INVESTIGATION OF DISPERSED CONTAMINATES INFLUENCE ON THE HYDRAULIC ENERGY CONSUMPTION OF ELEMENTS OF GAS PIPELINE SYSTEMS WITH COMPLEX GEOMETRY

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Abstract. *The subject of the research* is the energy losses of gas pipeline systems of complex geometry (bends, tees) with consideration of different operational parameters (pressure, velocity of two-phase flow, volume fraction of the disperse phase).

Methodology. CFD (computational fluid dynamics) simulation was used to perform the research, which included a set of physical, mathematical and numerical methods designed to calculate the characteristics of gases and liquids. CFD modeling was performed in ANSYS Fluent R19.2 Academic software. The Eulerian approach and the Mixture model were used.

The purpose of the research is to determine the dependence of hydraulic energy losses of two-phase gas flow in elements of gas pipelines with complex geometry on the transmission mode of parameters, dispersed phase characteristics and the geometric parameters of the studied elements.

Research results. It is established that energy losses of gas pipeline systems elements with complex geometry are significantly influenced by the volume fraction of the dispersed phase. The most significant effect of such volume fraction was observed in bends with a large angle and a small bending radius. In particular, pressure drop values at the outlets increased at high multiphase flow velocities and

low pressures. Also, the energy losses of two-phase flow in small diameter bends are significantly increased.

With regard to tees, their hydraulic energy loss is affected by the volume fraction of the dispersed phase when the rounding radius of the connection between main line and the branch is the smallest or no rounding is present at all (welded branches). The increase in the volume fraction of the dispersed phase leads to a significant increase in pressure drop values in the tees, where the gas flow from the line transfers completely into the branch.

Introduction

Most of Ukrainian gas fields are in their final stages of development. At this stage, the extracted gas is characterized by a high content of formation water and carbohydrate condensate. Also, gas from wells removes rock particles, sand, sulphur and the like. These substances are transmitted to the separation plants by the gas-flow through the field gas pipelines. A large amount of harmful impurities is carried out through the separation installations due to the bumpers worn-out and many other reasons, into gathering pipelines and further to the main gas pipelines. Installation of new separation installations or their reconstruction considering the gas production reduction in Ukraine is inefficient.

Also, in the inner cavity of most gas pipelines, there is a scale that is detached from the pipes as well as products of intrinsic corrosion. When the dew point of the transferred gas is reached, the condensate occurs within the hydrocarbons.

If the velocity of the gas stream is a sufficiently high liquid drops and solid particles are trapped so that two- or multiphase flows occur. Compared to single-phase two- and multiphase flows are much more complex because they can have different structures (stratified, dispersed, etc.) and are described by different models.

Many researches were aimed to the study of multiphase flows in rectilinear sections of pipelines [1-4]. Researchers have found that dispersed harmful impurities in pipeline flows lead to an increase in hydraulic energy losses.

The problem of predicting energy losses of two-phase flows in elements of gas pipelines with complex geometry is much more complicated than in straight sections of pipelines, since the physical picture of the flow in such elements is extremely complex and clearly uncertain. This is especially true of bends and tees, which are the most common elements of gas pipeline systems. In such elements, the direction of the two-phase flow changes, resulting in a centrifugal force, which leads to an uneven phase re-distribution and friction between the phases (the phase of higher density undergoes greater action by the centrifugal force), the momentum is lost, and secondary flows of force occur depending on the geometry curvature. All this causes a complex redistribution of speed and flow pressure, resulting in significant losses of hydraulic energy.

As the concentration of the dispersed phase increases, its influence on the movement of the transported medium and energy loss increases. In this case, the gas phase has a significant impact on the dispersal distribution processes. Therefore, when investigating the flow of pipelines, the mutual effect of the phases on one another must be taken into account.

Multiphase gas-dynamic processes and the amount of hydraulic energy losses depend significantly on the elements geometry of gas pipeline systems. There are many complex pipeline systems with a large number of complex geometry elements – bends, tees, fittings, etc. Hydraulic energy losses in such elements are quite significant. Given the large scale of the gas transmission system, even a slight reduction in energy losses in its individual elements can significantly reduce overall energy costs for transmission.

Today's energy efficiency requirements call attention to many aspects and issues related to the design, operation and reconstruction of gas pipeline systems. Therefore, the study of the dependence of the energy loss of two-phase gas flows in elements of gas pipelines with complex geometry on the modes of operation, improving the design of these elements to reduce hydraulic resistance is an urgent task.

As of today, there are few publications on the results of pressure drop studies, dynamics of two-phase flow concerning pipelines with complex geometry. Researchers have found that if the flow is two-phased, then the pressure drop values in such elements are greater than if the flow is single-phased. Moreover, the value of the pressure drop is largely influenced by the concentration of the dispersed particles. The value of the energy losses of a two-phase gas stream is not yet well understood, as it depends on many factors.

Most studies of two-phase flows have been performed experimentally in laboratory conditions [5-7], since such flows are three-dimensional and not available for any simplified theoretical analysis. There are the following disadvantages of the experimental approach:

– limited parameters of multiphase flows and geometric parameters of pipeline elements;

– small operating pressures and diameters of the studied pipeline systems elements;

– the obtained correlation dependencies do not cover all modes of transmission, geometric parameters;

– it is extremely difficult, and in many aspects it is impossible to study the physical picture of the multiphase flows transmission along the elements with complex geometry.

In recent years, computer modeling of pipeline flows, specifically CFD modeling [8-10], has become popular. CFD modeling is a powerful tool that allows to study the dynamics of single, multiphase flow, change all output parameters in a wide range, quickly obtain high-quality results, visualize the simulation results, which gives an understanding of the physical picture of multiphase flow inside pipelines elements. It can be effectively used to investigate the influence of mode and geometric parameters on gas-dynamic processes, design of minimally energy-consuming pipeline systems.

