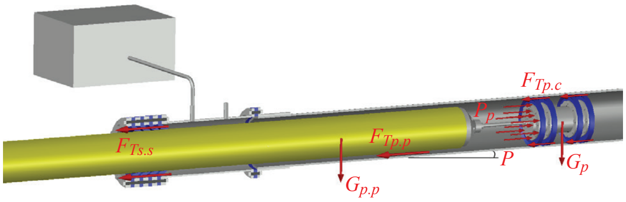

Fig. 4. The design scheme of pulling a polyethylene pipeline with a pig by an inclined section of worn-out steel

Pig gravity force:

$$G_p = m_p g \sin\varphi, \tag{20}$$

where m_p – mass of the pig.

Polyethylene pipeline gravity force:

$$G_{p.p} = q_{p.p} L_{p.p} \sin\varphi. \tag{21}$$

Where the necessary air pressure in the trans-pig space on the sloping ascending sections of the route:

$$P_A = \frac{4\left(n_{p.c} f_{p.c} E h_c D_{i.s} \dfrac{D_{p.c} - D_{o.s}}{D_{p.c}} + f_{p.p} q_{p.p} L_{p.p} + n_{c.s.s} \pi D_{o.s} B P_c f_{s.s} + m_p g \sin\varphi + q_{p.p} L_{p.p} \sin\varphi \right)}{\pi D_{o.s}^2}. \tag{22}$$

It should be borne in mind that in the ascending parts of the route, the gravity force causes resistance to the movement of the pig and the polyethylene pipeline attached to it, that is, the braking force, and in descending areas the force of attraction is the driving force.

6. The study of gas-dynamic processes in the annular space when pulling a polyethylene pipeline into worn-out steel by the pig

Unsteady air movement in the annular space between the polyethylene and steel pipelines and the complex dynamic conditions at the moving boundary make it difficult to calculate pressure losses in the annular space from the compressor to the pig. In addition, polyethylene and steel pipelines have different wall roughness, which makes such calculations difficult.

Therefore, in order to simplify, it was decided to consider gas-dynamic processes in a flat pipeline, since the influence of pipeline slope on the movement dynamics is estimated higher.

It is necessary to perform simulation of non-stationary gas-dynamic processes in the annular and trans-pig space, due to the movement of the pig with a polyethylene pipe attached to it.

The isothermal nature of air movement in the annular space can be modeled by the equations of gas dynamics, namely the Navier-Stokes equations (22), which express the law of conservation of momentum, and the continuity of flow (23), which expresses the law of mass conservation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + f_i, \tag{23}$$

$$\frac{\partial p}{\partial x_i} + c^2 \frac{\partial}{\partial x_j}(\rho u_j) = 0, \tag{24}$$

It should be noted that any mathematical model idealizes its physical prototype. In this problem, one-dimensional isothermal gas motion is considered. The design scheme for the study of gas-dynamic processes when pulling a polyethylene pipeline with a worn-out steel pipeline is shown in Fig. 5.

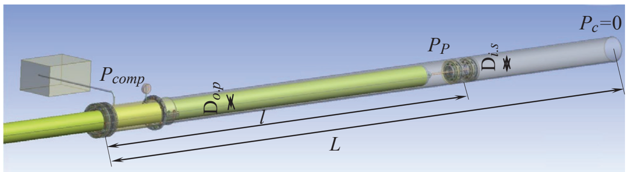

Fig. 5. The design scheme for the study of gas-dynamic processes when pulling a polyethylene pipeline into worn-out steel by the pig

The task is implemented under the following conditions:

– before starting the pig, the air supply to the annular space was not performed;

– after the beginning of the pig movement and towards its end, the excess pressure at the compressor outlet is maintained constant and equal to P_{comp}, and at the end of the steel pipeline and in front of the pig is zero;

– pressure on the pig P_P is determined by the friction force of the pig cuff against the walls of the steel pipeline, the friction force of the polyethylene pipe to the steel, the friction force of the polyethylene pipe in the cuffs of the sealing system;

– it is necessary to investigate the dynamics of the movement of the pig $l(t)$ in time and the dynamics of the movement of air in the trans-pig space;

– it is considered that the speed of movement of the pig is equal to the linear speed of movement of air in the section where the pig contacts with the air.

