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Numerical simulation of the stress state of an erosion-worn tee of the main gas pipeline

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ABSTRACT

Purpose: To investigate the strength of tees with regard to their erosion wear, it is necessary to consider the complex three-dimensional geometric shape of the erosion worn inner surface of the tee. In addition, the study of the strength of the erosion worn tees of the main gas pipelines is complicated by the occurrence of additional stresses caused by changes in the direction of movement of the gas stream, resulting in an uneven pressure distribution in the inner cavity of the tee, and the temperature difference in its walls.

Design/methodology/approach: Methodology for complex numerical three-dimensional simulation of the stressed state of tees of the main gas pipelines, taking into account the gas-dynamic processes that occur in the places of these defects, erosion wear of the tee wall, temperature difference in the tee walls.

Findings: The acceptable parameters of erosion defects of tees of gas pipelines, and residual life of tees with erosion defects of the wall should be determined.

Research limitations/implications: The developed model does not take into account internal corrosion and corrosion products as an additional erosion factor. Further studies plan to develop a model of corrosion-erosion wear of pipeline elements.

Practical implications: The developed technique allows determining the location of erosion defects, estimating the strength and determining the residual life of tees with erosion wear of the wall in order to ensure their reliability, to rank such defects according to the degree of danger, to determine which of them are critical and need an immediate repair.

Originality/value: Based on the gas-dynamic processes occurring in the internal cavity of the main gas pipelines' tees, the complex three-dimensional geometric form of wall erosion defects, and temperature difference, the technique of three-dimensional simulation of stress state of the main gas pipelines' tees is developed.

Keywords: Multiphase flow, Gas-dynamic process, Allowable wall thickness, Erosion wear, Residual life, Temperature difference, Form of erosion defect

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The main gas pipelines must meet some requirements, in particular reliability and environmental safety. These indicators depend on the quality of the design and construction of gas pipelines, the effectiveness of their maintenance, the correct assessment of the technical condition and the prediction of residual life, timeliness and quality of repair.

The modern gas transmission system is a complex network of gas pipelines, which consists of straight sections, curves of hot (outlets) and cold bending, tees, overlapping and adjusting valves. The largest number of tees is contained in the bundles of compressor stations, underground gas storage, and gas distribution stations. Accidents at such sites are extremely dangerous and can result in human casualties and the destruction of expensive equipment. Modelling of stress-strain state of pipeline materials, machine-building metal structures, etc. is important for predicting performance. This is especially important for long-term pipelines, metal structures of equipment that are affected by the corrosive environment [1-10], as well as on complex sections of the route (saline soils, landslides, marshy areas). There, stress corrosion cracking, pitting corrosion [1-10], etc. may occur, due to the strengthening of the corrosion factor by mechanical stresses. Therefore, the safety of such objects depends to a certain extent on the technical condition of the tees. There are also tees at the beginning of each branch from the main gas pipeline, at the places of jumps between gas pipelines, at the beginning and at the end of looping, multi-threaded underwater crossings, etc.

In the tees of gas pipelines, the direction of product movement changes, stipulating a complex physical picture of the gas flow. Turbulent gas flow occurs, as well as uneven pressure distribution; liquid and solid particles (discrete phase) contained in the natural gas flow impact to the tee wall, leading to erosion of its wall. The erosion affects the stress-strain state of the tee, reduces its residual life. Particularly erosive wear of the tee wall is dangerous for gas pipelines with a lifetime exceeding 40 years. Therefore, a physical picture of the gas flows movement by tees of main gas pipelines and their reliability should be comprehensively studied.

The tees of the main gas pipelines must meet the requirements of reliability. Firstly, the change in the shape and magnitude of the erosion defects of the tee wall should be monitored; the degree of danger of erosion worn tees and their residual life should be estimated. For this purpose, a technique for determining the location of erosion defects of the tee wall and a technique for investigating the strength of tees with erosion-worn wall should be developed, taking into account the extremely complex three-dimensional form of erosion defects and gas-dynamic processes that occur in the inner cavity of tees. The solution of this problem will allow to evaluate the efficiency of tees and to determine the residual life of tees with erosive wear of the wall, to prevent emergencies, to determine the frequency of regular work on inspection of gas pipelines' tees in places of erosive wear of the wall.

To investigate the strength of tees with regard to their erosion wear, it is necessary to consider the complex three-dimensional geometric shape of the erosion worn inner surface of the tee. In addition, the study of the strength of the erosion worn tees of the main gas pipelines is complicated by the occurrence of additional stresses caused by changes in the direction of movement of the gas stream, resulting in an uneven pressure distribution in the inner cavity of the tee, and the temperature difference in its walls.

Nowadays, these problems can be solved with the modern ANSYS computer simulation software, which can perform multidisciplinary calculations. The new ANSYS Workbench Integration Calculator integrates the strength, hydro-gas-dynamic and temperature modules. In addition, the state-of-the-art ANSYS Workbench platform enables to model physical processes using three-dimensional models built in most CAD packages.

The tees contain pipelines for various purposes (gas pipelines, oil pipelines, oil products pipelines, nitrogen pipelines, flow pipelines for nuclear and thermal power plants, pipelines for pneumatic transport, etc.). This stipulates the interest of many researchers to study the processes that occur in their internal cavity and the effect of these processes on the wall of tees.

Many modern scientists are engaged in the computer simulation of hydrodynamic processes in the inner cavity of pipeline tees, in the simulation of erosion wear and stress-strain state of the tee wall. Their results confirm that such software systems are an effective tool for such research.

Vasava P. in his master's thesis [11] performed numerical simulation of fluid flows in tees in the Ansys fluent software. The simulation was performed to investigate the loss of pressure in the flow during its passage inside the tee. The cross-sectional area of the pipeline and tee outlet was changed, as well as the fluid velocity at the inlet. Based on simulation results, velocity fields in the transverse and longitudinal sections of the tee are defined; and the pressure loss in the tee is determined. The simulation results are compared with the results of calculations using classical formulas; and the use of 3D modelling was concluded to be advisable for such studies.

Nan L., Hui-qing L., and Yu-Gong X. [12] performed CFD simulations of a two-phase gas stream in a tee with two inlets (pipeline and outlet) and one outlet. The place of maximum erosion wear of the tee wall is found to depend significantly on the flow velocity at the tee entrances. The places of maximum erosion wear of the tee wall for different values of flow velocity at the tee entrances are determined. Trajectories of particles' motion of the tee, pressure fields, velocity, and intensity of the tee turbulence are developed in the post processor of the software complex.

Vigolo D., Griffiths I., Radl S., Stone H. [13] CFD simulations and experimentally investigated the motion of a two-phase tee flow in which the flow from the divergence diverges on either side of the tee line. The trajectories of particle motion were monitored as the tee flow direction changed. Data were obtained on the impact points of the dispersed particles against the tee wall, the velocity of the particles, the angles of attack at the impact site. The experimental results were compared with the trajectories obtained theoretically and the reliability of the simulation was confirmed.

Pouraria H., Seo J., and Paik J. [14] compared the results of modelling the erosion wear of outlets and tees of offshore gas pipelines. The outlets and tees of different diameters (from 0.0254 to 0.6 m) were studied, as well as different inlet flow rates, and different sizes of solids. The small diameter pipelines' tees were proved to be more resistant to erosion of the wall than the outlets. Conversely, large diameter pipelines are more resistant to erosion than tees.

Mahdi E., Rauf A., Ghani S., El-Noamany A. and Pakari A. [15] stated that the offshore steel tee lost its strength due to the combined effect of erosion, corrosion and fatigue. Applying CFD modelling, during flow motion from the outlet to one side of the tee pipeline, a significant increase in flow turbulence was found at the place of the erosion wear of the tee wall. In addition, at this place, an increase in pressure occur. All mentioned caused the origin and growth of fatigue cracks in the tee.