In order to determine the pressure drop in the elements of gas pipelines with complex geometry by CFD modelling, Eulerian approach was chosen in this work, which considers the dispersed phase as a continuum. Variable parameters of the experiment were the volume fraction of the dispersed phase, gas flow velocity, pressure, geometric parameters.

The results of CFD modelling were visualized by the creation of pressure fields in longitudinal cross-sections of simulated elements of gas pipeline systems with complex geometry. The pressure drop in the simulated elements and their dependence on the studied parameters of two-phase flows, geometrical parameters of the elements were determined.

1. Analysis of gas pipeline flows composition

Condensate, water, products of in-pipe corrosion, lubricant, scale, which were peeled off from pipes, particles of rocks, sand, are accumulated in the internal cavity of gas pipelines, which have been operated for many years. Condensate and water are removed from the wells and occur when the dew point of the gas over water and hydrocarbons is reached. In gas pipelines, this occurs at a distance of more than 25 km from the compressor stations at the places where the pipeline route is lowered to the surface. The acidic environment created by the liquid accumulations in the internal cavity of the gas pipelines leads to an increase in the rate of in-line pipeline corrosion and, as a result, an increase in the content of metals and corrosion products in the internal cavity of the gas pipelines, which are solid harmful impurities. For example, the inspection results of an industrial pipeline with a diameter of 920 mm with a length of 45 km on the outskirts of Doha (Q_{atar}) revealed 7 tonnes of in-line corrosion products. [11]

Field and gathering gas pipelines contain much more impurities than main lines. The major contamination substances of such pipelines are formation water and hydrocarbon condensate. The type and qualitative composition of harmful impurities for each of the fields is specific and inherent only for the studied gas-bearing area:

- for Lviv region there is a presence of formation and condensation water with a considerable content of fine mechanical impurities as a corrosion by-product;
- for Poltava deposits - localization of condensate with different density;
- for the group of wells of Shebelinsky GCF in the area of CGPI-19 - clay-liquid suspension. [12]

The harmful impurities in the cavity of gas pipelines are one of the biggest problems of gas transmission organizations. They can accumulate at lowered sections, drop off at pipeline walls, or move in a stream. The accumulated and delayed harmful impurities exert additional hydraulic resistance, which leads to an increase in energy costs for gas transportation (compression at compressor stations) and a reduction in the extraction of hydrocarbons from the reservoirs.

The appropriate gas flow velocity is required in order the harmful impurities extracted from the well and accumulated in the internal cavity of field, gathering and main gas pipelines continue to move in the flow. According to J. Smart [13], the minimum velocity of flow when solid particles move through a pipeline depends on the properties of the substance of the stream, the diameter of the pipeline, pressure, density and particle size. For example, at a pressure of 7 MPa, the minimum flow velocity for moving solids is about 3 m/s for pipelines with a diameter of 200 mm, 4 m/s for pipelines with a diameter of 600 mm, and 4.2 m/s for pipelines with a diameter of 1200 mm. As soon as the solid particles start to move, the movement will continue until the flow rate decreases or the pressure is to be increased.

Transfer of droplets of liquid or solid particles in the gas flow, removal of liquid accumulations from lowered sections of the route leads to the occurrence of multiphase flows. Multiphase are called flows, which consist of a continuous phase (gas or liquid) and the dispersed phase (liquid and solids) mixed in it. The simplest case of multiphase flow is a two-phase one. The two-phase medium consists of a continuous phase and a dispersed phase, for example: gas - liquid droplets; gas - solid particles; fluid - solid parts; liquid - bubbles of steam.

The concentration of harmful impurities in gas pipelines in real time can be measured by an optical method. The optical device emits optical waves of different lengths within the infrared range into the gas stream. [14]

Two-phase flow leads to an increase in the loss of hydrodynamic flow energy in pipeline systems. These losses increase significantly in the elements of gas pipelines with complex geometry.

2 Elements of gas pipeline systems with complex geometry

Modern gas pipeline systems contain a large number of various elements with complex geometry. The most common of these are bends, tees, couplings. They are also called moulds or fittings. These shaped elements are produced by various manufacturers and have different geometry.

Specifically, many bends and tees are as a part of piping of various technological objects – compressor stations, gas refineries, underground gas storages, gas distribution stations, etc. The bends also contain compensators for above-surface pipe crossings, they are also located in places of sharp terrain breaks, pipeline route turns.

The bends are curves with an angle of 30, 45, 60 and 90° and small radius (Fig. 1*a*).

In welded tees, the connection of the main line (base line) and the bend (side elbows) is made at right angles (Fig. 1*b*). In hot stamping tees, stamped tees, the branch connects with the main line by means of rounding (Fig. 1*c*). According to the requirements of SNiP 2.05.06 [15], the radius of curvature R must be not less than 0.1 $D_{\text{o.b.}}$, where $D_{\text{o.b.}}$ is the outer diameter of the branch.

Fig. 1. Elements of gas pipeline systems with complex geometry: *a* – bends; *b* – welded tee; *в* – stamped tee

The flow (separation) of the main pipe in tees is basically divided and the flows out of two pipes merged into one pipe.

In practice, there are a lot of tees, in which the flow moves in main line from which it flows completely into the branch. Such tees are a part of piping at the compressor stations of the main gas pipelines, underground gas storage, gas distribution stations and the like. In addition, in the place of technological crossings between gas pipelines, where all the flow from one line flows to another, as well as in case of multi-line offshore pipelines, where all the flow is transmissed by backup lines, etc.