To accomplish the task, the initial conditions for equations (23) and (24) will be:

$$P_{comp} = 0, \tag{25}$$

$$P_c = 0. \tag{26}$$

The boundary conditions at the beginning and at the end of the steel pipeline are determined by the constancy of pressure:

$$P_{comp}(0,t) = P_{comp}, \tag{27}$$

$$P_c(L,t) = 0, \tag{28}$$

where L – total length of the steel pipe.

In the zone of contact of air with the pig, let's assume that the linear speed of the air behind the pig is equal to the pig speed, that is,

$$\upsilon_1(l,t) = \frac{dl}{dt}, \tag{29}$$

where υ_1 – linear speed of the air behind the pig.

It is necessary to determine the nature of the movement of the pig $l_p(t)$ in time, as well as to establish the gas-dynamic nature of the movement of air in the annular and rear pig spaces.

Implement the task should be an iterative method. For this, the period of motion of the pig by the pipeline must be divided into time intervals Δt, during each of which the speed of movement of the pig is considered constant. To ensure this condition, the time intervals Δt can be chosen sufficiently short.

Since the speed of the pig at the initial moment of movement is equal to the speed of air w_0, the path traveled by the pig during the time Δt is equal to:

$$l_0 = w_0 \Delta t. \qquad (30)$$

Such an algorithm can be implemented by computer simulation of three-dimensional turbulent flows in the ANSYS Fluent R19.1 Academic (USA) software package using dynamic networks.

ANSYS Fluent is based on the Navier-Stokes equations (23) and flow continuity (24), closed by the well-known Launder-Sharma two-parameter k–ε turbulence model using wall function with the corresponding initial (25) and (26) and (28) conditions.

In ANSYS Fluent, these equations are closed by a two-parameter k–ε (k – turbulent energy, ε – dissipation rate of turbulent energy) by the turbulence model, which involves solving the following equations:

– turbulent energy transfer equation k:

$$\frac{\partial(\rho k)}{\partial t} + \nabla(\rho u k) = \nabla\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right) + \mu_t G - \rho\varepsilon; \qquad (31)$$

– transport equation of turbulent dissipation ε:

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla(\rho u \varepsilon) = \nabla\left(\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right) + C_1\frac{\varepsilon}{k}\mu_t G - C_2\rho\frac{\varepsilon^2}{k}, \qquad (32)$$

where u – gas flow rate; μ_t – turbulent dynamic viscosity of a gas; σ_k – coefficient equal to one; G – calculated parameter; σ_ε – coefficient equal to σ_ε 1.3; C_1 – coefficient equal to $C_1=1.44$; C_2 – coefficient equal to $C_2=1.92$.

The k–ε turbulence model is the so-called «high-Reynolds» model based on the averaging method of the Navier-Stokes equations and is intended for calculating turbulent processes.

Three-dimensional models of the trans-pig and annular space between the worn-out steel pipeline and the new polyethylene, where a complex turbulent movement of air flow occurs, was modeled with a branch pipe that air is fed into the annular space (Fig. 6).

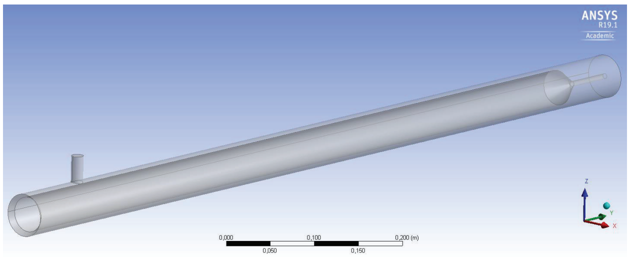

Fig. 6. Model of trans-pig and annular space

To model the flow of air into the Fluent-Meshing preprocessor, a Hex Dominant volumetric computational mesh was generated – volume was filled with hexahedral elements. The size of the mesh elements was set to 0.003 m. For a better description of the boundary layer, a near-wall layer was created with a lattice height of 0.001 m and the number of mesh layers 4. At the point of connection of the nozzle to the steel pipeline, the mesh was crushed to better visualize the flow in this zone before the size of the mesh elements was 0.001 m (Fig. 7). For this size of the mesh elements, the calculation results were qualitatively visualized, and in the calculation it was about one and a half hours.

