CFD моделюванням досліджено турбулентні потоки в рівнопрохідних трійниках газопроводів, у яких з магістралі газовий потік повністю перетікає у відвід. Дослідження виконано для трійників різної геометрії – штампованих з різним радіусом заокруглення переходу від відводу до магістралі трійника та зварних, де з'єднання магістралі і відводу виконується під прямим кутом. Зовнішній діаметр трійників змінювався від 219 мм до 1420 мм, радіус заокруглення переходу від відводу до магістралі трійника від мінімально допустимого до максимально можливого, тиск у газопроводі в місці розміщення трійника від 3 МПа до 7 МПа.

Математична модель базується на розв'язанні рівнянь Нав'є-Стокса, нерозривності і перенесення енергії, замкнених двопараметричною високорейнольдсовою k–ε моделлю турбулентності Лаундера-Шарма. Для опису процесів, які відбуваються біля стінки, застосовано пристінну функцію.

Встановлено, що заокруглення переходу від відводу до магістралі трійників, збільшення радіуса заокруглення призводить до послаблення інтенсивності відривання потоку в місці заокруглення, зменшення кінетичної енергії турбулентності в місцях рециркуляції. Поле швидкості газового потоку після його перетікання з магістралі у відвід трійника стає більш рівномірним. Все це сильно впливає на величину втрат гідравлічної енергії газового потоку в трійниках. При цьому найбільші втрати енергії спостерігались у трійниках, розміщених у місцях найменших тисків у газопровідній системі. Аналіз результатів показав, що якщо відношення радіуса заокруглення з'єднання магістралі та відводу трійника до його зовнішнього діаметра більше за 0,25, то вплив такого трійника на енерговитратність газопровідної системи є мінімальним. Розраховані коефіцієнти місцевих опорів рівнопрохідних трійників газопроводів та отримане рівняння для їх розрахунку будуть корисними для фахівців, які проектують газопровідні системи

Ключові слова: втрати тиску, гідродинамічний напір, коефіцієнт місцевого опору, радіус заокруглення, рівняння Нав'є-Стокса, турбулентний потік

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INVESTIGATION OF THE INFLUENCE OF THE GAS PIPELINE TEE GEOMETRY ON HYDRAULIC ENERGY LOSS OF GAS PIPELINE SYSTEMS

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1. Introduction

In pipelines of any purpose, there is a loss of hydrodynamic flow energy or pressure loss to overcome resistance caused by pipe wall friction and local resistance. The amount of energy loss depends on the pipe material, the product transported, the geometry of local resistance. In order to keep the product moving in the pipeline, it is necessary to replenish the lost energy with pumps, compressors, etc.

Modern pipeline systems have a large variety of local resistances, such as tees, branches (hot bends), reducers, and the like. These shaped elements are made by various manufacturers and have varied geometry.

There are many complex pipeline systems containing a large number of tees, branches, reducers, and energy loss in the shaped elements of such systems is quite significant and determining in the overall hydraulic resistance of the system.

The scale of energy loss in tees is not yet well understood and documented, as it depends on many factors. Such factors are tee geometry, tee gas flow patterns, wall roughness, operating parameters, and so on. In addition, gas flows in tees are very complex and three-dimensional and are not available for any simplified theoretical analysis, so they are studied experimentally, which is impossible in the conditions of gas pipelines (especially main), or by numerical modeling.

Today's energy efficiency requirements call for many aspects and issues to be addressed in the design and reconstruction of various pipeline systems. Therefore, research on the energy loss of gas flows in shaped elements of pipelines, improvement of their design in order to reduce hydraulic resistance is an urgent task.

2. Literature review and problem statement

Investigations of gas-fluid flow energy loss in shaped elements of pipeline systems of various purposes began in the early 1960s. Such studies were carried out experimentally mainly in laboratory conditions, and their results were pressure (energy) loss factors for many shaped elements and pipeline valves, which are given in specialized directories [1].

But there are still unresolved issues of flow energy loss in gas pipeline systems, especially main. The reason for this is the impossibility to perform such experimental studies in real conditions of gas pipelines, geometry specifics of shaped elements of gas pipelines. Such problems can be solved in modern CFD simulation software. In this way, the studies of energy loss of gas-liquid flows in shaped elements of various pipeline systems were performed in [2–7]. In [2], convergence and divergence of fluid flows in tees with different angles between the main line and the branch are investigated. The results of CFD simulation are visualized by plotting pressure and flow fields and compared to experimental data. The results obtained indicate a significant hydraulic energy loss in tees, where the angle between the main line and the branch is 90°. Reducing the angle between the branch and the main line can significantly reduce this loss.

