Main aspects of liquefied natural gas process line thermal and hydraulic calculations

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Abstract. The rapid growth of liquefied natural gas consumption makes the issues of its transportation more urgent. At present, liquefied natural gas pipeline transportation is carried out only by means of short length process lines. This paper discusses the main features of cryogenic liquids pipeline transportation that obstruct its spread. The proposed model allows to carry out thermal and hydraulic calculations of an underground cryogenic pipeline. The distinctive feature of this model is the fact that it takes into account the changes in basic thermodynamic parameters of cryogenic liquid. The model is based on the Darcy-Weisbach equation and a differential heat transfer equation. In addition, the influence of the Joule-Thomson coefficient inversion on the temperature of the pumping cryogenic liquid was discussed. The comparative analysis of the pipeline construction efficiency made of ultra-high molecular weight polyethylene and AISI 321 steel was conducted. It was found that the use of polymer materials contributes to an increase in the transportation distance. The developed model can be applied for estimation of the transportation parameters change of single-phase fluid flow. The obtained results can be used in initial analysis of the process lines designing and construction.

1. Introduction

The main difficulty in pumping liquefied natural gas (LNG) by pipelines is related to the possibility of a two-phase flow due to the influx of heat from the environment. In this regard, there are processes of mass exchange between vapor and liquid, which leads to a nonequilibrium state of the phases. It causes pressure changes, acting as a force in the axial direction of the pipe. In [1], the LNG two-phase flow is considered as a compressible gaseous volume and a liquid phase mass that forming an oscillatory system. The compressible gaseous volume acts as an asymmetric non-linear spring and generates axial forces that are non-linear with respect to displacement over time.

The complex nonlinear effects of two-phase flow in an LNG pipeline cause the need to continuously monitor them and investigate their fluctuations and vibrations in order to maintain the safety and reliable system operation. Besides additional stresses in the pipeline, the presence of a two-phase flow leads to decreasing throughput, entails the occurrence of cavitation and disruption of the pumping equipment. In order to prevent the two-phase flow formation, it is vitally important to maintain the pressure at any point through the pipeline route higher than the LNG saturation pressure for the given temperature [2,3].

The next problem is the initial filing and cooling processes, which are associated with the occurrence of such adverse hydrodynamic effects such as pressure pulsations; geysering and water hammers [4].
Geysering arises due to the temperature difference between the liquefied natural gas supplied to the filing and the pipeline, which leads to overheating of some amount of LNG and the fluid begins to boil intensively. Heat is accumulated due to the contact with the environment, leading to bubble formation. Bubbles form and rise to eventually merge into a larger bubble called the “Taylor bubble” [5,6], which fills the entire diameter of the pipeline. When the “Taylor bubble” rises, it pushes the liquid from the tube back into the storage, which is being emptied. The cold liquid at the bottom of the tank then rushes into the empty line, driven not only by gravity, but also by the vacuum pressure in front of it, created by the condensation of steam in the line. This column of liquid hits a block valve or another obstruction at the bottom of the line at a fairly high speed. The pressure rises sharply and the liquid is thrown back into the emptied storage. The pressure rises sharply and liquid is ejected back into the emptied storage. Pressure pulsations occur because of the cyclic nature of the effects. They represent the most dangerous phenomenon, since in the filing process the magnitude of the pressure fluctuations can exceed the working ones up to 3-5 times [7,8].

In [2,3,9,10] and according to international experience of process lines construction transporting cryogenic liquids, it is recommended to pre-cool the pipeline with the gas phase to an intermediate level, which will significantly reduce the temperature deformations of the pipeline, and, as a result, reduce unfavorable gas-hydrodynamic phenomena during boiling of LNG in the filing process.

The pumping modes and structural performance should be selected in terms of reducing the cooldown time. It is recommended to vent boil-off gas to maintain the constant gas flow rate and vapor pressure at the beginning of the pipeline. Due to this, an increase in the speed of fluid movement along the length of the pipeline is observed.

2. Methodology

2.1. The main characteristics of pipeline

It is assumed that the liquid is in a single-phase state. The pipeline is laid underground; polyurethane foam with a density of $\rho = 70$ kg/m$^3$ with a thermal conductivity coefficient $\lambda = 0.03$ W/(m · K) and a thickness of 30 mm is used as the material of the heat-insulating layer [11]. The composition of LNG is displayed on the table 1.

| Component   | Content (% vol) |
|-------------|-----------------|
| Methane CH$_4$ | 99.8 %          |
| Nitrogen N$_2$  | 0.13 %          |
| Ethane C$_2$H$_6$ | 0.07 %          |

The main thermodynamic parameters can be determined by the Peng-Robinson equation [12] and reference tables [13] or using the formulas described in [10].