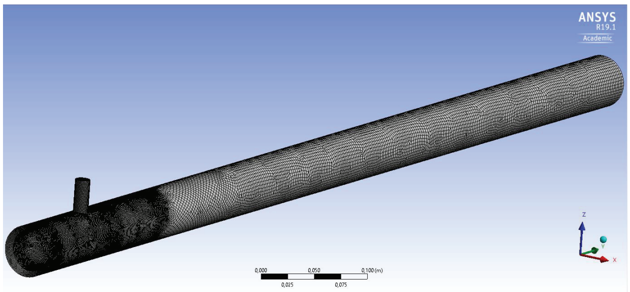

Fig. 7. Design volume mesh

Air was selected from the ANSYS Fluent material database and assigned to the design grid.

For the inner wall of the worn-out steel pipeline, the equivalent pipe roughness coefficient was set to $h_{s.c}=0.75$ mm, and for the outer wall of the new polyethylene pipeline, $h_{s.n}=0.007$ mm.

The internal diameter of the steel pipeline was taken equal to $D_{i.s}=49$ mm, the outer diameter of the polyethylene pipe $D_{o.p}=40$ mm. The internal diameter of the nozzle, by which air is supplied from the compressor to the annular space $D_{i.n}=10$ mm and it is equal to the hydraulic diameter, which was set in ANSYS Fluent.

To study the dynamics of the movement of the annular air and trans-pig space while pulling a new polyethylene pipeline in a worn-out steel were set such boundary conditions at the entrance (Fig. 8):

– mass flow rate $M_{in}=0.00645$ kg/s;
– turbulence intensity 5 %;
– hydraulic diameter $D_{in}=0.018$ m;
– air temperature $t_{in}=293$ K.

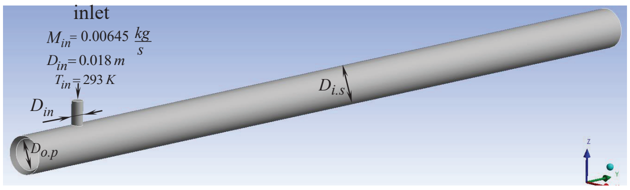

Fig. 8. Design scheme

The process of pulling a new polyethylene pipeline into worn-out steel one is dynamic – a pig and a new polyethylene pipeline attached to it are moving in a worn-out steel pipeline. To study the gas-dynamic processes in the annular space during such movement in ANSYS Fluent used a dynamic grid model that is compatible with all models of turbulence. Since such a process is non-stationary, the non-stationary formulation of the transient problem was chosen in the main menu of ANSYS Fluent. The type of adjustment of the parameters of the dynamic grid was chosen while pulling a new polyethylene pipeline into worn-out steel pig – Layering, which is best suited for translational motion. The type of adjustment of the parameters of the dynamic grid Layering includes the algorithm for creating and deleting a grid of grids (grid grids are added if the zone is enlarged, or deleted if the zone is reduced). After that, it was asked that the grids of the grid should be attached from the face, which is the back of the pig (Fig. 9), and from the face, which is the inner surface of the tip attached to the polyethylene pipeline (Fig. 10), should be removed. The speed of movement of the faces was determined experimentally and was set at 1.72 m/s.

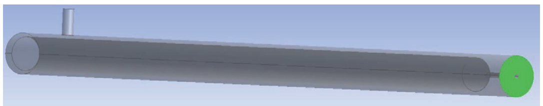

Fig. 9. Scheme of the moving face, which is the back of the pig

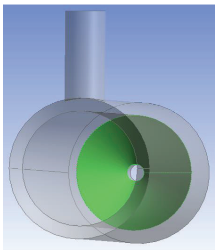

Fig. 10. Scheme of the moving face, which is the inner surface of the tip attached to the polyethylene pipeline

The simulation results were visualized in the postprocessor of the software package, which made it possible to see the structure of the air flow in the annular space while pulling a new polyethylene pipeline into worn-out steel pipe and collecting data about it.

The speed vectors were constructed along (Fig. 11) and at the inlet (Fig. 12) into the annular space, streamlines (Fig. 13), pressure fields on the contours (Fig. 14) and pressure fields in the plane of vertical longitudinal section (Fig. 15).