In [3, 4] investigated the confluence of fluid flows in tees with a ratio of the main line and branch area equal to 1 and 4. Local resistance coefficients were determined for different ratios between the fluid flow through the main line outlet and the branch. The simulation results show that the increase in local resistance coefficient increased total energy loss due to recirculation and strong flow curvature. The value of the local resistance coefficient for the branch was higher than for the main line due to repeated flow recirculation. The influence of the angle between the main line and the branch on the dynamics of compressed air flow in the tee is examined in [5]. The minimum pressure drop in the tee was observed when the angle between the main line and the branch was 46°. Similar studies were performed in [6], but the transported substance was a lubricant, and the simulation results were visualized by constructing velocity fields. The branch was modeled both straight and bent. [7] investigated the structure of the gas flow in the tees of the piping of the main gas pipeline compressor station. The places of confusor and difusor effects, vortices, reverse gas movement, gas flow separation from the wall of the studied tees were revealed. All these phenomena affect energy loss in tees.

However, all studies mainly deal with the convergence and divergence of flows in tees. Such results are incomplete because they do not cover all possible combinations of flow directions in tees that occur in various pipeline systems, including gas pipelines. The effect of tee geometry on hydraulic energy loss of pipeline systems has not been established for the non-covered combinations of flow directions.

Therefore, it is advisable to study the energy loss in gas pipeline tees for all possible combinations of flow directions by CFD simulation.

3. The aim and objectives of the study

The aim of the work is to study the influence of the geometry of equal gas pipeline tees, in which the flow from the main line completely moves to the branch, on hydraulic energy loss in them.

To achieve the aim, the following objectives were set:

– to investigate the features of gas pipeline tee geometry;

– to investigate patterns of pressure redistribution, flow rate and turbulence kinetic energy in tees of different geometry;

– to determine local resistance coefficients of tees, hydrodynamic pressure loss in them;

– to investigate the dependence of local resistance coefficients and pressure loss in tees on tee geometry and gas flow parameters.

4. Investigation of the features of gas pipeline tee geometry

In practice, the tees are quite common, in which the flow moves in the main line from which it flows completely to the branch. Such tees are contained in the piping of compressor stations of main gas pipelines, underground gas storages, gas distribution stations and the like. In addition, at the point of gas pipeline interconnectors, where the entire flow from one line moves to another, in places of multi-line underwater pipelines, where the entire flow is transported by standby lines, etc. For such a flow pattern in tees for today there is little information about energy loss in them.

According to the manufacturing method, there are hot-stamped, stamped-weld (with hot-stamped branches), weld without special reinforcing elements and weld tees, reinforced with plates.

In weld tees, the main line and branch connection is made at right angles. In hot-stamped tees, stamped tees, the transition from the branch to the main line is bent. According to the requirements of SNiP 2.05.06 [8], the bending radius R must be at least $0.1{\cdot}D_{\text{Out}.b}$, where $D_{\text{Out}.b}$ is the outer diameter of the branch.

5. Method for the study of gas-dynamic processes in tees

Bending of the main line and branch connection affects the gas flow dynamics and hydraulic flow energy loss in tees. The magnitude of this impact has not been sufficiently studied.

In order to investigate the effect of the magnitude of tee bending at the point of the main line and branch connection on hydraulic energy loss of pipeline systems, deep knowledge of the relationship between the tee flow geometry, pressure field and flow kinematics is required. This information will help to understand the mechanisms of pressure loss.

Flows in tees are very complex and three-dimensional, so they must be studied experimentally or by hydraulic analysis through CFD simulation.

In real conditions of gas pipelines, especially main, such experiments cannot be performed because:

– it is impossible to visualize the gas flow in a steel gas pipeline;

– it is impossible to determine the exact velocity, pressure at any point of 3D flow in the tee;

– gas pipelines are under high pressure and explosive.

CFD simulation gives an understanding of the dynamics of gas flows in tees, allows better seeing of the flow in the tee and studying the pressure loss, turbulence, kinetic energy and more.