3. Selection of research method

Multiphase gas flow in bends and tees is much more complicated than single-phase. These elements of the gas pipeline systems change the direction of gas flow, resulting in an unequal redistribution of phases (the phase of greater density undergoes more centrifugal force), flow velocity and pressure, which cause hydraulic energy losses. The value of hydraulic energy losses depends on the mode and geometric parameters, the dispersed phase concentration. Quantitative determination of hydraulic energy losses of two-phase flows in bends and tees is a big problem during the design and hydraulic analysis of gas pipeline systems. There is very little experimental data in the literature. The reason for this is the large number and range of variable parameters of multiphase flows and geometric parameters of pipeline fitting elements. In addition, considering gas pipelines, especially main lines, it is extremely difficult to study experimentally multiphase flows, and in many aspects it is impossible. The reasons for this are the following:

- it is impossible to determine the exact value of velocity, pressure at any point in a complex 3D stream;
- it is impossible to visualize the flow of gas in the steel fitting element;
– gas pipelines are under high pressure and are explosive.

CFD modeling is an effective tool for quantifying the effect of multiphase flow parameters and geometric parameters of gas pipeline system elements on hydraulic energy loss. This method has become especially popular in the study of complex multiphase flows in recent years, when the computers' capabilities increased many times and the calculation time has decreased significantly. CFD modeling is mainly used for two purposes:

- research purposes - to gain an understanding of the various basic processes;
- designing purposes. The designer can predict what will happen in the design. Thus, it is possible to optimize the design, to create a new one without experimental research, which saves considerably time and costs.

CFD modeling gives an understanding of the complex dynamics of multiphase gas flows motion along the elements of gas pipeline systems, it visualize in detail the three-dimensional multiphase flow and study the pressure drop, phase distribution (volumetric particles), flow velocity, turbulence, kinetic energy and more. It is also possible to change the initial mode parameters, element geometry under study and investigate their influence on the physical picture of multiphase flows movement, hydraulic energy losses. At any point in the 3D stream, the value of any parameter can be easily determined. Many of the above-mentioned aspects cannot be determined experimentally.

For the proper modeling of pipeline flows, CFD incorporates various complex multiphase models that have proven themselves to be more accurate than other models, especially when complex flow geometry is important. [16, 17]

It is best to use the Eulerian approach to study hydraulic energy losses in pipeline system elements. For multiphase flows, the concept of volume fraction, another additional flow parameter, is introduced. The Eulerian approach is applied when the volume fraction of the dispersed phase is significant. The Eulerian approach contains several models.

VOF model - surface tracking. This model is designed to model two or more streams of immiscible substances (stratified flows) with a clear extended (i.e., comparable in size to the size of the calculated geometry) interface (separation limit). The form of this interface is the only result of the simulation. The VOF model contains a set of momentum conservation equations and the tracking of the volume fraction of each of the fluids at each computational point of the entire 3D flow geometry. In this model, there is no sliding between the phases, and it is not possible to capture the flow dynamics for large slip coefficients. The simulation results are in good agreement with the experimental data up to the slip factor 20.

Mixture model is a multiphase model. The Mixture model is designed for two or more phases (liquid or solid). The phases are interpenetrating continua.

The Mixture model differs from the VOF model in two respects:

- the Mixture model allows the phases to penetrate each other. The volume fractions of the continuous phase q and the dispersed phase p can have any value from 0 to 1, depending on how much space they take;

- the Mixture model allows the phases to move at different speeds. The concept of slip speed is introduced for this purpose. It performs well at high slip ratios of over 262. Also, the phases can move at the same speed and the Mixture model is then reduced to a homogeneous multiphase model.

Only one of the phases can be docked in the Mixture model.

The Eulerian model is a model of interpenetrating environments. The Eulerian model contains a set of n momentum and continuity equations for each phase. The equations are closed by coefficients of pressure and inter-phase exchange. Phases are interpenetrating continua. [18]

In this study the Mixture model will be used because it is designed to model dispersed multiphase flows where phases can move at different speeds, capable of simulating any number of phases (liquid or solids) and is relatively easier to be understood than the Eulerian model and is accurate enough.

CFD modeling will be performed by ANSYS Fluent R19.2 Academic software.

4. Mathematical model

The Mixture model contains continuity equations for mixture, momentum conservation and mixture energy, volume equation for dispersed phases, and algebraic expressions of relative velocities (if the phases move with different velocities).

Continuity equation for mixture:

$$\frac{\partial}{\partial t}(\rho_m)+\nabla\cdot(\rho_m\bar{v}_m)=0, \tag{1}$$

where ρ_m– mixture density;

$\bar{v}_m$ – mixture average velocity.

Mixture density:

$$\rho_m=\sum_{k=1}^{n}\alpha_k\rho_k, \tag{2}$$

where α_k – phase k volume fraction;

ρ_k – phase k density;

n – phase number.

Mixture average velocity

$$\bar{v}_m=\frac{\sum_{k=1}^{n}\alpha_k\rho_k\vec{v}_k}{\rho_m}, \tag{4}$$

where $\bar{v}_k$ –average mass velocity of the phase k .

By adding individual momentum equations of each phase, the momentum equation of the mixture can be obtained

$$\frac{\partial}{\partial t}(\rho_m \bar{v}_m) + \nabla \cdot (\rho_m \bar{v}_m \bar{v}_m) = -\nabla p + \nabla \cdot \left(\mu_m \left(\nabla \bar{v}_m + \nabla \bar{v}_m^T \right) \right) +$$

$$+ \rho_m \bar{g} + \bar{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \bar{v}_{dr,k} \bar{v}_{dr,k} \right), \quad (5)$$

where $\bar{F}$ - bode force;

μ_m - mixture viscosity;

$\bar{g}$ - gravity acceleration;

$\bar{v}_{dr,k}$ - drift velocity of the dispersed phase k ;

Mixture viscosity

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k , \quad (6)$$

where μ_k – phase k viscosity.