According to the calculation results in the ANSYS Fluent software package, it was determined that the air flow rate along the axis at the inlet port is 19.2 m/s. From the flow axis in the direction of the wall there is a slight decrease in the flow rate, and at the wall the gas flow rate decreases sharply. From the inlet pipe the air flow flows into the annular space. In the annular space opposite the inlet nozzle, the air flow diverges in different directions through an angle of 360° (Fig. 12, 13). At the same time, in the center of such a difference opposite the inlet nozzle, the air flow is slowed down to 12 m/s, and at the edges (outside the inlet nozzle) acceleration to 24.5 m/s (Fig. 12). After such a difference in the air flow in the annular space, the main part of the air flow flows down the side of the annular space downward (Fig. 12, 13), where the flow speed is 14.4 m/s. Next, most of the flow moves along the lower part of the pipe in the direction of pulling at a speed of about 14 m/s, which decreases along the annular space (Fig. 12). At the top of the pipe with the inlet nozzle, the flow speed is insignificant and amounts to about 1 m/s (Fig. 12). At a distance of about 3 m from the inlet nozzle, the flow speed in the cross section is equalized and is about 1.7 m/s.

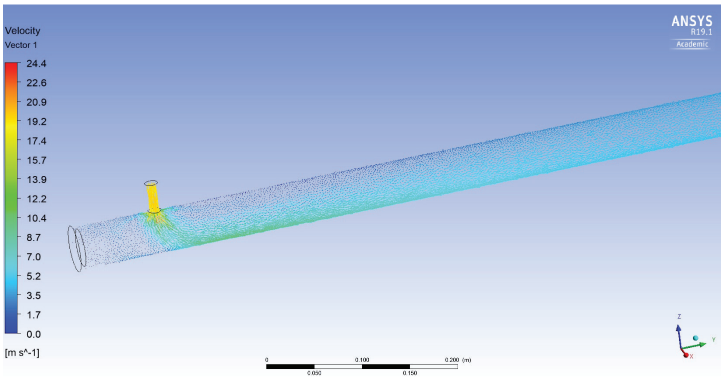

Fig. 11. Speed vectors along the annular space

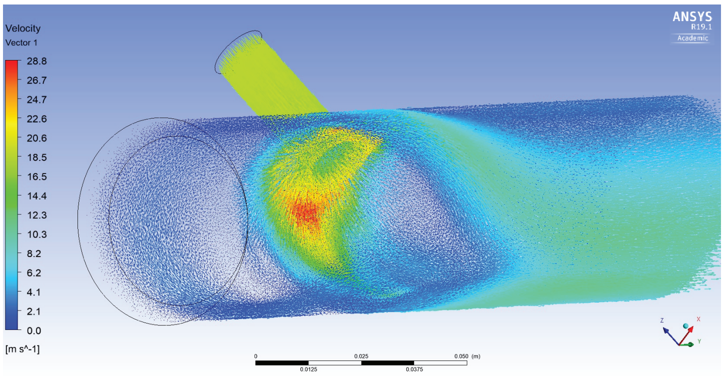

Fig. 12. Speed vectors at the entrance to the annular space

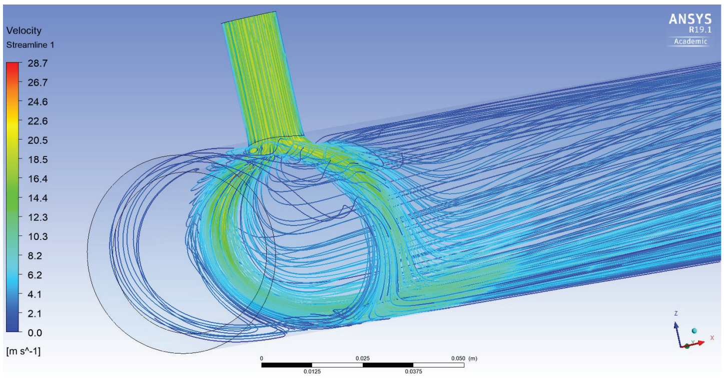

Fig. 13. Flow lines painted in colors of the flow rate of air at the entrance to the annular space