Ryabov A., Kudryavtsev A., Voronkov O. and etc [16] modeling in the STAR-CCM + software complex investigated a multiphase flow in a gas field well tee. The gas stream coming from the well contains sand and water. In the tee, the flow from the drain completely flowed into one side of the tee line. The flow motion was modeled by the Langrangian model, and the Oka model was used to model the erosion wear of the tee. As a result of the simulation, the geometric shape of the erosion-worn inner surface of the tee was obtained. The results obtained from the simulation results in the location and velocity of the erosion wear of the tee were in good agreement with the results of the visual inspection of the real tee of the gas well borehole.

Based on the numerical simulation in the Ansys software complex, Qing-Ren W., Zhen C., Xue-Qing L., Kui W., and Lu-Yi L. [17] studied the stress-strain state of a reinforced welded tee of a power plant without defects and with cracks at different places of welded joint and close to it. Simulations were performed for different crack sizes. The results of the calculation were visualized by developing three-dimensional colour fields of stresses. Based on these fields, the highest stresses in the tees were concentrated at the point of welding of the outlet to the tee line. The length and the depth of the crack were found to affect the values of the stress intensity factor. A surface crack is more dangerous than a hidden deep crack.

Current methods of calculating the stress-strain state of tees do not take into account the complex three-dimensional geometric curvilinear shape of the erosion defects of the tee wall and the uneven pressure distribution in the inner cavity of the tees.

Therefore, the task of the study is to develop a methodology for complex numerical three-dimensional simulation of the stressed state of tees of the main gas pipelines, taking into account the gas-dynamic processes that occur in the places of these defects, erosion wear of the tee wall, temperature difference in the tee walls. The acceptable parameters of erosion defects of tees of gas pipelines, and residual life of tees with erosion defects of the wall should be determined.

The strength of tees of gas pipelines should be studied in three-dimensional formulation. In addition, in the place of tees, there is a change in the direction of product movement, which leads to a complex physical picture of the gas flow movement. An uneven pressure distribution occurs that affects the stress state of the tee wall. The stress state in the wall is influenced by the stress state of the tee wall. Therefore, it is necessary to perform multidisciplinary calculation by combining gas dynamic, temperature calculation with mechanical calculation.

This problem can be solved by the ANSYS software package. The simulation was performed in the ANSYS R18.2 Academic finite element analysis software.

The complex procedure of numerical simulation of the problem under consideration consists of six stages:

- simulation of geometry of tee walls and modelling of flow geometry;
- simulation of the gas flow in the tee in the ANSYS Fluent module;
- import of three-dimensional wall geometry and the obtained results from the ANSYS Fluent hydro-dynamic module into the ANSYS Static Structural mechanical module of the software complex;
- simulation of temperature difference in the walls of the tee in the module of calculation of thermal processes Transient Thermal;
- import of the obtained results from the calculation module of thermal processes Transient Thermal into the mechanical module of ANSYS Static Structural software complex;
- simulation of the tense state of the outlets in the mechanical module ANSYS Static Structural.

For the numerical simulation of the problem under consideration in the ANSYS Workbench calculation environment, the calculation scheme was applied (Fig. 1). ANSYS Fluent has a Lagrangian approach (Discrete Phase Model) to model erosion wear.

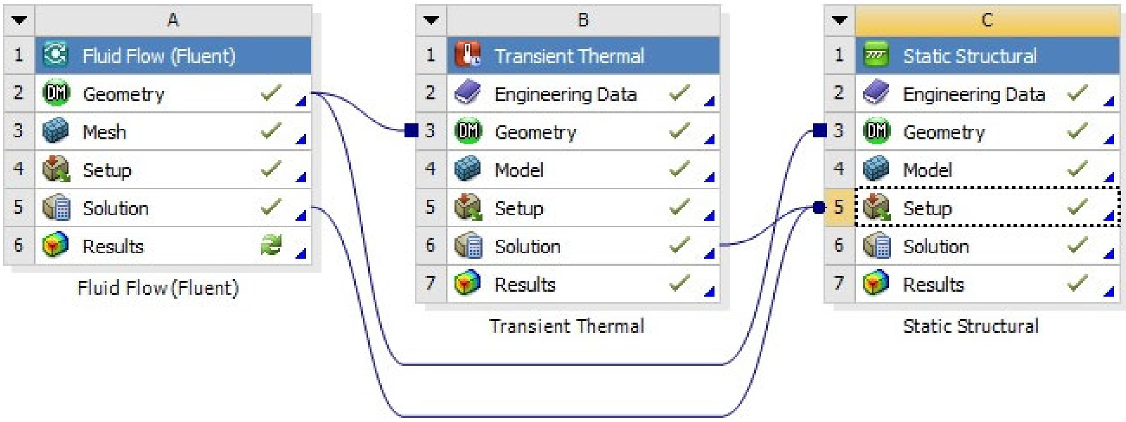

Fig. 1. Calculation scheme specified in the ANSYS Workbench calculation environment

The comprehensive procedure for numerical simulation of erosion wear in ANSYS Fluent consists of three stages:

- simulation of gas flow (solid phase) in tees of gas pipelines;
- simulation of the motion of liquid and solid particles in the gas stream by tees of gas pipelines;
- calculation of erosion wear of gas pipeline tees.

The solid phase motion in ANSYS Fluent is simulated by numerically solving equation systems that describe the most common case of gaseous medium motion. Such are the Navier-Stokes equation (1), which expresses the law of conservation of momentum, (or Reynolds (3) if the flow is turbulent) and the continuity (2), which expresses the law of conservation of mass:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)= -\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right)+f_i \quad (1)$$

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j)=0 \quad (2)$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i)+\frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j)+\frac{\partial}{\partial x_j}(\rho \bar{u}_i' \bar{u}_j')= -\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)\right)+f_i \quad (3)$$

if x_i, x_j – coordinates; t – time; u_i, u_j – velocity components; ρ – gas density; μ – molecular dynamic viscosity of gas; f_i – an application that takes into account the action of mass forces; p – pressure; $\bar{u}_i$ – time averaged values of velocities; $\bar{u}_i'$ – components of speed ripple [18].

In ANSYS Fluent, these equations are closed by a two-parameter model of turbulence $k-\varepsilon$ (k – turbulent energy, ε – rate of dissipation of turbulent energy).

In order to fully and comprehensively investigate the erosion wear of the main gas pipeline tees, one must know the places of intense impact of liquid and solid particles transported by natural gas flow (multiphase flows) to the pipeline wall, as well as the velocity, diameters, particle density, angles of attack at the point of impact. Until recently, some of this information could only be obtained through experimental laboratory testing by visualizing flow in transparent tubes. However, in the real conditions of gas pipelines, such experiments cannot be performed.

The natural gas transported by gas pipelines is known to contain liquid and solid particles (fouling). The liquid discrete phase includes gas condensate, water, oil and other hydrocarbons. To the solid phase – rock, sand, sinter, which was detached from the inner wall of the pipes, and products of intrinsic corrosion made from wells.

In the continuous phase discrete phase motion simulation, ANSYS Fluent uses the Lagrange approach, is, the motion of individual particles under the action of forces from the continuous phase flow is monitored.