Drift velocity of the dispersed phase

$$\bar{v}_{dr,k} = \bar{v}_k - \bar{v}_m . \quad (7)$$

The relative velocity (also called slip velocity) is the difference between the velocity of the dispersed phase *p* and the velocity of the continuous phase *q*

$$\bar{v}_{pq} = \bar{v}_p - \bar{v}_q , \quad (8)$$

where $\bar{v}_p$ – dispersed phase velocity;

$\bar{v}_q$ – continuous phase velocity.

The mass fraction of the dispersed phase *k*

$$c_k = \frac{\alpha_k \rho_k}{\rho_m} , \quad (9)$$

Disperse phase drift velocity is the difference between the slip velocity and the algebraic sum of the product of mass particles on the velocity of the dispersed phase

$$\bar{v}_{dr,p} = \bar{v}_{pq} - \sum_{k=1}^{n} c_k \bar{v}_{pk} . \quad (10)$$

The algebraic slip formula is used in the Mixture model. The basic assumption of the algebraic slip model of the mixture is that the local equilibrium between the phases must be reached at a short spatial length. Then the relative velocity is equal

$$\bar{v}_{pq} = \frac{\tau_p}{f_{drag}} \frac{(\rho_p - \rho_m)}{\rho_p} \bar{a}, \qquad (11)$$

where τ_p – relaxation time of the dispersed phase particles;

f_{drag} – function switch;

ρ_p – density of the dispersed phase;

$\bar{a}$ – acceleration of dispersed particles.

The relaxation time of the dispersed phase particles

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_q}, \qquad (12)$$

where d_p – diameter of dispersed particles;

μ_q – continuous phase viscosity.

Function switch

$$f_{drag} = \begin{cases} 1+0{,}15\,Re^{0{,}687} & Re \le 1000 \\ 0{,}0183\,Re & Re > 1000 \end{cases}, \qquad (13)$$

Acceleration of dispersed particles

$$\bar{a} = \bar{g} - (\bar{v}_m \cdot \nabla)\bar{v}_m - \frac{\partial \bar{v}_m}{\partial t} a. \qquad (14)$$

The particle acceleration is given by gravity and/or centrifugal force in the dispersive flow model. To account the presence of other particles, the particle relaxation time changes. In turbulent flows, the relative velocity must contain the diffusion component caused by the dispersion, which should be in the momentum equation for the dispersed phase. In the Mixture model, this variance is added to the relative speed

$$\bar{v}_{pq} = \frac{(\rho_p - \rho_m) d_p^2}{18\mu_q f_{drag}} \bar{a} - \frac{\nu_m}{\alpha_p \sigma_D} \nabla \alpha_q, \qquad (15)$$

where α_p – volume fraction of the dispersed phase;

α_q – volume fraction of continuous phase;

ν_m – turbulent viscosity of the mixture;

σ_D – the Prandtl number.

The energy equation of the mixture

$$\frac{\partial}{\partial t} \sum_{k=1}^{n} (\alpha_k \rho_k h_k) + \nabla \cdot \sum_{k=1}^{n} (\alpha_k \bar{v}_k (\rho_k h_k + p)) = \nabla \cdot (k_{eff} \nabla T) + S_E, \qquad (16)$$

where k_{eff} - effective conductivity;

h_k - enthalpy of phase k ;

S_E - energy transfer due to conductivity. S_E includes any other volumetric heat source;

From the continuity equation of the dispersed phase p, the volume fraction equation for the dispersed phase p can be obtained

$$\frac{\partial}{\partial t}\left(\alpha_p \rho_p\right)+\nabla \cdot\left(\alpha_p \rho_p \bar{v}_m\right)=-\nabla \cdot\left(\alpha_p \rho_p \bar{v}_{dr,p}\right). \text{ [18]} \quad (17)$$

5. Geometric modeling

Both the multiphase gas-dynamic processes occurring in these elements and their hydraulic energy losses, depend significantly on the geometric shape and geometric parameters of the gas pipeline systems elements. Since multi-phase flows in elements of gas pipelines with complex geometry are extremely complex, and their physical transmission pattern is three-dimensional, the study should be performed using 3D geometric modeling.

3D geometric models of the internal cavity of gas pipeline system elements were designed in the academic version of the AutoCAD software. The shape and geometric dimensions of the elements are identical to the industrial designs and correspond to TU 27.2-05747991-001 [19] and OST 102-61 [20].

Modern pipeline systems contain a large number of various elements of gas pipeline systems of complex geometry such as tees, bends, fittings and the like. These elements are produced by various manufacturers and have different geometry.

The geometric parameters of the pipeline bends, on which the hydraulic energy losses of the multiphase flow depend, are the internal diameter of the bend D_{in}, the bending angle φ, and the bending radius of the bend R_B (Fig. 2*a*). The influence of these parameters on the hydraulic energy loss in gas pipeline branches has not been sufficiently investigated. Five different outside diameters were selected to perform such studies - 89 mm, 219 mm, 530 mm, 1020 mm and 1420 mm. For a diameter of 530 mm, bends were drawn with a bend radius equal to DN (DN - conditional bend diameter) and bending angles of 30°, 45°, 60° and 90°, as well as with an elbow angle of 90° and bending radii of DN, 1.5 DN, 2 DN, 2.5 DN and 3.5 DN. Bends were drawn with adjacent pipe sections.