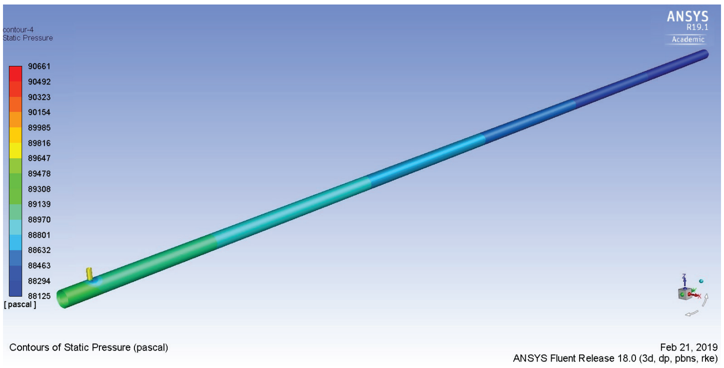

Fig. 14. Pressure fields on contours

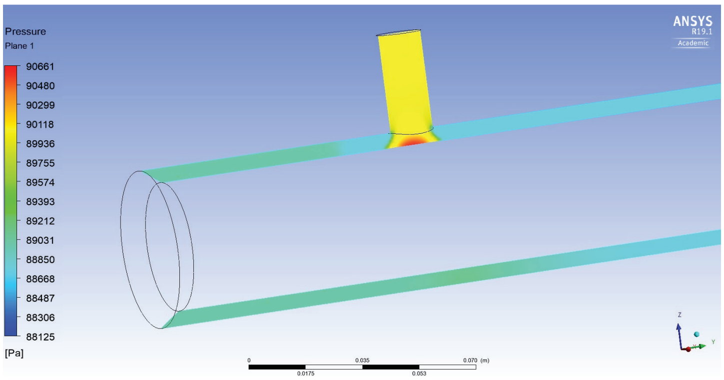

Fig. 15. Pressure fields in the plane of vertical longitudinal section

As can be seen from the pressure fields (Fig. 14, 15), the pressure in the annular and trans-pig space while pulling a new polyethylene pipeline in worn-out steel is unevenly distributed. In the inlet pipe pressure is 89800 Pa. From the pressure fields, it was noticed that in the annular space opposite the inlet nozzle there is an increase in pressure to 90661 Pa (Fig. 15), and around the inlet nozzle the pressure drops to 88461 Pa (Fig. 14). Along the annulus from the inlet to the moving pig pressure drop occurs. So, if the pig is located at a distance of 4 m from the inlet nozzle, the inlet pressure is 89602 Pa, and in the trans-pig space 88125 Pa. Thus, the drop in pumping in the annular space by one linear meter is 369 Pa. Then the pressure loss in the annular space along the pipeline from the compressor to the pig during the movement of the annular air, which is one of the terms in (1) will be equal:

$$\Delta P_L = 369L. \tag{33}$$

If 50 m of the polyethylene pipeline is pulled, the pressure loss in the annular space is 18450 Pa, and if 100 m – 36900 Pa.

7. Experimental studies of the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig

For the practical implementation of the developed technology «Pulling pig P» it is necessary to experimentally:

– check whether the pig can pull a new polyethylene pipeline into worn-out steel pipeline;

– check the manufacturability of the operations of trenchless pipeline reconstruction with a pig;

– explore the dynamics of pulling ta new polyethylene pipeline into worn-out steel pipeline by the pig.

For experimental studies, an experimental installation (Fig. 16, 17) has been developed and constructed, which consists of a worn-out steel pipe 10 with an internal diameter of 49 mm and a length of 4 m. In a steel pipe 10 with a flange 9 a sealing system is attached, which consists of a pipe coil 8, flanges 5 and three annular cuff seals 7 with a thickness of 3 mm clamped by bolts 6, a manometer 3 and a pipe to which the meter 2 and the compressor 1 are connected. In the steel pipe 10 there is a pig 12 up to which a new polyethylene pipe 4 is attached to the head 11 as in a black marker with a step of 0.25 m marked marks. Experimental studies were performed for polyethylene pipes with an outer diameter of 32 mm and 40 mm.

The experiment was repeated for different inclinations of the worn-out steel pipeline to the horizon, various air flow rates.

After completing the experimental tests, it was found that the developed technology «Pulling pig P» is laborious and technological and can be used for the reconstruction of pipeline communications. Preparation of equipment for the execution of work is 1–2 minutes.

During pulling, the pressure is measured with a manometer 3 (Fig. 16), air consumption by a meter 2. The pulling speed of a polyethylene pipe 4 was also determined by a steel pipe 10 (the time taken for the polyethylene pipe with a step of 0.25 m to put black marks into annular rubber is recorded seals). To do this, perform a second video.