6. Mathematical model of gas flows in tees

Three-dimensional CFD simulation of gas flows in tees is performed by numerical solution of the Navier-Stokes (1) and continuity (2) equations

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

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0, \tag{2}$$

where x_i, x_j are coordinates; t is time; u_i, u_j are velocity components; ρ is gas density; μ is the molecular dynamic viscosity of gas; f_i is the term taking into account the action of mass forces; p is pressure [9].

To describe turbulence, the standard, one of the most common k–ε (k – turbulence kinetic energy, ε – dissipation rate of turbulence kinetic energy) turbulence model was used in CFD simulation, which involves the solution of the following equations:

– equation of turbulence kinetic energy k

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j k\right)=$$

$$=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right)+\mu_t G-\rho\varepsilon; \tag{3}$$

– equation of dissipation rate of turbulence kinetic energy ε

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\varepsilon\right)=$$

$$\aleph\aleph\aleph\frac{\partial}{\partial x_j}\left(\left(\quad \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right)\quad C_1\frac{\varepsilon}{k}\quad {}_tG\quad C_2\ \frac{\varepsilon^2}{k}, \tag{4}$$

where u is the gas flow rate; μ_t is the turbulence dynamic viscosity of gas; σ_k is the coefficient equal to one; G is the generation of turbulence kinetic energy due to an average velocity gradient; σ_ε is the coefficient equal to σ_ε=1.3; C_1 is the coefficient equal to C_1=1.44; C_2 is the coefficient equal to C_2=1.92 [9].

Generation of turbulence kinetic energy

$$G=-\rho u_i u_j\frac{\partial u_j}{\partial x_i}. \tag{5}$$

In this study, three-dimensional CFD simulation was performed in the ANSYS Fluent 2019 R2 Academic software using the finite volume method.

7. Geometric modeling of the inner cavity of gas pipeline tees

To study gas-dynamic processes in tees, it is necessary to take into account the significant influence of their geometry on the flow formation. The three-dimensional models of the inner cavity of the tees corresponding to TU U 27.2-05747991-001 [10] and OST 102-61 identical to industrial samples are outlined [11]. Five different outer diameters of equal tees were chosen – 219 mm, 530 mm, 1,020 mm and 1,420 mm. The wall thickness of each tee was calculated depending on the pressure at its location and its inner diameter was determined. The tees were drawn with adjacent pipe sections, the geometric dimensions of which correspond to the specifications.

To investigate the effect of tee geometry on flow parameters, hydraulic energy loss of pipeline systems, a geometric model of the inner cavity for each of the selected tee diameters was drawn. The inner cavity of the weld tee was drawn, in which the main line and branch connection was made at right angles (Fig. 1, *a*), and the inner cavity of the stamped tee, in which the transition from the branch to the main line was bent. Since the bending radius of the stamped tee R should be at least $0.1{\cdot}D_{\mathrm{Out.b}}$, five models of the inner cavity with a bending radius varying from $0.1{\cdot}D_{\mathrm{Out.b}}$ to the maximum possible were drawn for each of the five different diameters of such tees. Examples of geometric models of such stamped tees are shown in Fig. 1, *b*–*d*.

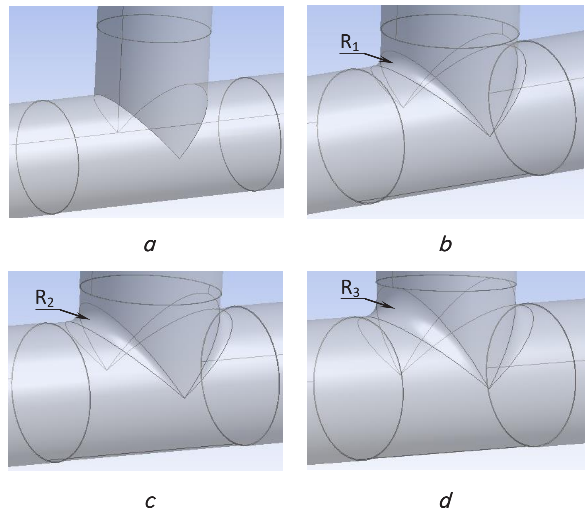


Fig. 1. Geometric models of tee inner cavity: *a* – weld; *b*–*d* – stamped

The working media modeled by tees were natural gas, which was taken as a compressed medium. Steel was used as the material of the tee wall. The equivalent roughness coefficient of the tees and adjacent pipe sections was set to 0.03 mm.