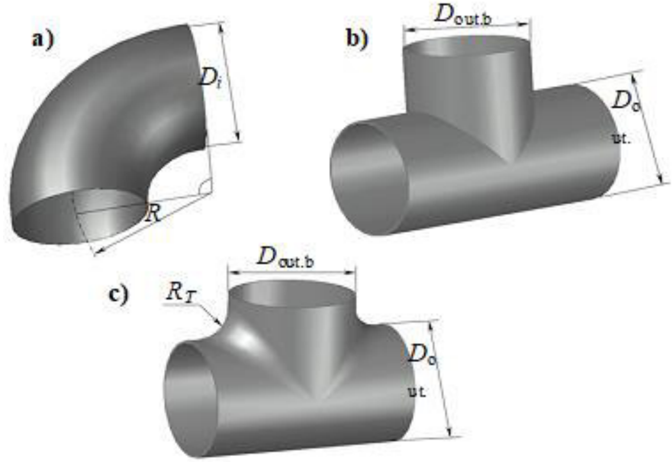

Fig. 2. Geometric models: *a* – bend; *b* – welded tee; *c* – stamped tee

The geometric parameter of the pipeline tees, on which the hydraulic energy loss of the multiphase flow largely depends, is the rounding radius of the connection between the main line and the branch. The effect of this parameter on hydraulic energy losses in pipeline tees has not been sufficiently investigated. To perform such studies, an internal cavity of the welded tee with an outside diameter of 530 mm was drawn, in which the connection of the main line and the bend is made at elbow angles (Fig. 2*b*). Also, an internal cavity of the stamped tees with an outside diameter of 530 mm was drawn, in which the transition from the bend to the line is made by rounding (Fig. 2, c). Since the rounding radius of the stamped tee R_T must be not less than 0.1 $D_{out.b}$, five models of the inner cavity were drawn, with a rounding radius varying from 0.1 $D_{out.b}$ to the maximum possible (53 mm, 95 mm, 136 mm and 178 mm).

The wall thicknesses of each bend, tee, and adjacent pipe sections were calculated for the appropriate pressure. According to the value of the nominal wall thickness of the taps and pipes, their internal diameter was determined.

Geometric models of bends and tees were imported from AutoCAD to Ansys Fluent.

6. Boundary conditions

In addition to the geometric shape and geometric parameters, the hydraulic energy losses in the elements of the gas pipeline systems are significantly influenced by the mode parameters of multiphase flow transmission and the characteristics of the dispersed phases, which were set in the ANSYS Fluent pre-processor. The continuous phase was selected as natural gas, which was accepted as a compressible medium. Steel was used as the material of the tee wall. The coefficient of equivalent roughness of tees and adjacent sections of pipes was set equal to 0.03 mm.

Experience of gas pipelines operation shows that the main cause of gas pipelines hydraulic resistance increase is liquid harmful impurities. Liquid contaminants may be condensate or water, which in large volumes are drawn from wells, fall out of gas when the dew point of the pumped gas is reached. The presence of condensate in the gas pipeline leads to the transmission of the two-phase mixture, which causes an increase in hydraulic energy losses. Therefore, the condensate density of 960 kg/m^3 was set as the dispersed phase. This value is close to the density of water.

The main transmission mode parameters, which have the greatest influence on energy losses, and the effect of which was studied are the velocity of multiphase flow and pressure. The velocity of the continuous and dispersed phase, which was assumed to be equal to each other, was set at the inlet of each bend, and the pressure was set at the outlet of the bend. The inlet velocity varied from 7 m/s to 19 m/s in 3 m/s increments and pressures was ranging from 3 MPa to 7 MPa in 1 MPa increments. A separate simulation was performed for each velocity and pressure values.

The temperature of the continuous and dispersed phases corresponds to the conditions of the gas pipelines operation and was set at 273 K. Also at the inlet and the outlet of the bend a turbulence intensity of 5% (for this value the flow is considered to be completely turbulent) and the hydraulic diameter were set. The hydraulic diameter was assumed to be equal to the inside diameter of the pipeline. The main characteristics of the dispersed phase, which have the greatest effect on energy loss, and the effects of which were studied are particles concentration and size.

The maximum diameter of the dispersed liquid phase droplets according to [21, (14.13)] is equal to

$$d_{liq}^{max} = 2D_{in} k_f^{-\frac{3}{5}} We^{-\frac{3}{5}} \left(\frac{\rho_{gas}}{\rho_{liq}} \right)^{\frac{2}{5}}, \qquad (18)$$

where D_{in} - pipeline internal diameter;

k_f - coefficient of aerodynamic drag resistance, $k_f = 0,4$;

ρ_{gas} - gas density;

ρ_{liq} - liquid phase density;

We – dimensionless parameter – Weber number

$$We = \frac{\rho_{gas} u^2 D_{in}}{\Sigma}, \qquad (19)$$

where Σ - the surface tension of the liquid phase at the gas boundary.

The surface tension of the liquid phase at the gas boundary depends on the pressure and temperature of the gas and was determined according to [22, Tab. VI.2].

The maximum calculated (18) diameter of liquid phase droplets was about 100 μm. Therefore, the droplet diameters were assumed to be 100 μm, 50 μm, 10 μm, 5 μm, and 1 μm. The particle concentration in Ansys Fluent is given as the volume fraction of the dispersed phase, which varied from 0.1 to 0.3 in 0.05 increment. The volume fraction is determined by the amount of dispersed phase in the continuous. The volume fraction is taken to be a dimensionless value, which is the ratio of the volume of the dispersed phase to the total volume of the multiphase system.

In tees, the loss of hydraulic energy, in addition to the geometric shape and geometric parameters, is strongly influenced by the flow direction and the ratio of costs in the branch and main line. However, almost all theoretical and experimental studies in the laboratory are mainly concerned with the separation and merging of flows in tees. These results are incomplete because they do not cover all possible combinations of flow directions in tees found in various gas pipeline systems. The influence of tee geometry on hydraulic energy losses has not been established for the combinations of flow directions not covered.