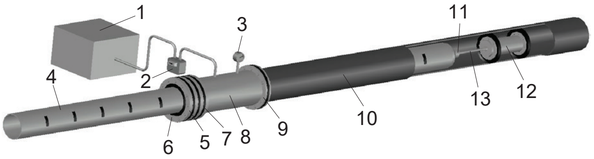

Fig. 16. Diagram of the experimental device for studying the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig: 1 — compressor; 2 — meter; 3 — manometer; 4 — pulling polyethylene pipeline; 5, 9 — flange; 6 — bolt; 7 — ring rubber seal; 8 — tubular coil; 10 — worn-out steel pipeline; 11 — tip; 12 — pig; 13 — rod

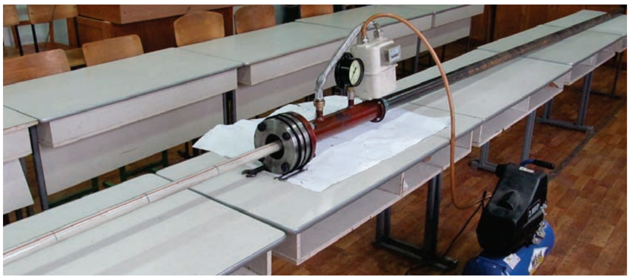

Fig. 17. Experimental device for studying the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig

For a polyethylene pipe with an outer diameter of 32 mm with a volumetric air flow rate of 0.005 m^3/s, the pulling time was 2.1 s. The estimated average pulling speed is 1.9 m/s. According to a series of measurements of pressure values, a curve (Fig. 18) for pressure changes at the beginning of the pipeline with time during pulling was plotted. The pressure after opening the crane before the start of pulling increases to 0.087 MPa, which is caused by the friction force at rest. After the start of pulling, the pressure drops to 0.074 MPa, since the friction force decreases with increasing speed. Next, there is a slight fluctuation in pressure with a slight increase to 0.075 MPa. At the time of departure of the polyethylene pipe with annular rubber cuffs of the sealing system, there is a sharp drop in pressure to zero, with the sound of a «pop» sound being heard.

In the case of increasing the slope of the steel pipeline to 30°, there is a slight (up to 0.03 MPa) increase in pressure at the beginning of the pipeline compared to the pressure that was when the pipe was horizontal, during the whole pulling time.

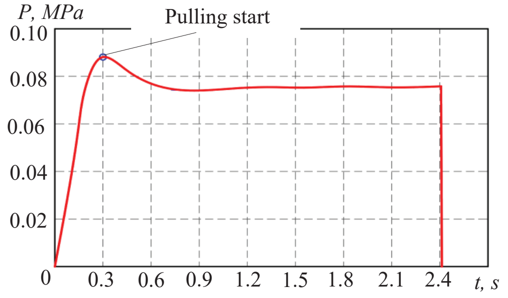

Fig. 18. Pressure change at the beginning of the pipeline in time when the pulling a polyethylene pipe with an outer diameter of 32 mm with a worn-out steel pipe by the pig

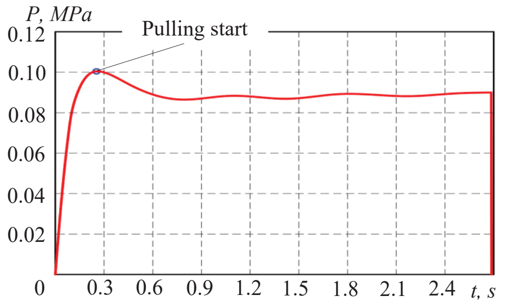

Fig. 19. Pressure change at the beginning of the pipeline in time when the pulling a polyethylene pipe with an outer diameter of 40 mm with a worn-out steel pipe by the pig

Similar studies were performed for a polyethylene pipe with an outer diameter of 40 mm. With a volumetric air flow rate of 0.005 m^3/s, the pulling time was 2.5 s, and the calculated average pulling speed was 1.64 m/s. The curve of pressure change at the beginning of the pipeline over time when pulling a polyethylene pipe with an outer diameter of 40 mm is shown in Fig. 19. From the graph (Fig. 19) it can be seen that the pressure after the opening of the crane before the start of pulling increases to 0.1 MPa. After the start of pulling, the pressure drops to 0.086 MPa. Next, there is a slight fluctuation of pressure with its increase to 0.09 MPa. The required pressure at the outlet of the compressor R_{comp} so that the pig with a polyethylene pipe attached to it with an outer diameter of 40 mm is moved by a horizontal pipe of 0.085 MPa is calculated according to the above method with (1). This value is approximately equal to the experimentally determined – 0.09 MPa, which confirms the adequacy of the theoretically derived dependencies.