Boundary conditions were specified in the ANSYS Fluent preprocessor. Because the tees were studied, in which the flow from the main line completely moves to the branch, the mass flow rate was set at the main line inlet, and pressure – at the branch outlet. The mass flow rate at the main line inlet depended on the tee diameter. For the tee outer diameter of 219 mm, the mass flow rate was 17 kg/s, for 530 mm – 102 kg/s, for 1,020 mm – 373 kg/s and for 1,420 mm – 698 kg/s.

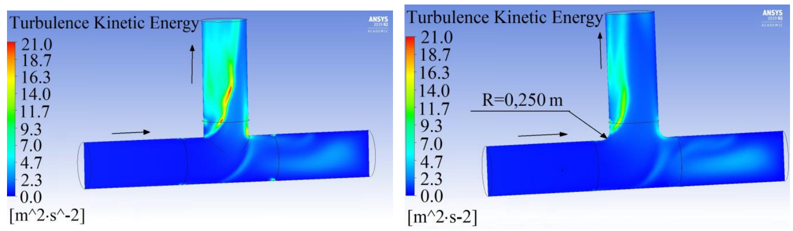
As the pressure in the pipeline decreases, and the tee can be installed anywhere along the route, the pressure at the branch outlet varies from 3 MPa to 7 MPa in 1 MPa increments. A separate simulation was performed for each pressure value.

Also, the natural gas temperature at the main line inlet of 297 K was set. At the main line inlet and branch outlet, turbulence intensity of 5 % (fully turbulent flow) and hydraulic diameter were set. The hydraulic diameter was assumed to be equal to the inner diameter of the pipeline.

8. Study of redistribution patterns of pressure, flow rate and turbulence kinetic energy in tees

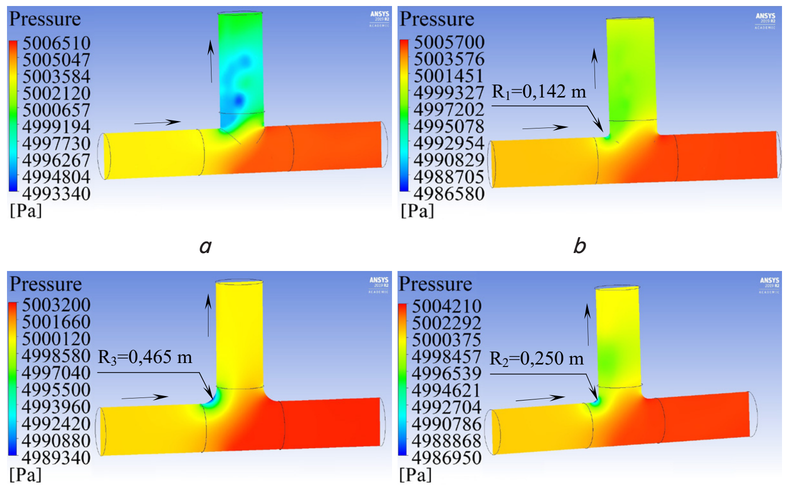
The gas flow rate and pressure loss in the tees are two indicators that can be used to estimate hydraulic energy loss in tees. Therefore, the simulation results were visualized in the postprocessors of ANSYS Fluent and ANSYS CFX software systems by constructing the velocity field and pressure field in the longitudinal sections of the tees. For example, consider weld and stamped equal tees with an outer diameter of 1,420 mm, tee outlet pressure of 5 MPa, bending radius of the transition from the branch to the main line of the stamped tees was 0.142 m, 0.250 m and 0.465 m. The velocity fields in the longitudinal sections of these tees are shown in Fig. 2, turbulence kinetic energy fields in Fig. 3, and pressure fields in Fig. 4.