2.2. Model aspects

The LNG flow through a pipeline is described by the following equations, which represent the energy consumption during the movement of the liquid. The pressure drop in the considered section of the pipeline is determined from the Darcy-Weisbach equation:

$$\Delta p = \lambda \frac{l \cdot v^2 \cdot \rho}{2 d_{int}} \cdot 1.015$$

(1)

where $\lambda$ - friction coefficient; $l$ – length of pipeline section; $d_{int}$ – internal diameter, $v$ – flow velocity, $\rho$ - density of LNG mixture.
\( v = \frac{4Q}{\pi d_{\text{int}}^2} \)

\( Q \) – volume flow rate.

Note: In formula (1), the influence of direction changes and its restriction are taken into account by increasing the pressure drop by 1.5%.

The friction coefficient is determined by the well-known formulas of hydraulics, depending on the fluid flow structure of pipeline, determined by the Reynolds number and the relative roughness. In general terms, this dependence can be represented by the expression: \( \lambda = f(Re, \varepsilon) \).

\[ \text{Re} = \frac{vd_{\text{int}}\rho}{\mu} \]

\( \mu \) - mixture viscosity.

The pressure change at any point of the flow is described by an iterative expression:

\[ p_{i+1} = p_i - \Delta p_i \]

2.3. Determination of the LNG temperature distribution along the pipeline length

For obtaining the temperature distribution, it is necessary to consider the physical processes occurring with it. A differential heat balance equation, which was written for the steady-state pumping mode, should take the main factors influencing the change in the temperature of the LNG flow into account.

Liquefied natural gas temperature changes are associated with heat content increasing, which occurs due to heat influx from the environment (in this case, soil) and the work performance when moving a cryogenic liquid with a mass flow rate \( G \), overcoming the resistance \( idx \). The temperature change from fluctuations in the flow rate is neglected due to its insignificant value. Moreover, it is assumed that a steady flow takes place in the pipeline. Thus, we obtain the following heat balance equation:

\[ Gc_p dT = -K\pi d_{\text{int}} (T - T_0)dx + Ggidx \]

\( G \) – the LNG mass flow rate; \( c_p \) — LNG heat capacity; \( K \) is the total heat transfer coefficient; \( d_{\text{int}} \) - the inner diameter of the pipeline; \( T \) - the LNG temperature in the section \( x \); \( T_0 \) - soil temperature at the depth of laying; \( i \) - hydraulic slope.

The equation shows that the heat exchange through the pipe walls will lead to an increase in the temperature of the transported medium, and the second term on the right side will be positive, therefore, thermal energy is transferred from the environment to the transported product, i.e. dissipation of mechanical energy leads to an increase in temperature [14,15,16,17].

2.4. Theoretical aspects of the Joule-Thomson coefficient inversion and its impact on the temperature change of the pumped liquid

In the international practice of performing thermal calculations for main gas pipelines, the influence of the Joule-Thomson effect is usually not taken into account, since it is considered to be of minimal value [18]. It is assumed that consideration of this effect can have a significant influence on the LNG temperature.

The Joule-Thomson coefficient can be either positive or negative. The state in which there is a transition from cooling to heating and vice versa, under the influence of isenthalpic differential expansion, is called inversion. Each gas has two points of inversion. It is either cooling or heating up depending on whether its temperature and pressure are below or above a certain inversion point. Both of these effects are explained in the molecular kinetic theory and reflect changes in the nature of intermolecular interactions in real fluids. At the molecular level, this phenomenon is explained by the fact that the forces of intermolecular interaction change from attraction to repulsion and vice versa.
A change in the sign of the Joule-Thomson coefficient is not always accompanied by a transition through a zero value, most often an intermittent transition is observed and this value never reaches zero. The inversion curve is domed in p-T coordinates. The graph in figure 1 shows that each pressure corresponds to two inversion temperatures. In this graph the inversion curve can be divided into two branches related to the upper and lower inversion temperatures. This fact is clearly demonstrated by the presence of an extremum of the inversion curves, when the maximum inversion pressure is reached (at 55 MPa for methane). Beyond this dome, the value of the Joule-Thomson coefficient is negative and the fluid heats up, whereas in the area below the dome the Joule-Thomson coefficient has a positive value and the liquid cools [19,20,21].

Figure 1. Joule-Thomson coefficient inversion curve in p-T coordinates for methane and nitrogen.