The main method of regulating the pulling speed is changing the volume flow of air by changing the size of the opening of the compressor valve. To determine the functional dependence of the average pulling speed on the volumetric air flow, a number of definitions of the average pulling speed V were made for different values of the air flow rate Q. The outer diameter of the pulled polyethylene pipeline (32 mm and 40 mm) also changed.

Measurements (for the same values of factors) were performed several times. The average values of the measurement results are presented graphically (Fig. 20). Such studies provide an opportunity to adjust the pulling speed.

The dependence of the pulling speed of a polyethylene pipe using a worn-out steel pipe on the length of the pulled sections of a polyethylene pipe was experimentally investigated. The pulling speed was measured (the time was recorded during which they were applied to the polyethylene pipe with a step of 0.25 m; black marks enter the rubber ring seals (Fig. 16)) at a constant volume flow rate.

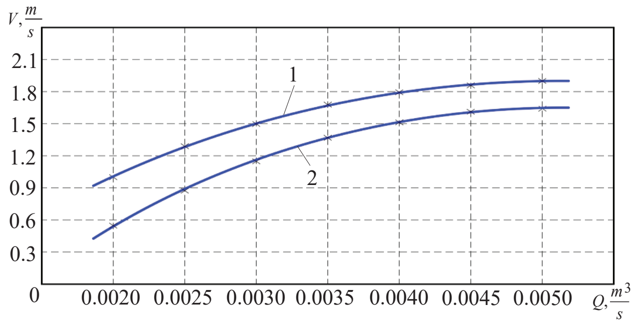

Fig. 20. Dependence of the pulling speed on the volume air flow: 1 – $D_{o.p}$=32 mm; 2 – $D_{o.p}$=40 mm

Based on a series of measurements of the pig pulling speed of a new worn-out polyethylene pipe, graphs of the pulling speed V are plotted against the length of the pulled sections of the polyethylene pipe into steel for constant values of the volume flow. Studies were performed for polyethylene pipes with an outer diameter of 32 mm (Fig. 21) and 40 mm (Fig. 22).

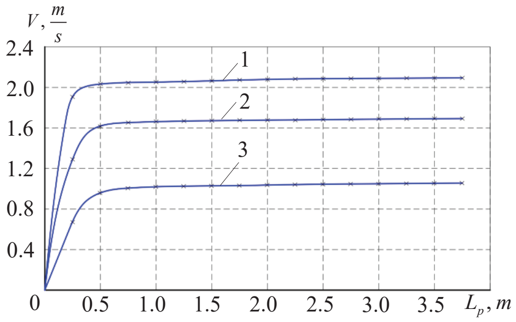

Fig. 21. Dependence of the pulling speed on the length of a section of a polyethylene pipe pulling by a pig with an outer diameter of 32 mm: 1 – Q=0.0050 m^3/s; 2 – Q=0.0035 m^3/s; 3 – Q=0.0020 m^3/s

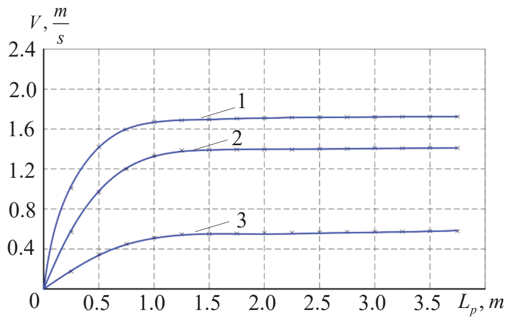

Fig. 22. Dependence of the pulling speed on the length of a section of a polyethylene pipe pulling by a pig with an outer diameter of 40mm: 1 – Q=0.0050 m^3/s; 2 – Q=0.0035 m^3/s; 3 – Q=0.0020 m^3/s

At the initial stage (Fig. 21, 22), the pulling speed increases dramatically and after such growth stabilizes.

8. Discussion of the results of theoretical and experimental studies of the dynamics of pulling a new polyethylene pipeline into worn-out steel by the pig

Implementing the idea of reconstructing pipeline communications by pulling the pig into a new polyethylene pipeline into worn-out steel was made possible by developing a sealing system that sealed the annular space between the new polyethylene pipeline and the worn-out steel. A sealing system has been developed that seals the annular space and does not have a significant resistance to pulling through the polyethylene pipeline, which allows the pig to move.