The change in the direction of the gas flow in the tee, due to its movement from the main line to the branch, leads to a complex redistribution of the flow rate. A rather intense recirculation motion is formed in the branch, caused by the flow separation from the wall at the point of the main line and branch connection (Fig. 2). This behavior is due to the complex nature of the pulse redistribution process in the tee. Turbulent vortices with high kinetic energy are formed at the recirculation point (Fig. 3). A detailed analysis of flow velocity fields (Fig. 3) and turbulence kinetic energy fields (Fig. 3) shows a significant dependence of gas-dynamic processes in the branch on tee geometry. That is, on how the main line and branch connection (at right angles or bent) is made, on the bending radius of the connection. Bending of the main line and branch connection, increasing the bending radius lead to a decrease in the intensity of flow separation at the bending point, a decrease in the recirculation area and intensity (Fig. 2) and a decrease in the vortex formation intensity and turbulence kinetic energy in the recirculation area (Fig. 4).



a *b*

Fig. 3. Turbulence kinetic energy fields in longitudinal sections of tees: *a* — weld; *b* — stamped

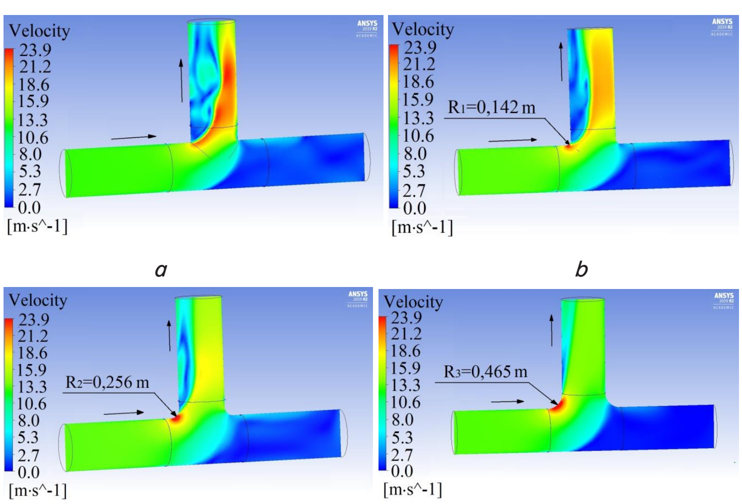


a *b*

c *d*

Fig. 4. Pressure fields in longitudinal sections of tees: *a* — weld; *b*–*d* — stamped

The change in the flow direction in the tees, its movement to the branch result in the formation of a complex pressure field, pressure drop (Fig. 4). The reasons for this are the change in the flow pulse due to friction and geometry of the tees. The flow energy loss occurs due to frictional heating and intense flow turbulence in the recirculation area.



a *b*

c *d*

Fig. 2. Velocity fields in longitudinal sections of tees: *a* — weld; *b*–*d* — stamped

Bending of the main line and branch connection, increase in the bending radius are the key factors affecting the magnitude of pressure drop in the tee and reducing its hydraulic resistance, and therefore reducing the loss of hydraulic flow energy in the tee. As the bending radius increases, the flow separation rate at the bending point decreases, recirculation area and intensity decrease, turbulence kinetic energy in the recirculation area decreases, all this together leads to a decrease in the magnitude of pressure drop in the tees. The greatest pressure drop in the weld tee occurs at the point of intense recirculation, where the gas flow turbulence is most intense (Fig. 4). Recirculation in the weld tee branch is the main cause of energy dissipation. Reduction of its magnitude and intensity with increasing bending radius of the main line and branch connection has a positive effect on the energy loss in the tee. Therefore, the pressure drop is no longer so significant in the stamped tees at the point of recirculation intensity, and its maximum can be observed at the bending point of the main line and branch connection where the gas flow rate is maximum.

The pressure drop in the tee can be determined by subtracting the pressure at the branch outlet from the pressure at the main line inlet. The greatest pressure drop occurs in the weld tee (Fig. 4, *a*) and is 4,100 Pa. The reason for this is that the main line and branch connection is made at right angles and there is a significant flow separation, which causes the most intense recirculation (Fig. 2, *a*). In stamped tees, the pressure drop is less than in the weld one and decreases with increasing bending radius of the main line and branch connection. So, if the bending radius is 0.142 m (Fig. 4, *b*), the pressure drop is 2,212 Pa, if 0.250 m (Fig. 4, *c*) – 950 Pa and if 0.465 m (Fig. 4, *d*) – 449 Pa. Therefore, as we can see, the minimum pressure drop occurs when the bending radius of the main line and branch connection is the maximum possible and 10 times less than the pressure drop in the weld tee.