In practice, there are a lot of tees in which a stream moves in a main line from which it flows completely into a branch. Such tees are a part of piping of the main gas pipelines compressor stations, underground gas storages, gas processing plants, gas distribution stations and the like. In addition, they are in place of technological overriders between gas pipelines, where all the flow from one line flows to another, in places of multiline underwater pipelines, where all the flow is transmissed by backup lines and the like. For such a scheme of flow movement in the tees, there is little information about the loss of energy in them today, not only considering multiphase flows, but also single-phase ones. In addition, as a result of the complete flow of gas from the main line to the branch, the gas flow from the wall at the beginning of the branch is detached, resulting in a significant vorticity, recirculation of the flow, and therefore the energy losses for this direction of flow of the tee will be maximum.

As tees were studied in which the gas flow from the main line completely flows into the bend, then the velocity of each phase was set at the branch inlet, and the pressure was set at the branch outlet. The velocity was set at 13 m/s and the pressure value was 5 MPa. The dispersed phase was given at spherical form with a diameter of 50 μm. The volume fraction of the dispersed phase was set to 0.2.

7. Research of hydraulic energy losses

Pressure losses of multiphase flow in gas pipelines elements with complex geometry are the main indicators by which their hydraulic energy losses can be estimated. Therefore, in the postprocessor of the ANSYS Fluent software, the results of each simulation were visualized by constructing a pressure field in the longitudinal cross sections of each bend and tee. For example, the outlet with an external diameter of 530 mm is considered. The continuous and dispersed phase velocity at the inlet is 13 m s, the outlet pressure is 5 MPa, the droplet diameter of the dispersed liquid phase is 50 μm, the volume fraction of the dispersed phase is 0.1 and 0.3. The pressure fields in the longitudinal cross sections of the bends are shown in Fig. 3.

Changing the direction of the multiphase gas flow in the bend leads to a complex pressure redistribution (Fig. 3). In the bend there is a radial pressure gradient, which is caused by the centrifugal force acting on the multiphase flow. In addition to the radial pressure gradient, pressure losses in the bend are caused by turbulent vortices on the internal side of the bend after the bending place. By increasing of the volume fraction of the dispersed phase increases, the pressure drop in this place falls down (Fig. 3), which has a significant effect on the total pressure drop in the bend.

The pressure drop in the bend ΔP was determined by subtracting the inlet pressure and the outlet pressure at the bend. The greatest pressure drop occurs when the volume fraction α of the dispersed phase is 0.3 and these value equals to 17504 Pa. When the volume fraction of the dispersed phase α is 0.1, the pressure loss in the bend is 9864 Pa. As a result of volume fraction of the dispersed phase is increasing from 0.1 to 0.3, the pressure drop values in the outlet increase almost twice.

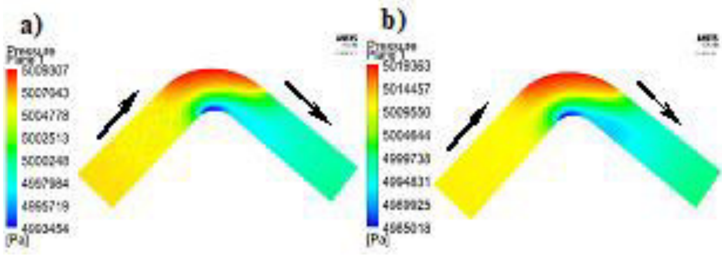

Fig. 3. Pressure field in the longitudinal cross sections of bends: *a* - volume fraction of the dispersed phase 0,1; *b*- volume fraction of the dispersed phase 0,3

The dependence of the pressure drop in the bends on their geometrical parameters (bend external diameter, radius and bending angle) was investigated at continuous two-phase flow mode parameters and unchanged dispersed phase characteristics. The speed of the continuous and dispersed phase at the inlet was set equal to 13 m/s, the bend outlet pressure was 5 MPa, the droplet diameter of the dispersed liquid phase was 80 μm. Only the volume fraction of the dispersed phase changed.

Pressure drop in bends of different diameters was determined for bends with an elbow angle of 90° and a bending radius equal to the nominal diameter of the bend DN. Fig. 3 shows the graphical dependence of the pressure drop in the bend ΔP on the bend outside diameter $D_{out\cdot b}$ for different volumetric fractions of the dispersed phase, namely 0.1, 0.2 and 0.3.

The results obtained show that with all other parameters being equal, the pressure drop in the bend increases with decreasing diameter for all volume fractions of the dispersed phase (Fig. 4). Moreover, the larger the volume fraction of the dispersed phase, the greater the pressure drop in the bend of the same diameter. It can also be observed that the increase in pressure drop in small diameters (less than 500 mm) is much more intense than in large diameters. Therefore, the influence of the bend diameter on the energy loss must be taken into account, especially with regard to the bend diameters less than 500 mm.

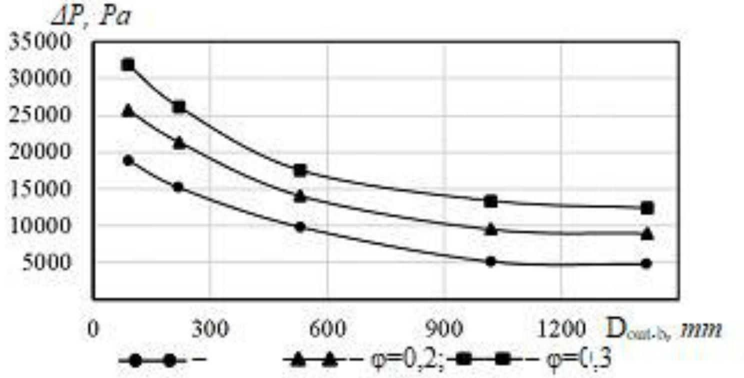

Fig. 4. Dependence of the pressure drop in the bend on the bend outside diameter for different volumetric fractions of the dispersed phase

Pressure drops in bends with different bending angles were determined for bends with an outside diameter of 530 mm with a bending radius equal to the nominal diameter of the DN bends. Fig. 5 shows a graphical dependence of the pressure drop in the bend ΔP on the its bending angle φ for different volume fractions of the dispersed phase, namely 0.1, 0.2 and 0.3. As we can see, as the bending angle increases, the pressure drop falls down with in a linear dependence for all volume fractions of the dispersed phase. Moreover, the larger the volume fraction of the dispersed phase, the greater the inclination of the straight line to the abscissa and the more intense the pressure drop in the bend.