The possibility of pulling a new polyethylene pipeline into worn-out steel by the pig confirmed mathematical modeling of the pig-pulling dynamics of a new polyethylene pipeline into worn-out steel and CFD modeling of gas-dynamic processes in the annular space. It was found that the resistance forces acting on the moving system, calculated from theoretically derived formulas, are insignificant and do not have a significant effect on the pulling process (Table 1). The drop of a pump in the annular space due to gas-dynamic processes in the annular space is also not large and amounts to 369 Pa for one linear meter of worn-out steel pipeline (Fig. 14).

Experimental studies have shown that the developed technology «Pulling pig P» is difficult to work and can be used for the reconstruction of pipeline communications. It was found that the speed of pulling at the beginning of the work increases dramatically and after such growth stabilizes (Fig. 21, 22). Such a sharp increase in the pulling speed at the initial stage is due to the high speed of the air flow in the annular space after it leaves the inlet (Fig. 12).

The required pressure in the trans-pig space is calculated for that the pig with a polyethylene pipe attached to it with an outer diameter of 32 mm moves to 0.071 MPa and is approximately equal to the experimentally determined 0.075 MPa (Fig. 18), which confirms the reliability of theoretical studies. Also, the calculations for (1) were performed for a polyethylene pipeline with an outer diameter of 40 mm and the required pressure in the trans-pig space was 0.083 MPa, which is approximately equal to the experimentally determined 0.08 MPa (Fig. 19).

The advantages of the developed technology «Pulling pig P» are a small amount of preparatory work, high pulling speed, which is impossible to achieve with any of the existing methods of trenchless reconstruction of pipeline communications, the ability to perform work in complicated conditions.

The disadvantage of the developed «Pulling pig P» technology, which was found experimentally, is the inversion of the rubber cuffs of the annular space seals in the opposite direction to dragging with a large pressure in the annular space.

The direction of further research is the selection of materials for seal cuffs, which have greater rigidity and a small coefficient of friction to polyethylene. Another direction is the development of the «Pulling pig P» technology, which consists of pulling a polyethylene sleeve into worn-out steel pipeline.

9. Conclusions

1. A feature of the trenchless reconstruction of pipeline communications «Pulling pig P» is the hermetic space between the new polyethylene pipeline and the worn-out steel developed sealing system. Due to this, compressed air does not leave the annular space, but presses on the pig, which in turn pulls a new worn-out steel polyethylene pipeline. The technical result of the application of the developed «Pulling pig P» technology is reducing the time of the working process, reduce the amount of preparatory work, simplify the process of pulling through the pipeline, and ensure the possibility of using it in complicated conditions.

2. Equations are derived for calculating the resistance force acting on the moving system when the pig is being pulled by a new polyethylene pipeline into worn-out steel. It has been established that the friction force of the pig cuffs to the walls of the worn-out steel pipeline and the friction force of the polyethylene pipe in the cuffs of the sealing system are insignificant (do not exceed 100 N) and do not have a significant effect on the pulling process. The frictional force of one meter of a polyethylene pipe to a steel pipe is scanty and ranges from 1 to 2 N, and therefore the «Pulling pig P» technology can reconstruct extended sections of pipeline communications.

3. Having performed modeling of gas-dynamic processes in the annular space in the Ansys Fluent software package while pulling a worn-out steel pipeline with a pig, places for slowing down and accelerating air flow, pressure drop and pressure growth are found. If a pig pulls fifty meters of a polyethylene pipeline with an outer diameter of 40 mm, a drop of a spear in the annular space is 18.450 Pa, and if 100 m – 36.900 Pa.

4. It has been established experimentally that when preparing the equipment for carrying out the reconstruction of the «Pulling pig P» pipeline technology, it takes 1–2 minutes. The pulling speed at the beginning of pulling increases dramatically and after such growth stabilizes. With a volumetric air flow rate of 0.005 m^3/s, the drawing speed of a polyethylene pipe with an outer diameter of 32 mm is 2.1 m/s and 40 mm is 1.7 m/s, which is an extremely high speed and can't be achieved by any of the existing trenchless methods of reconstruction of pipeline communications.

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