Discrete phase particles are considered spheres. The forces acting on the particle are due to the difference between the velocity of the particle and the flow rate of the solid phase, as well as the displacement of the solid phase medium by this particle. The equation of motion of such a particle was deduced in [19].

$$m_p \frac{du_p}{dt} = 3\pi\mu d_p C_{cor}\left(u - u_p\right) + \frac{\pi d_p^3 \rho}{6}\frac{du}{dt} + \frac{\pi d_p^3 \rho}{12}\left(\frac{du}{dt} - \frac{du_p}{dt}\right) + F_e - \frac{\pi d_p^3}{6}\left(\rho_p - \rho\right)\vec{\omega}\times\left(\vec{\omega}\times\vec{r}\right) - \frac{\pi d^3 \rho_p}{3}\left(\vec{\omega}\times u_p\right) \quad (4)$$

if m_p – particle mass, u_p – speed of movement of the particle; d_p – particle diameter; C_{cor} – coefficient of viscous resistance; F_e – external force that acts directly on the particle (for example, gravity or electric field strength); $\vec{\omega}$ – angular velocity of rotation; $\vec{r}$ – radius vector (when considering motion in relative frame of reference).

To simulate the stress-strain state of tees and calculate their residual resource, one must know the speed of erosion wear, the location of the erosion wear of tees, and the geometric shape of their defective inner surface. The calculation of erosion wear is performed applying the Finney model developed for rigid plastic materials by analyzing the equations of motion of a single particle during its impact with the surface. According to the Finney model, the specific erosion rate (surface mass removed from unit area per unit time) on the surface is equal to

$$E = K u_p^{\ n} f\left(\theta\right) \quad (5)$$

if K – coefficient that depends on the modulus of elasticity of the wall material and the particle density; n – steel depending on the wall material (for steel varies from 2.3 to 2.5); $f(\theta)$ – dimensionless function that takes into account the effect of the angle of attack θ on the speed of erosion wear [20].

The simulation of the stress-strain state of tees in the ANSYS Static Structural module is performed by the finite element method. The basic ideas of the finite element method were laid down in [21].

2. Geometric simulation

Three-dimensional geometric models of tees with reinforcing linings on the pipeline and tee outlet (Fig. 2), in which gas is moved by the tee outlet and from it is directed to one side of the tee line, correspond to OST 102-61 [22].

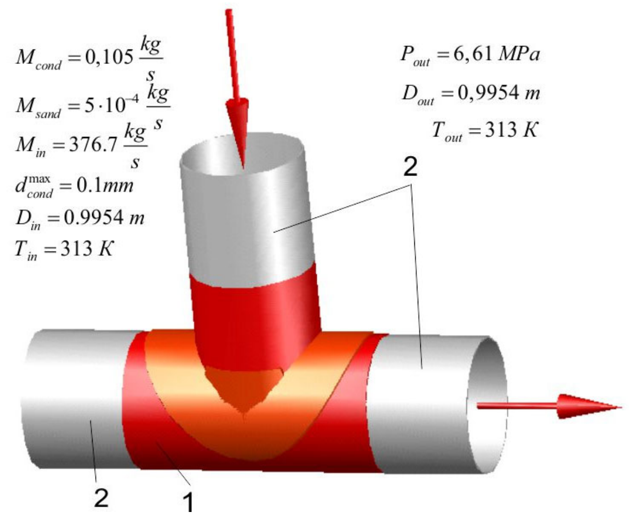

Fig. 2. Geometric model of tee: 1 – welded straight tee with reinforcing linings 1020×20 – 1020×20; 2 – pipe 1020×12.3

The tee is straight with the outer diameter of the line and the outlet $D_{out.l} = D_{out.o} = 1020\ mm$ and the nominal wall thickness of the line and outlet $\delta_{n.l} = \delta_{n.o} = 20\ mm$. The internal diameter of the line and outlet $D_{in.l} = D_{in.o} = 980\ mm$. The tee was drawn with the adjacent sections of the 3 m long pipeline and the outer diameter $D_{out} = 1020\ mm$ and nominal wall thickness $\delta_н = 12.3\ mm$. The inside diameter of the pipes $D_{in} = 995.4\ mm$ and equal to the hydraulic diameter specified in ANSYS Fluent. To study the strength of tees with all the loads applied to them, it is necessary to solve the related problem of the dynamics of gas flow by the tee, and the stresses of the tee walls. For this purpose, two separate three-dimensional geometric models were developed – for the internal cavity of the gas-driven tee, and for the tee wall.

3. Simulation of gas dynamics

The simulation of the gas flow in the tee was performed in the ANSYS Fluent module. Fluent-Meshing preprocessor generated a volumetric calculation grid. For a better description of the wall processes, a wall grid was created. The standard two-parameter turbulence model Realizable was chosen. The wall function Enhanced Wall treatment was chosen simulate qualitatively the flows near the wall. Natural gas was selected from the ANSYS Fluent material database and then assigned to the settlement grid. The Lagret Discret Phase model was chosen to specify the characteristics of the discrete phase. Condensate, water and sand as contaminants dominates in natural gas transported by pipelines. Condensate, whose density was approximately equal to the density of water, was chosen for the liquid phase, and for solids, is was sand. The Erosion/Accretion option was applied in the Discret Phase Lagrangian model to calculate erosion wear.

The boundary conditions and characteristics of each discrete phase that were specified in the ANSYS Fluent preprocessor are given in Table 1 and Figure 2. The simulation results were visualized in the ANSYS Fluent, ANSYS CFD postprocessors. Visualization allowed identifying the gas flow structure in the simulated tee, to study and collect comprehensive data on the motion of condensate droplets and solids by tees, to identify the locations of the most intensive impact of liquid and solid particles to the tee wall and the place of maximum erosion wear of the tee wall.

Table 1.
Parameters of simulation of the multiphase flow in the tee of a gas pipeline in which gas moves along the tee line, and from the line the whole flow flows into the tee outlet

Substance	Natural gas	Condensate	Sand
Input mass flow rate, kg/s	376.7	0.105	0.0005
Temperature, K	313	313	313
Turbulence intensity, %	5	-	-
Outlet pressure, MPa	6.61	-	-
Density, kg/m^3	-	960	2800
Hydraulic diameter, m	0.9954	-	-
Maximum particle diameter, mm	-	0.1	0.1
The minimum particle diameter, μm	-	3	0.1

The filling of the velocity module in the inner tee cavity (Fig. 3a), the flow lines and velocity fields in the cross sections of the tee (Fig. 3b), the filling of the pressure in the inner tee cavity (Fig. 3c), pressure fields in the planes of horizontal longitudinal and cross sections of the tee (Fig. 3d) were developed.

Based on simulation results, the gas flow velocity along the axis was determined to be at the inlet to the tee outlet. The velocity of the gas flow slightly decreases from the axis of the flow in the direction to the wall and sharply decreases near the wall. The gas stream changes its direction and flows from the outlet to the right side of the tee line while passing the tee, which causes a complex picture of movement. The velocity profile both in the longitudinal and in cross sections is a restructured (Figs. 3a,b). In this case, a small part of the gas flow in the lower part of the tee line opposite the outlet flows into the left side of the tee line, where it is twisted and returned to the main flow by the upper part of the tee line (Fig. 3b). The gas flow that flows into the right side of the tee line in the pipeline and in the pipe welded to it flows mainly near the wall opposite the outlet (Figs. 3a,b). The highest velocity of the gas stream, which is 19.3 m/s, is observed near the lower wall of the tee line at the point of exit from the flow line and near the bottom wall welded to the pipe tee line at a distance of 1.8 m (Figs. 3a,b). In the near-wall layer at this point, the flow velocity is 16.8 m/s; near the opposite wall, there is a significant vortex of the gas flow with reverse gas movement (Fig. 3b). The gas velocity at the vortex site is 0.5-6 m/s (Fig. 3b). The transition to a uniform velocity profile captures a straight section of the pipeline of considerable length up to 10 m. Thus, in the line of the tee on the right side of the outlet, a diffuser effect occurs in the upper part, and in the lower part – confusion effect.