Pressure drop in bends with different ratio of bending radius to nominal bending diameter was determined for bends with an outside diameter of 530 mm with an elbow angle of 90°. Fig. 6 shows a graphical dependence of the pressure drop in the bend ΔP on the ratio of the bending radius to the nominal diameter of the bend R_B/DN for different volume fractions of the dispersed phase, namely 0.1, 0.2 and 0.3. The bending radius of the bend has a significant effect on the pressure drop in it when it is less than 2.5 *DN*. There is a sharp increase in pressure drop in the bend while reducing the outside radius. Moreover, the larger the volume fraction of the dispersed phase, the more intense the pressure drop with decreasing the bend radius. At large radii of bend when it is more than 2.5 *DN* the pressure drop is minimal and practically does not change.

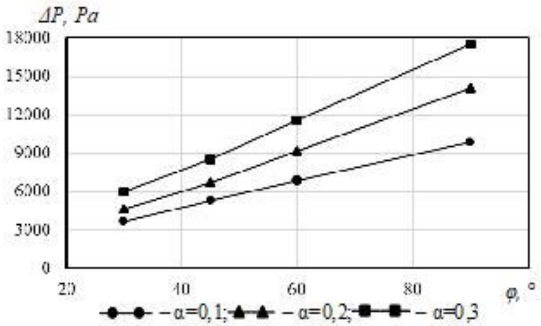

Fig. 5. Dependence of the pressure drop in the bend on the bending angle for different volume fractions of the dispersed phase

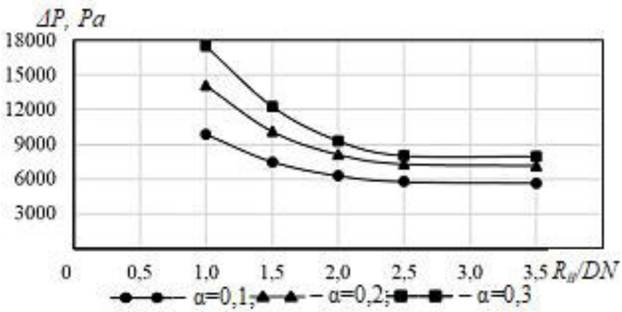

Fig. 6. Dependence of the pressure drop in the bend on the ratio of its bending radius to its nominal diameter for different volume fractions of the dispersed phase

The dependence of the pressure drop in the bend on the mode parameters of the two-phase flow, the characteristics of the dispersed phases were investigated at constant bend geometric parameters. The bend diameter was 530 mm, the bend elbow angle - 90°, the bending radius of bend was equal to the nominal diameter of the bend. The greatest pressure drop occurs in the bends with an elbow angle of 90° and a bending radius equal to the nominal diameter of the bend (Fig. 5, 6).

The dependence of the pressure drop in the bend ΔP on the velocity of the two-phase flow at the bend inlet *V* (Fig. 7) and the volume fraction of the dispersed phase α (Fig. 8) was investigated at a pressure at the bend outlet equal to 5 MPa and the diameter of the droplets of liquid dispersion phase equal to 80 μm.

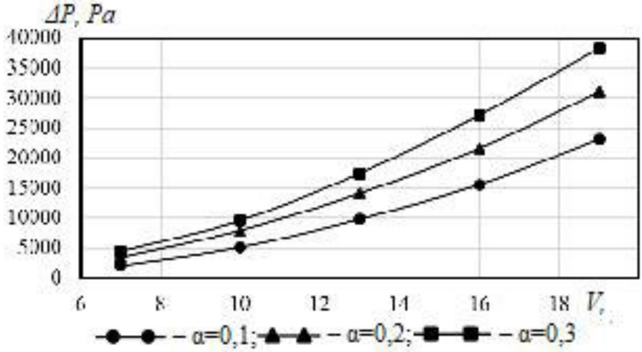

Fig. 7. Dependence of the pressure drop in the bend on the velocity of the two-phase flow at the bend inlet for different volume fractions of the dispersed phase

With the increase in the velocity of the two-phase flow there is a significant increase in the pressure in it (Fig. 7). Trends remain unchanged for all volume fractions of the dispersed phase. In the low velocity zone, the volume fraction of the dispersed phase has less influence than in the high velocity zone. Such a pattern can be better seen in Fig. 8. At low velocities of two-phase flow at the bend inlet (about 7 m/s), with the increase of the volume fraction of the dispersed phase, the pressure drop values do not increase significantly. Instead, at high velocities (about 19 m/s), there is a sharp increase of pressure drop values in the bend with an increase in the volume values of the volume fraction.

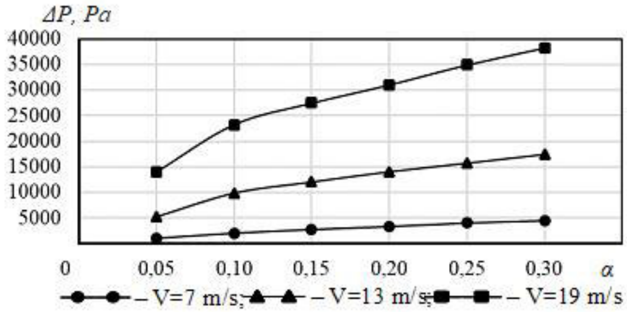

Fig. 8. Dependence of the pressure drop in the bend from the volume fraction of the dispersed phase for different velocities of two-phase flow at the inlet

The dependence of the pressure drop in the bend ΔP on the diameter of the dispersed particles d_p was investigated at the inlet for the two-phase flow velocity equals to 13 m/s and the pressure at the bend outlet equals to 5 MPa. As the diameter of the dispersed particles increases, their effect on the pressure drop in the bend increases with a linear dependence (Fig. 9). This trend is typical for all volume fractions of the dispersed phase. Only in the area of dispersed particles of small diameters with a volume fraction of the dispersed phase equal to 0.3 a sharp increase in pressure drop values was observed.