9. Determination of local resistance coefficients of tees, hydrodynamic pressure loss in tees

Certain values of pressure drop in the tees allow finding energy losses in them. For this purpose, dimensionless local resistance coefficients ξ are usually calculated, also called energy loss coefficients (K factors). The energy loss coefficient is the ratio of the total energy loss in a given pipeline section to the kinetic energy in the accepted section. The overall local resistance (energy loss) coefficient is equal to

$$\xi = \frac{\Delta P_{tot}}{\rho V^2 / 2}, \tag{6}$$

where ΔP_{tot} is the total pressure loss in the given pipeline section (pressure drop in the tee); ρ is the gas density, depending on gas pipeline pressure and gas temperature; *V* is the gas flow velocity [1].

The exact value of the local resistance coefficient allows calculating the pressure (energy) loss in any tee by the formula

$$h_{l.r} = \xi \frac{V^2}{2g}, \tag{7}$$

where *g* is gravitational acceleration.

For tees in which the flow from the main line completely moves to the branch, there is little information on energy loss today, and there are no clearly defined local resistance coefficients.

By the pressure drop in each tee, local resistance coefficients ξ were calculated for different outer diameters of tees D_{out}, different pressures at the tee outlet *P* and different bending radii of the main line and branch connection *R*. For the weld tees, the bending radius was *R*=0. As a result, 100 values of local resistance coefficients were obtained (Table 1). Substituting the values of local resistance coefficients in (7), the value of pressure (energy) loss $h_{l.r}$ in each tee is calculated (Table 1). Also Table 1 shows the value of the average velocity at the tee outlet *V*, which is a component of (6) and (7), determined by CFD simulation.

Table 1

Local resistance coefficients ξ and pressure loss $h_{l.r}$ in equal tees with a bending radius of the main line and branch connection *R*

No.	*P*, MPa	*V*, m/s	ξ	$h_{l.r}$, m	ξ	$h_{l.r}$, m	ξ	$h_{l.r}$, m	ξ	$h_{l.r}$, m	ξ	$h_{l.r}$, m
D_{out}=1420 mm												
			R=0		*R*=142 mm		*R*=250 mm		*R*=358 mm		*R*=465 mm	
1	7	8.8	1.55	6.12	0.91	3.59	0.43	1.70	0.17	0.67	0.15	0.59
2	6	10.5	1.54	8.65	1.00	5.62	0.44	2.47	0.18	1.01	0.15	0.84
3	5	12.8	1.37	11.44	0.74	6.18	0.32	2.67	0.17	1.42	0.15	1.25
4	4	16.4	1.72	23.58	0.92	12.61	0.41	5.62	0.18	2.47	0.16	2.19
5	3	23.3	1.41	39.02	0.77	21.31	0.37	10.24	0.17	4.70	0.15	4.15
Average			1.52		0.87		0.39		0.17		0.15	
D_{out}=1020 mm												
			R=0		*R*=102 mm		*R*=193 mm		*R*=262 mm		*R*=351 mm	
6	7	8.6	1.49	5.62	0.78	2.94	0.29	1.09	0.16	0.60	0.15	0.57
7	6	10.3	1.50	8.11	0.79	4.27	0.29	1.57	0.16	0.87	0.15	0.81
8	5	12.6	1.53	12.38	0.85	6.88	0.34	2.75	0.19	1.54	0.16	1.30
9	4	16.1	1.52	20.08	0.80	10.57	0.32	4.23	0.18	2.38	0.16	2.11
10	3	21.9	1.51	36.91	0.81	19.80	0.30	7.33	0.17	4.16	0.15	3.67
Average			1.51		0.81		0.31		0.17		0.15	
D_{out}=529 mm												
			R=0		*R*=53 mm		*R*=95 mm		*R*=136 mm		*R*=178 mm	
11	7	8.8	1.59	6.28	0.84	3.32	0.34	1.34	0.15	0.59	0.13	0.51
12	6	10.4	1.43	7.88	0.74	4.08	0.28	1.54	0.12	0.66	0.11	0.61
13	5	12.8	1.50	12.53	0.79	6.60	0.30	2.51	0.15	1.25	0.12	1.00
14	4	16.3	1.48	20.04	0.77	10.43	0.29	3.93	0.14	1.90	0.12	1.63
15	3	22.3	1.54	39.03	0.82	20.78	0.32	8.11	0.15	3.80	0.13	3.30
Average			1.51		0.79		0.31		0.14		0.12	
D_{out}=219 mm												
			R=0		*R*=22 mm		*R*=40 mm		*R*=58 mm		*R*=74 mm	
16	7	8.5	1.41	5.19	0.70	2.58	0.25	0.92	0.11	0.41	0.10	0.37
17	6	10.2	1.62	8.59	0.81	4.30	0.27	1.43	0.13	0.69	0.12	0.64
18	5	12.5	1.71	13.62	0.87	6.93	0.28	2.23	0.14	1.12	0.12	0.96
19	4	15.9	1.49	19.20	0.74	9.54	0.26	3.35	0.11	1.42	0.10	1.29
20	3	21.6	1.29	30.68	0.60	14.27	0.22	5.23	0.08	1.90	0.08	1.90
Average			1.50		0.74		0.25		0.11		0.10	