Based on the description of the filling of pressure in the inner cavity of the tee (Fig. 3c) and the pressure fields in the planes of horizontal longitudinal and cross sections (Fig. 3d), the pressure in the tee is unevenly distributed. At the inlet of the tee, outlet pressure is 6613906 Pa. Along the tee outlet, there is a slight pressure decrease – up to 6613660 Pa. In the left side of the tee line, where a small part of the gas flows, twists and turns back into the main flow, the pressure is practically constant and amounts to 6614900 Pa (gradually increasing by some Pascal). The picture of the fields and pressure filling shows that at the place where the gas flow diverges (a small part of the gas flows to the left side of the tee line and the main flow to the right side), the pressure significantly increases to 6615593 Pa (Fig. 3c,d). In the right side of the tee line and welded pipe, the pressure is significantly decreases. Moreover, at the place of the diffuser effect, the pressure decreases more to 6606080 Pa; and at the place of the confusion effect, it decreases less – to 6608460 Pa. After the pressure drop in the tee outlet, a slight increase in the pipe welded to the tee outlet occurs, which is caused by the flow stabilization. The uneven distribution of pressure in the tee affects the stress state of the tee walls.

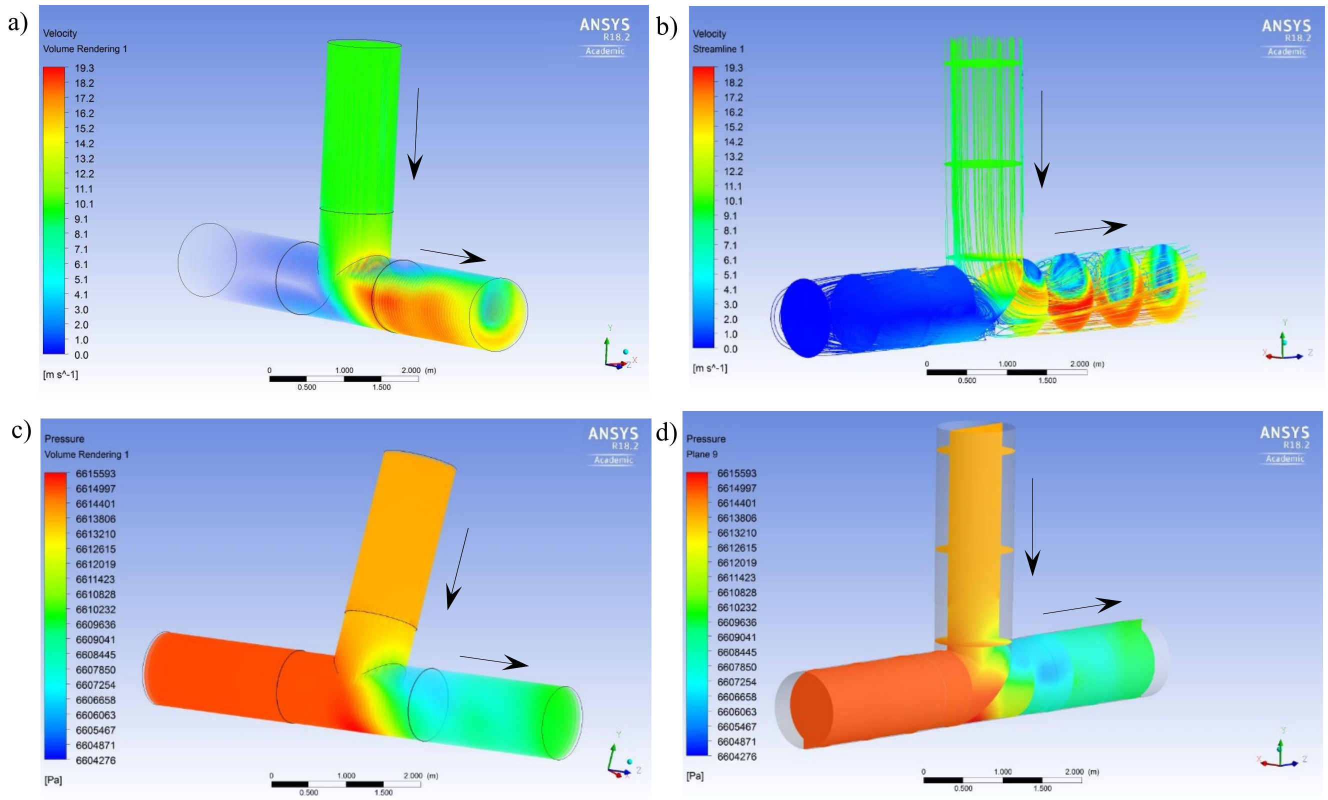

Fig. 3. Results of simulation of gas motion by a straight tee, in which the tee outlet moves the gas, and from the outlet, all the flow is directed to one side of the tee line; a) filling the velocity module in the inner cavity; b) flow lines and velocity fields in cross sections; c) filling of pressure in an inner cavity; d) pressure fields in the planes of horizontal longitudinal and cross sections

The results of simulation of the motion of condensate droplets and sand grains in the gas flow by tee were visualized by developing the calculated trajectories of motion of these particles in the natural gas flow (Fig. 4a). They were coloured with correspondence to velocity (Fig. 4b) and diameter (Fig. 4c) of particles according to the scale of values. During the passage of a straight tee, the gas flow with liquid and solid particles changes its direction and flows from the tee outlet to the right side of the tee line, resulting in a complex motion pattern (Fig. 4). Having studied the trajectories of motion of discrete phases in an equilateral tee, it was established that at the point of change of the flow direction in the tee line opposite to the outlet, the liquid and solid particles move in arcuate trajectories and flow to the right side of the tee line. The flow of gas with liquid and solid particles moves into the right side of the tee line, in the line and in the welded pipe; it moves mainly near the wall opposite the outlet. The discrete phase affects the wall of the tee line. The place of impact is the wall of the tee line opposite the outlet, which is located at the point of intersection of the axis of the tee outlet with the wall of its line to the right (Fig. 4a, place of impact 1).

The angle of impact near the intersection of the axis of the tee outlet with the wall of its line is maximum and is about (Fig. 4a). The velocity of condensate droplets and solids in this place is minimal and is 2 m/s (Fig. 4b). As the distance from the intersection of the axis of the tee with the wall of its line to the right side increases, the angle of impact decreases (Fig. 4a), the rate of droplets of condensate and solids increases and reaches 18.5 m/s at the end of the line of the tee (Fig. 4b).

Near the upper wall on the right side of the tee line, gas flow is twisted with a discrete phase, which is caused by the separation of the flow from the wall at the point of welding of the outlet to the tee line. The velocity of gas with liquid and solid particles in this place is 0.5-6 m/s (Fig. 4b).

Having studied the trajectories of the motion of discrete phases in the straight tee, a small part of the liquid and solid particles was found to deflect from the main flow at the place of change in the flow direction near the lower part of the tee line opposite the outlet. Then, the particles move to the left side of the tee line along the arcuate trajectories, causing the impact to the tee line wall. The point of impact is the wall of the tee line opposite the outlet, located at the point of intersection of the axis of the tee outlet with the wall of its tee to the left (Fig. 4a, impact point 2). The angle of impact near the intersection of the axis of the tee outlet with the wall of its line is maximum and is about 65° (Fig. 4a). As the distance from the intersection of the axis of the tee outlet with the wall of its line to the right side increases, the angle of impact decreases (Fig. 4a). The velocity of condensate droplets and solids at this point is 3 m/s (Fig. 4b). After impact, the discrete phase is twisted and rotated back into the main flow, moving the upper and middle part of the tee line (Fig. 4).