The dependence of the pressure drop in the outlet ΔP on the pressure at the bend outlet P was investigated with a velocity of two-phase flow at the inlet that was 13 m/s and the droplet diameter of dispersed liquid phase was 80 μm. As the pressure in the pipeline decreases, there is an increase in the pressure drop values in the bend for all volume fractions of the dispersed phase. (Fig. 10) Moreover, in the area of small pressures with decreasing pressure at the bend outlet, the pressure drop values in the bend are increasing more intensely.

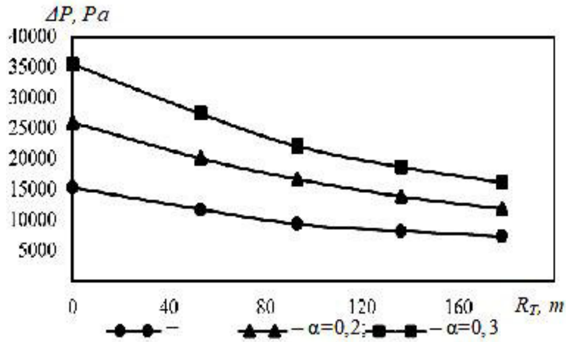

Fig 9. Dependence of the pressure drop in the bend on the diameter of the dispersed particles for different volume fractions of the dispersed phase

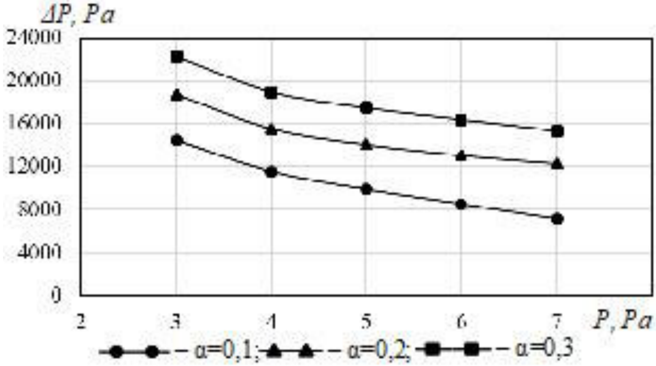

Fig. 10. Dependence of the bend pressure drop on the outlet pressure for different volume fractions of the dispersed phase

For tees, the effect of the rounding radius at the connection of the line and the branch R_T on the tee pressure drop for different volume fractions of the dispersed phase was investigated, namely 0.1, 0.2 and 0.3. The tee is equilateral with a diameter of 530 mm. The gas flow moves the tee main line from which flows completely into the branch. The speed of the continuous and dispersed phase at the inlet of the tee main line was set equal to 13 m/s, the pressure at the outlet of the tee outlet was 5 MPa, the droplet diameter of the dispersed liquid phase was 80 μm.

If the rounding radius connection between the main line and the branch is reduced, there is a significant increase in the tee pressure drop values (Fig. 11). It has been found that the larger the volume fraction of the dispersed phase, the more intense the pressure drop will be in case of the rounding radius the connection between the main line and the branch being decreased.

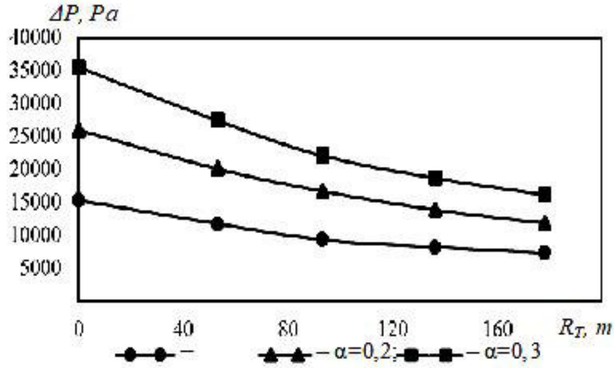

Fig. 11. Dependence of the pressure drop in the tee on the rounding radius of the connection between the main line and the branch for different volume fractions of the dispersed phase

Conclusions.

1. The performed researches give understanding of regularities of liquid dispersed harmful impurity influence in gas pipelines on hydraulic energy losses of gas pipeline systems' elements with complex geometry. The increase of the volume fraction of the dispersed phase leads to an increase in pressure drop values in the bends and tees. The most significant such effect of the volume fraction was observed in bends with a large angle and a small bending radius. In particular, pressure drops in bends increase at high multiphase flow velocities and low pressures. Also, the energy losses of two-phase flow in small diameter bends are significantly increased. In the case of tees, the most significant effect on the hydraulic energy loss is caused by the volumetric fraction of the dispersed phase when the rounding radius of the connection between the main line and the branch is the smaller or rounding is absent at all (welded tees). The increase in the volume fraction of the dispersed phase leads to a significant increase in pressure drop values in the tees, in which the gas flow from the main line transfers completely into the branch.

2. In order to minimize the energy losses of multiphase gas flow in gas pipeline elements, it is recommended, when designing new and refurbishing old gas pipeline systems, to give priority to bends with the largest possible bending radius and stamped tees with the largest rounding radius of the connection of the main line and the branch.

3. The obtained knowledge is useful for operators of gas pipeline systems that can optimize the operating parameters of two-phase gas flow transportation and can reduce the energy losses of pipelines, and engineers who can optimize the geometric parameters of bends and tees to minimize these hydraulic energy losses.

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