If the energy losses in the tees are known, then it is possible to determine their effect on the energy loss of the entire pipeline system. It is also possible to determine the effect of tee geometry on energy loss.

10. Study of the dependence of energy loss on tee geometry, gas flow parameters

The local resistance coefficient of the tee is largely independent of the pressure at the tee location (Table 1). So for each tee diameter, the average value of the local resistance coefficient for different bending radii of the main line and branch connection is found. According to the results of the calculations given in Table 1, a graphical dependence of the average value of the local resistance coefficient ξ of the tee on the ratio of the bending radius of the main line and branch connection R to the tee outer diameter D_{out} is constructed for each tee diameter D_{out} (Fig. 5). The bending radius of the main line and branch connection has a significant influence on the local resistance coefficient of the tee. With an increasing bending radius, the local resistance coefficient of the tee decreases significantly. Moreover, with increasing ratio of the bending radius of the main line and branch connection R to the tee outer diameter D_{out} from 0 to 0.25, there is a significant decrease in the local resistance coefficient of the tee, and therefore the energy loss in it (Fig. 5). Further increase of the bending radius has practically no effect on the local resistance coefficient of the tee.

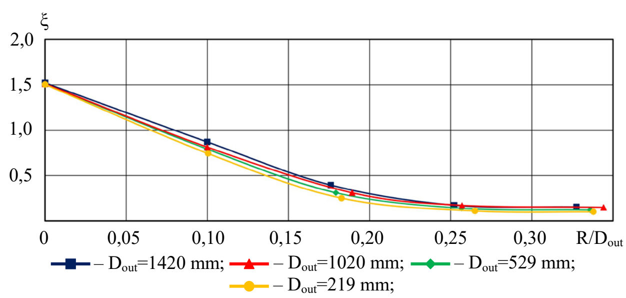


Fig. 5. Dependence of local resistance coefficients of the equal tee ξ on the ratio of the bending radius of the main line and branch connection *R* to the tee outer diameter D_{out}

Analyzing Fig. 5, it can be seen that there is a functional relationship between the local resistance coefficient of the equal tee and the ratio of the bending radius R to the tee outer diameter D_{out}. The least-squares method is used to determine the equation for calculating the local resistance coefficients of equal gas pipeline tees, in which the gas flow completely moves from the main line to the branch

$$\xi = 1{,}58e^{-7{,}7\frac{R}{D_{out}}}. \qquad (8)$$

By (8) it is possible to determine the local resistance coefficient of the equal tee of any diameter.

Also, according to the data in Table 1, graphical dependences of pressure (energy) loss in tees on the bending radius of the main line and branch connection at different pressure values at the tee location were constructed for different tee diameters (Fig. 6).

Energy losses in tees have a dependence on the bending radius similar to their local resistance coefficients (Fig. 6). Also, energy losses in the tees depend significantly on the pressure at the tee location. With a constant mass flow rate, energy loss decreases with increasing pressure, which is caused by a decreasing flow rate. The lower the pressure, the more its changes affect the energy loss in the tees.