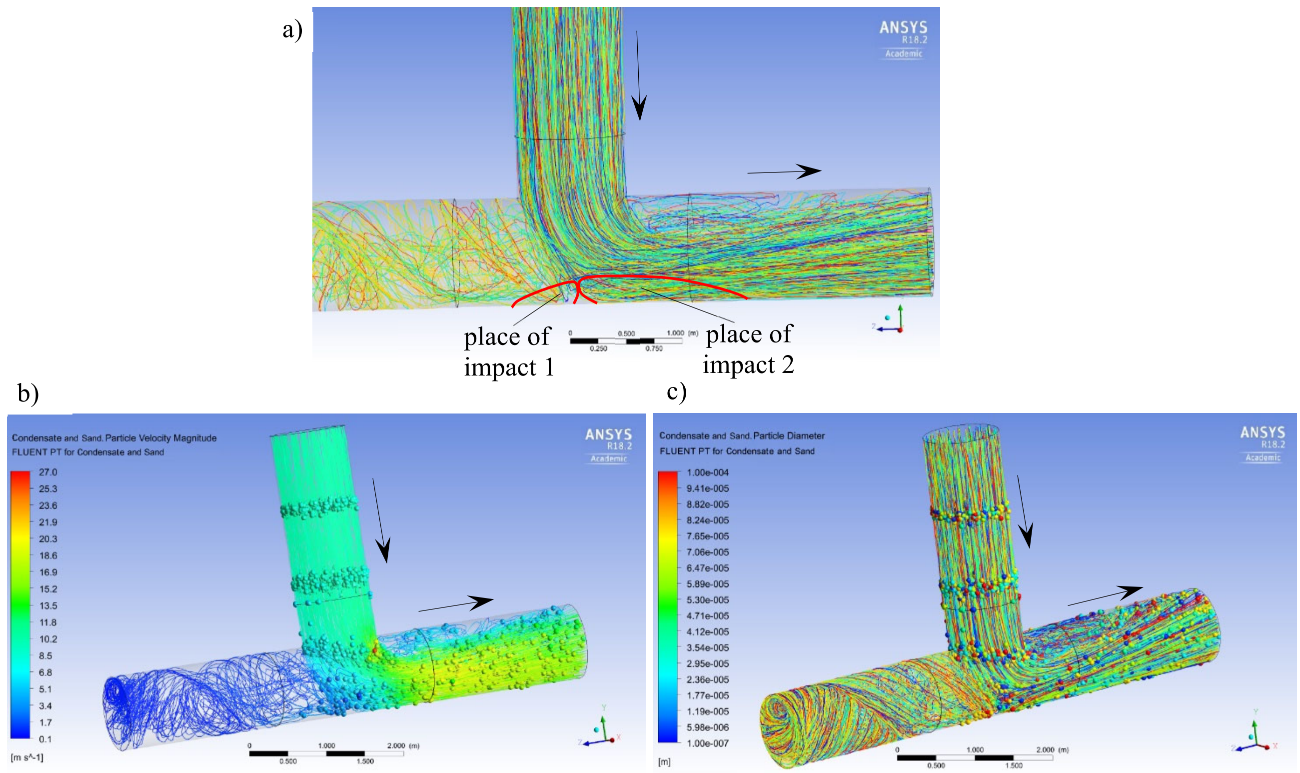

Fig. 4. Results of the simulation of the discrete phase motion by the tee, in which gas is moved by the tee outlet, and from the outlet the entire flow is directed to one side of the tee line; a) trajectories of motion of the discrete phase; b) trajectories of motion of condensate droplets and solids are coloured in colours corresponding to the velocity; c) trajectories of motion of condensate droplets and solids are coloured in colours corresponding to the diameter of the droplets and particles

The ANSYS Fluent software package also allows studying the trajectories of condensate droplets and solids of different diameters. Based on the simulated results, in a straight tee, the gas is moved by the tee outlet, and from the outlet, the entire flow is directed to one side of the tee line. Thus, a uniform distribution of condensate droplets and solids of different diameter throughout its inner cavity occurs in the tee, except the place of gas flow twisting, in which particles of the smallest diameter prevail (Fig. 4c). The results of simulation of the tee erosion wear in the postprocessor of the ANSYS Fluent software complex were visualized by constructing the fields of concentration of condensate droplets and solids (Fig. 5a) and erosion wear velocity fields (Figs. 5b,c) on the tee contours.

Based on the fields of the discrete phase concentration on the contours of the tee (Fig. 5a), the wall of the tee line opposite the outlet is the place of the most intense impact of the liquid and solid particles. The point of impact is pear-shaped. The round part of the pear-shaped impact site almost completely coincides with the projection of the tee's removal to the inner wall of its line. The elongated portion of the pear-shaped impact site extends toward the product movement of the tee line, approaching the welded pipe to the tee for a distance of 0.3 m. The maximum concentration of the discrete phase on the contours of the tee line is 0.21 kg/s.

Based on the fields of erosion wear on the tee contours (Figs. 5b,c), the place of the most intense erosion wear of the tee is located in the place of the most intense impact of liquid and solid particles to the wall of the tee line and also has a pear-shaped form of the same size. The angle of impact of discrete particles at the place of the most intense erosion wear of the tee is maximum and is about (Fig. 4a). The maximum rate of tee erosion wear is $2.37 \cdot 10^{-8}$ kg/m$^2 \cdot$s. At such an erosion rate, the wall is thinned with the speed 0.094 mm per year. The validity of simulation of the erosion wear was proved experimentally [23]. Also the results obtained are valid with those obtained in [15, 16].

For a better understanding of the processes of the tee erosion wear, it is advisable to read the results of the study of the dynamics of the movement of flows by the shaped components of the compressor station [24-26] of the pipeline and their erosion wear [27].

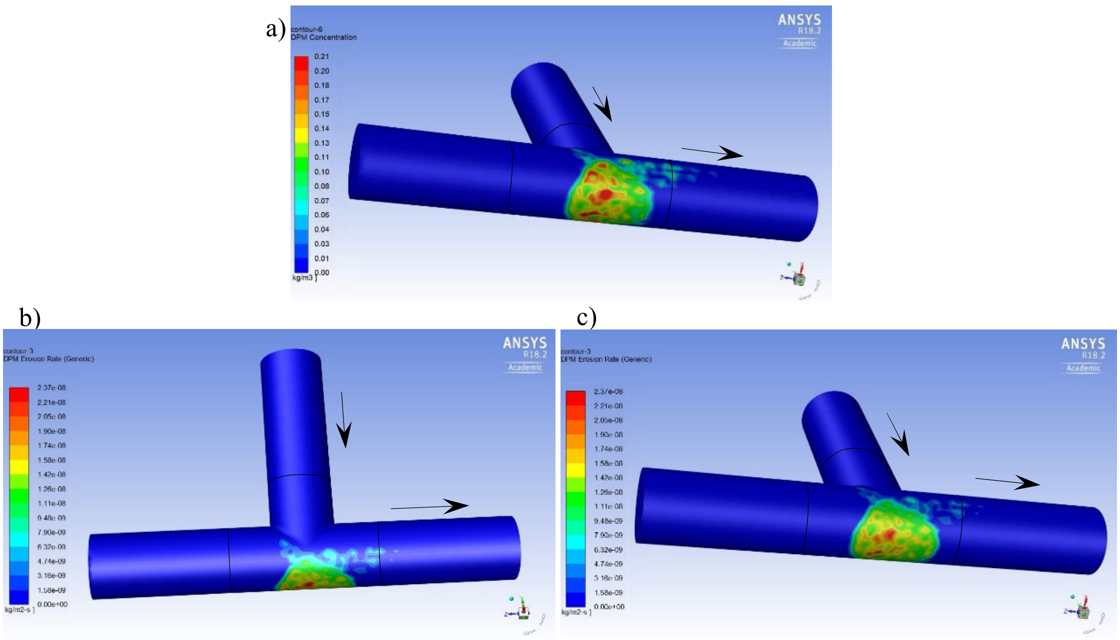

Fig. 5. Results of simulation of the tee erosion wear, in which gas is moved by the tee outlet and from the outlet the entire flow is directed to one side of the tee line; a) fields of concentration of discrete phase on contours; b), c) fields of the velocity of erosion wear on contours

Tees' erosion wear occurs at a certain rate and the shape of erosion defects changes over time. The magnitude of erosion defects is increasing all the time. To account the influence of the shape of the inner surface of the tee wall at the site of erosion wear and the increase for wear on its stress state, the geometric models of tees with wall erosion defects, which will occur at certain intervals of time of operation of the pipeline, should be developed. The tee wall at the site of erosion wear should "move" in accordance with the speed of erosion wear. Therefore, based on the field of erosion wear rate on the tee contours (Fig. 5c), the values of the erosion rate of the tee at many points were determined and the wall thinning rate at these points was calculated as the ratio of the erosion wear rate to the metal density. Based on the velocity of wall thinning, values of the tee wall thinning at many points in the period of 68, 76, 80 and 84 years of the gas pipeline operation was determined; geometric models of tees with complex three-dimensional geometric shape of erosion defects were developed in the system of automated design and AutoCad drawing (Fig. 6). The maximum depth of erosion defects of the tee line wall opposite the outlet (Fig. 6), after 68 years of operation was 6.4 mm, 76 years – 7.1 mm, 80 years – 7.5 mm and 84 years – 7.9 mm.

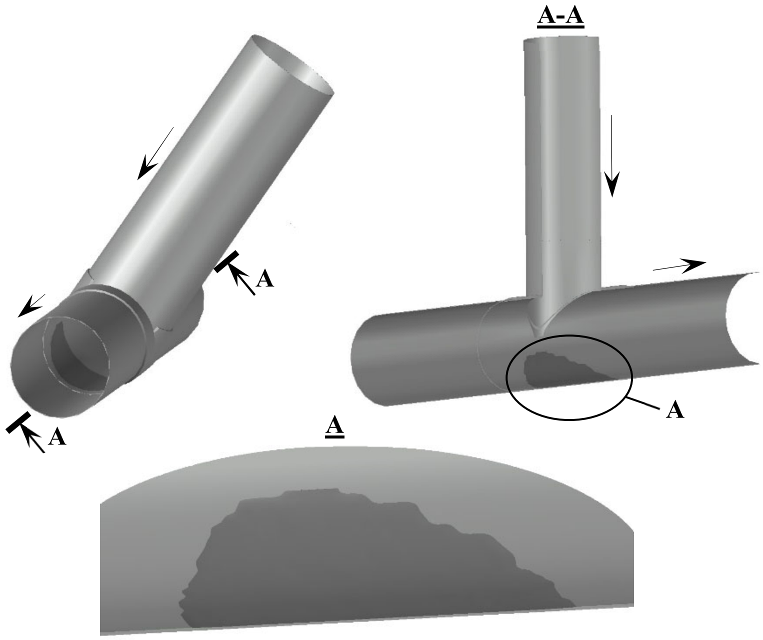

Fig. 6. Geometric model of tee with erosion wear

4. Temperature difference simulation

Temperature effects cause longitudinal stresses in the pipeline wall. The magnitude of the temperature stress depends on the calculated temperature difference, which is taken to be equal to the difference between the maximum or minimum possible temperature of the pipeline walls during operation and the minimum or maximum temperature of the pipe walls, which fixes the pipeline design scheme (after laying the pipeline). For underground pipelines, the temperature difference is assumed to be ±40ºC.

The temperature difference simulation in the tee walls was performed in the Transient Thermal calculation module. The characteristics of the tube steel, the tee wall temperature at the initial time (+20ºC) and the tee wall temperature at the end time (–20ºC) were specified.

5. Stress state simulation

The simulation of the stress state of the tee was performed in the ANSYS Static Structural mechanical module. This module imported a three-dimensional geometry of the tee wall. In the database of materials of the program complex, pipe steel of the strength class K60 (limit of strength $\sigma_B = 589$ MPa, limit of yield of $\sigma_{0.2} = 441$ MPa) was specified. To consider the influence of the uneven pressure distribution in the inner cavity of the tee (Figs. 3c,d) on its stress state, the results of the calculation of the pressure distribution on the inner wall of the tee from the ANSYS Fluent hydrodynamic module were imported into the ANSYS Static Structural mechanical module. An integrated Mora-Coulomb model of elastic-plastic material simulated the connection of the pipeline to the soil. Free-fall acceleration was applied to account for its own weight. To take into account the effect of the temperature difference on the tee stress state, the results of the simulation of the temperature difference in the tee walls from the Transient Thermal module were imported into the ANSYS Static Structural mechanical module of the software complex. Based on the action of only internal pressure (Fig. 7a) and the action of internal pressure and temperature difference (Fig. 7b), the results of simulation of the stress state of the tee with reinforcing linings on the line and the outlet were visualized by developing three-dimensional colour fields of equivalent stresses according to Mises. According to the obtained results, an uneven distribution of equivalent stresses occurs in the tee wall.

The maximum equivalent stresses in the tee are concentrated at the point of connection of the outlet to the tee line, where there is no reinforcing lining on the tee outlet (the highest value is 281.1 MPa in case of internal pressure only and 306.8 MPa in case of internal pressure and temperature difference). Therefore, a minimum margin of tee strength is observed at the point of connection of the outlet to the tee line, where there is no reinforcing lining on the tee outlet.