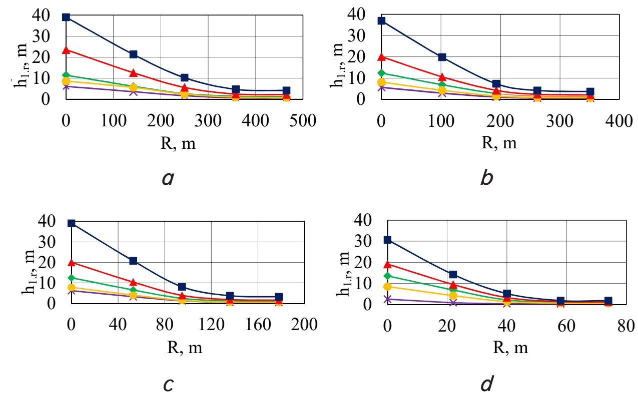


Fig. 6. Dependence of pressure (energy) loss in tees $h_{l.r}$, on the bending radius of the main line and branch connection *R*: *a* – D_{out}=1,420 mm; *b* – D_{out}=1,020 mm; *c* – D_{out}=529 mm; *d* – D_{out}=219 mm; *e* – D_{out}=89 mm; – *P*=7 MPa; – *P*=6 MPa; – *P*=5 MPa; – *P*=4 MPa; – *P*=3 MPa

11. Discussion of the results of studies of the influence of gas pipeline tee geometry on hydraulic energy loss of gas pipeline systems

Gas pipeline systems have a large number of tees. Such tees differ in manufacturing method, inner cavity geometry. The studies showed that the geometry of the inner cavity of equal tees, in which the gas flow from the main line completely moves to the branch, namely the bending radius of the main line and branch connection, has the most significant effect on the energy loss in the tees. As the bending radius increases, the local resistance coefficient of the tee decreases significantly (Table 1). Moreover, if the ratio of the bending radius of the main line and branch connection R to the tee outer diameter D_{out} is from 0 to 0.25, there is a significant decrease in the local resistance coefficient of the tee (Fig. 5). Further increase of the bending radius has practically no effect on the local resistance coefficient of the tee. Such patterns are explained by the essential dependence of gas-dynamic processes in the branch on tee geometry. Bending of the main line and branch connection, bending radius increase lead to a decrease in the area and intensity of recirculation in the branch (Fig. 2) and a decrease in the vortex formation intensity and turbulence kinetic energy in the recirculation area (Fig. 3). With large bending radii, the gas flow in the branch is stabilized and the magnitude of bending does not significantly affect the energy loss in the tee.

The CFD simulation made it possible not only to determine the energy loss in the tees, but also to understand the physical picture of gas flows, which is an absolute advantage of this method over the experimental one.

The results of these studies, the obtained equation for calculating the local resistance coefficients of tees (8) apply only to equal gas pipeline tees in which the gas flow from the main line completely moves to the branch.

The disadvantage of the studies is a large amount of time it takes to perform CFD simulations (150 three-dimensional CFD simulations were performed, each lasting at least 30 min).

The direction of further research is to perform CFD analysis of gas flows in unequal tees with changing the branch diameter.

12. Conclusions

1. In equal tees of gas pipelines, as a result of complete movement of the gas flow to the branch, the flow is separated from the wall, the flow field in the branch changes dramatically – recirculation and strong turbulent vortices with high kinetic energy occur. So, there is a significant drop in pressure and loss of energy. The results of CFD simulations showed that the bending of the transition from the branch to the main line, the increase in the bending radius strongly affect the dynamics of the gas flow in the tee. There is a decrease in the rate of flow separation at the bending point, decrease of the area and intensity of recirculation and decrease of turbulence kinetic energy in the recirculation area, the flow velocity field after movement from the main line to the branch becomes more uniform.

2. Based on the study of the physical picture of gas flows in tees, patterns of changes in local resistance coefficients and pressure loss in tees, it is determined that the bending radius of the transition from the branch to the main line determines the amount of energy loss in tees. The greatest energy losses were observed in the tees located at the lowest pressure points in the pipeline system. In this case, they are significant in stamped, with a small bending radius of the transition from the branch to the main line, and weld tees. With the increase in the bending radius of the transition from the branch to the main line and pressure at the tee location, the loss of gas flow energy in the tees decreases sharply.

3. In order to minimize the loss of gas flow energy in equal tees, in which the gas flow from the main line completely moves to the branch, it is recommended to give preference to stamped tees when designing new and reconstructing old gas pipeline systems. In such tees, the ratio of the bending radius of the main line and branch connection to the outer diameter should be greater than 0.25.

4. The relationship between the local resistance coefficient and geometrical parameters of the equal tee is revealed. The equation for calculating local resistance coefficients, whose components are the bending radius of the main line and branch connection and tee outer diameter, is determined. The calculated local resistance coefficients of equal tees, in which the entire flow from the main line moves to the branch, can be used to design gas pipeline systems.

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