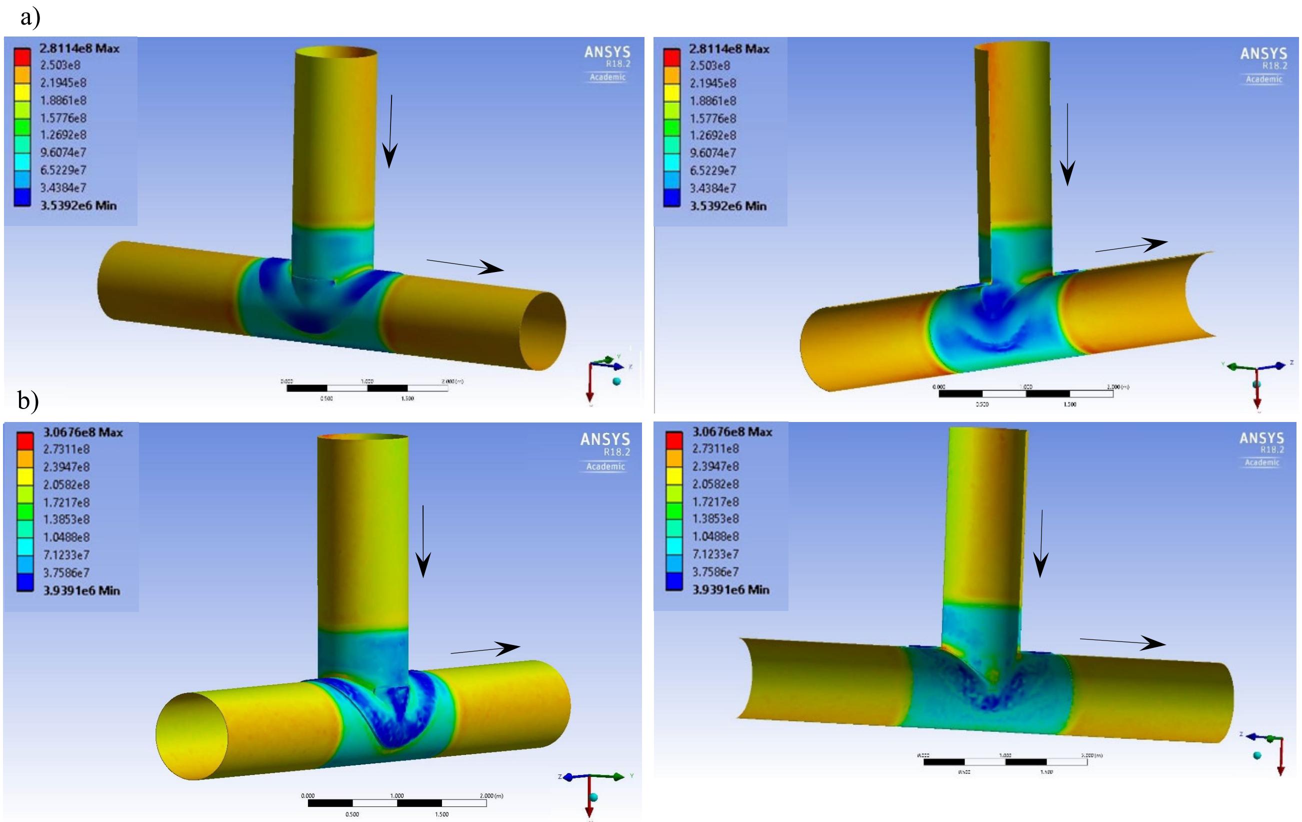

Fig. 7. Distribution of equivalent Mises stresses in the tee, in which the tee outlet moves gas, and from the outlet, the entire flow is directed to one side of the tee line; a) from the action of internal pressure; b) from the action of internal pressure and temperature difference

The simulation of the stress state of the tee with erosion wear of the wall was performed similarly to the above simulation of the stress-strain state of the tee without defects. For such simulation, the developed in AutoCad geometric models of tees with a complex three-dimensional geometric form of wall erosion defects (Fig. 6) were imported into the hydro-gas-dynamic module ANSYS Fluent to simulate the movement of gas flow; into the module of calculation of thermal processes Transient Thermal to simulate the temperature change in the tee wall; into the ANSYS Static Structural mechanical module to simulate their stress state. Based on the action of only internal pressure (Figs. 8a,b,c,d) and the action of internal pressure and temperature difference (Figs. 8a,b,c,d) for different magnitude of wall erosion defects, the results of simulation of the stress state of tees with wall erosive wear were visualized by developing three-dimensional colour fields of equivalent Mises stresses on the contours of the tee from.

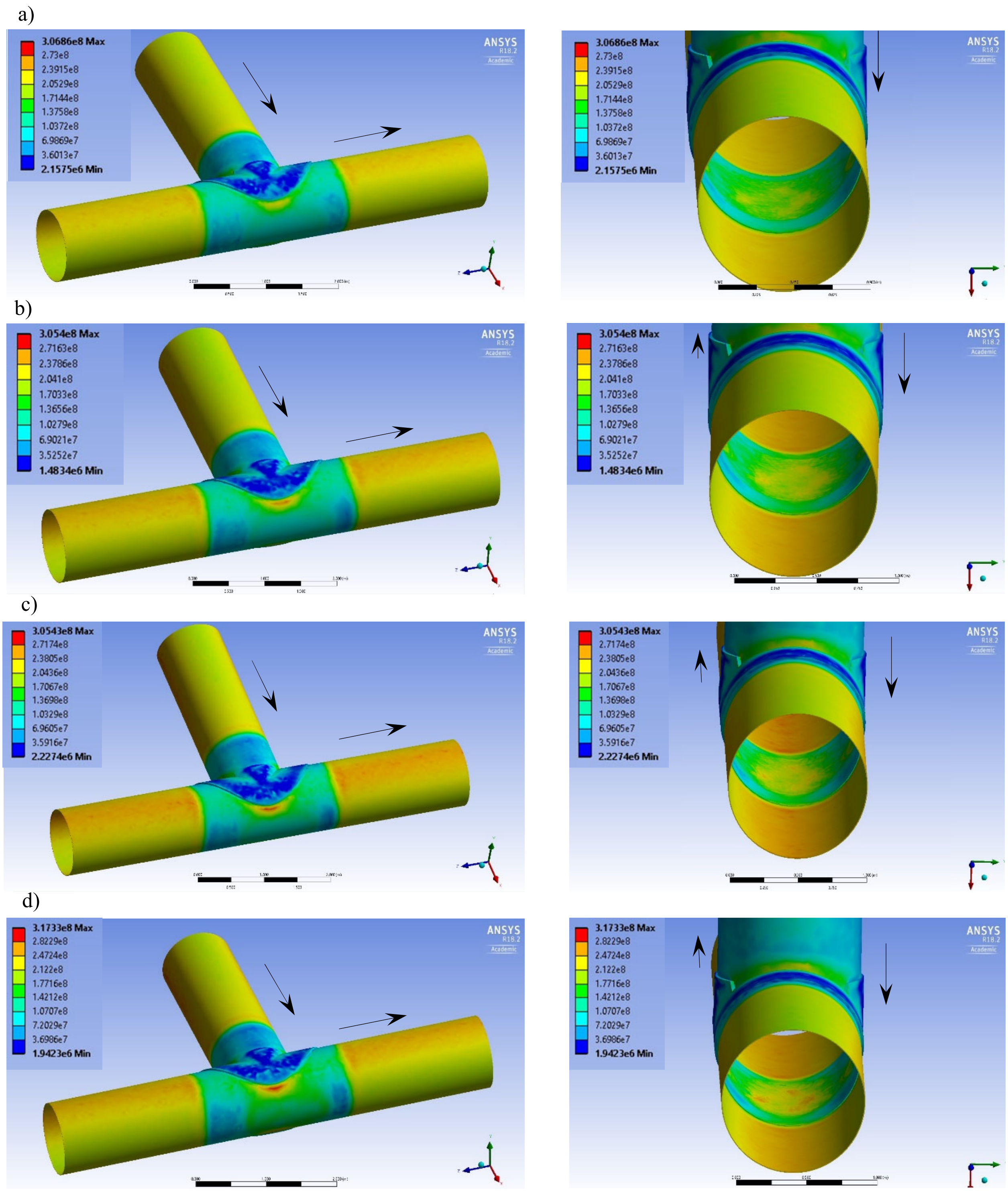

Fig. 8. Mises equivalent stress distribution in the tee with wall erosion wear due to internal pressure and temperature difference; a) maximum depth of wall erosion defect 6.4 mm; b) maximum depth of wall erosion defect 7.1 mm; c) maximum depth of wall erosion defect 7.5 mm; d) maximum depth of wall erosion defect 7.9 mm

According to the results of simulation of the stress state of tees with wall erosive wear (Fig. 8), erosion wear of the pipe welded to the tee outlets (Fig. 6) leads to a change in its stress state (Fig. 8). According to the results of the simulation of the stress state of tees with wall erosive wear (Fig. 8), erosion defects of the wall of the tee line opposite the outlet (Fig. 5) lead to a change in the stress state of the tee. Based on the simulation results, up to 62 years of tee operation, the equivalent stresses at the site of erosion wear of the tee are the same as they were at the beginning of its erosion wear. In the case of further tee operation, the equivalent stresses at the site of its erosion defect begin to increase. The maximum equivalent stresses at the site of the erosion defect of the tee are concentrated in the deepest places of the erosion defect on the inside of the tee line. Due to the action of only internal pressure, after 68 years of operation of the tee, they are 180 MPa, after 76 years – 198 MPa, after 80 years – 218 MPa, after 84 years – 249 MPa. Due to the effect of internal pressure and temperature difference, the maximum equivalent stresses at the site of erosion defect of the tee after 68 years of operation of the tee are 201 MPa, after 76 years 222 MPa, after 80 years – 244 MPa, and after 84 years – 272 MPa. From the outside of the tee line, at the site of erosion defect, there is a slight increase of equivalent stresses.

Based on the simulation results, the maximum equivalent Mises stresses in the tee are caused by the erosion wear of the wall of its line due to the action of internal pressure only, and due to the action of internal pressure and temperature difference (Fig. 8) concentrated on the outside of the tee line near the reinforcing lining on the tee line. The zone of maximum equivalent stresses has an arcuate shape and bends around the lower part of the reinforcing lining placed on the tee line on both sides of the tee line. The concentration of stresses in this place is stipulated by the increase of deformations of the non-reinforced part of the tee line, which is caused by the decrease of the wall thickness of the tee line at the site of erosion wear.

As the size of the erosion defect increases, the stresses on the external side of the tee line near the reinforcing lining located on its line increase as well (Fig. 8). The magnitudes of the maximum equivalent stresses in this place, which are caused by the erosion defect of the wall of the tee line due to the action of only internal pressure and due to the action of internal pressure and temperature difference, are given in Table. 2.

Table 2.
Maximum equivalent stresses in the tee line due to the erosion defect of its wall

№	Maximum depth of erosion defect, mm	Maximum equivalent voltages, MPa	
		to the action of internal pressure	due to the action of internal pressure and temperature difference
1	6.4	215	231
2	7.1	236	255
3	7.5	256	281
4	7.9	287	317

5.1. Permissible stresses

$$[\sigma]=\frac{m}{0,9k_n}R_2^n=\frac{0,6}{0,9\cdot 1,05}\cdot 441=280\ MPa, \quad (6)$$

if m – coefficient of pipeline operation conditions, which is assumed equal to 0.6 for tees and pipelines located in the territory of the compressor stations of the main gas pipelines considered the highest category of sections of the pipeline; R_2^n – normative resistance of the pipe material to the tensile (compression), which is equal to the yield strength $\sigma_{0.2}$ of the pipe steel of the strength class K60; k_n – coefficient of reliability for the purpose of the pipeline, which is assumed equal to 1.05 for a gas pipeline with an external diameter of 1420 mm at an operation pressure 4.93 MPa.

The permissible wall thickness at the place of erosion of the tee line will be equal

$$[\delta]=\delta_n-[h], \quad (7)$$

if δ_n – nominal thickness of the tee line wall.

For the model under consideration, $[\delta_1]=12.5\ mm$ only under internal pressure and $[\delta_2]=12.2\ mm$ under internal pressure and temperature difference. To predict the residual life of tees with wall erosive wear, to estimate the term of their safe operation, the actual maximum depth of erosion defect of the tee line wall should be determine by the research results. The wall of the tee line opposite the outlet, where the erosion wear occurs (Fig. 9), should be examined. Then, based on the above method, the value of the permissible maximum depth of erosion defect of the tee line wall should be determined.

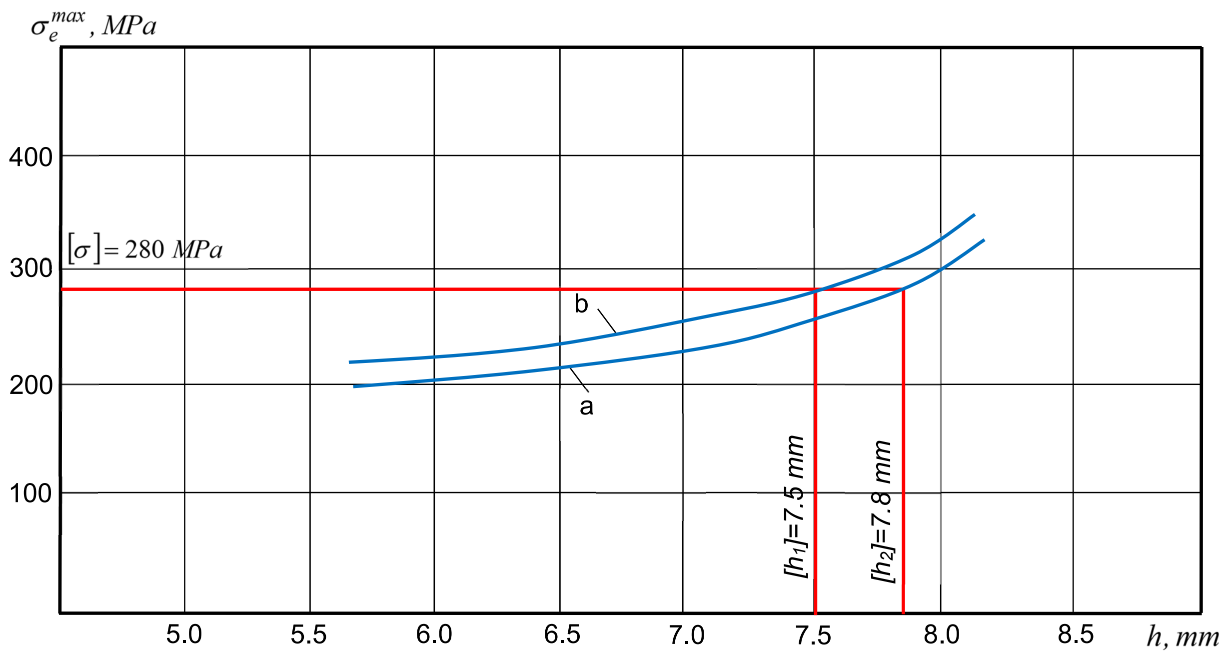

Fig. 9. Dependence of the maximum equivalent stresses in the tee line wall due to its erosion wear on the maximum depth of erosion defect of the tee line wall; a) due to the action of internal pressure; b) due to the action of internal pressure and temperature difference

Residual resource of the tee with erosion-worn wall is equal

$$\tau_r = \frac{[h] - h_f}{\upsilon_r}, \quad (8)$$

if h_f – actual maximum depth of erosion defect of the tee line wall, which is determined during the examination; υ_r – maximum rate of thinning the tee line wall.

The maximum rate of thinning the wall welded to the pipe tee is equal to the ratio of the maximum erosion rate of the wall, which is determined with accordance to the fields of the erosion rate of wear (Fig. 5b,c), to the density of the metal pipe.

6. Conclusions

According to the results of CFD simulation of gas-dynamic processes occurring in the inner cavity of the tee, in which gas is moved by the tee outlet and then is directed to one side of the tee line, the place of impact of condensate droplets and solids to the tee line walls and the most intense place the tee line wear are found to be pear-shaped and located opposite the tee outlet. Geometric models of tees with complex three-dimensional geometric form of erosion defects of the wall are developed.

Based on the gas-dynamic processes occurring in the internal cavity of the main gas pipelines' tees, the complex three-dimensional geometric form of wall erosion defects, and temperature difference, the technique of three-dimensional simulation of stress state of the main gas pipelines' tees is developed. The maximum Mises equivalent stresses in the tee caused by the erosion wear of its line wall are found to concentrate on the outside of the tee line near the reinforcing lining located on the tee line. The zone of maximum equivalent stresses has an arcuate shape and bends around the lower part of the reinforcing lining placed on the tee line on both sides of the tee line.

Moreover, the erosion reduction of the wall thickness of the tee line from 20 mm to 12.5 mm under the action of internal pressure only and from 20 mm to 12.2 mm under the action of internal pressure and temperature difference does not lead to loss of overall strength.

The practical result of the performed researches is the determined places of erosion wear of the tees of gas pipelines, which makes it possible to perform external ultrasonic diagnostics of such tees more qualitatively. The developed technique allows to estimate durability and to determine the residual life of tees with erosive wear of the wall in order to ensure their reliability, to perform ranking of such defects according to the degree of danger, to determine which of them are critical and in need of immediate repair. Also, the obtained results allow a more reasonable approach to determining the periodicity of inspection of tees of gas pipelines and extension of their life, to carry out studies of the influence of increasing the size of erosion defects on the stress-strain state of tees.

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