Figure 2 shows the graphs of the Joule-Thomson coefficient in function of temperature at various pressures for the LNG composition indicated in table 1.

Figure 2. The Joule-Thomson coefficient in function of T for different values of p.

As for assessing the influence of the Joule-Thomson effect on the temperature of liquefied gas, the area of the inversion curve lying below the critical point is the subject of interest. The condition of the vanishing of the partial derivative with respect to enthalpy, which determines the inversion curve,
manifests itself along any isenthalp in the (T, p) plane by changing its sign at the intersection point of the inversion curve. Isoenthalpic trajectories are maximal on the inversion curve. The lower wing of the inversion curve crosses the saturation line at point A, changing its direction. Below point A, any isenthalp changes the sign of its slope when it crosses the saturation line [20]. Figures 3 and 4 show the inversion curves in the T-p and p-h coordinates phase-diagram, respectively, for the LNG composition from table 1.

![Inversion curve in coordinates T-p at different constant values of h.](image1)

**Figure 3.** Inversion curve in coordinates T-p at different constant values of h.

![Inversion curve in coordinates p-h at different constant values of T.](image2)

**Figure 4.** Inversion curve in coordinates p-h at different constant values of T.

2.5. *Heat transfer in an underground cryogenic pipeline with the Joule-Thomson effect*

Having taken into account the assumptions mentioned earlier, the heat transfer equation takes the following form:
\[ Gc_p \, dT = -K_i \pi d_{int} \left( T - T_0 \right) dx + Ggi_i \, dx - Gc_p \cdot D_i \cdot \frac{P_i - P_{i+1}}{x} \, dx. \]  

(6)

By integrating equation (6), an expression is obtained that allows one to determine the temperature at any point of the flow:

\[ T(x) = T_0 + \frac{Ggi_i}{K_i \pi d_{int}} \cdot \frac{P_i - P_{i+1}}{x} + \left( T_{in} - T_0 \right) - \frac{Ggi_i}{K_i \pi d_{int}} \cdot \frac{P_1 - P_{i+1}}{x} \cdot e^{-K_i \pi d_{int} \frac{P_1 - P_{i+1}}{Gc_p}}. \]  

(7)

\( p_i, p_{i+1} \) – inlet and output pressures at the beginning and end of the pipeline section, \( x \) - pipeline section length, \( D_i \) - Joule-Thomson coefficient.

Heat flows from the ground to the insulated pipeline, then from the insulation coating to the pipe wall and from the pipe wall to the pumped stream. This process is mathematically expressed by the total heat transfer coefficient:

\[ \frac{1}{K_i} = \frac{1}{\alpha_i} + \frac{d_{ext}}{2\lambda_p} \ln \frac{d_{ext}}{d_{int}} + \frac{d_{int}}{2\lambda_{ins}} \ln \frac{d_{ins}}{d_{ext}} + \frac{d_{int}}{\alpha_2 d_{ins}} \]  

(8)

\( \lambda_p, \lambda_{ins} \) - the thermal conductivity coefficients of the pipe wall and insulating material, respectively, \( d_{ext} \) is the external diameter of the pipe; \( d_{ins} \) - diameter of pipe with insulation; \( \alpha_1 \) - the internal heat transfer coefficient characterizing the transfer of heat from the inner surface of the pipe to LNG:

\[ \alpha_i = \frac{\lambda_{LNG} \, Nu_i}{d_{int}} \]  

(9)

\( \lambda_{LNG} \) - coefficient of thermal conductivity of LNG; \( Nu \) - the Nusselt number.

\( \alpha_2 \) - external heat transfer coefficient characterizing heat transfer from the ground to the outer surface of the insulation:

\[ \alpha_2 = \frac{2\lambda_{gr}}{d_{ins} \ln \left( \frac{2h_{ins}}{d_{ins}} + \sqrt{\left( \frac{2h_{ins}}{d_{ins}} \right)^2 - 1} \right)} \]  

(10)

\( \lambda_{gr} \) - coefficient of soil thermal conductivity, \( h_0 \) - equivalent depth.

3. Results and discussion

For the model described in Section 2, in case the initial pressure and diameter of the pipeline are unknown [10], a hydraulic calculation is performed to determine them, assuming that the flow regime is steady at a constant temperature range selected from the phase diagram for a liquid of the given composition shown on the figure 5. The software Refprop 7.0 was used to obtain it.

The area on the left depicts a liquid in a single-phase state, as can be seen from the diagram, the critical point for LNG at a level of \(-80^\circ\text{C}\) at the respective pressure. Having examined the left region of the graph higher the saturation line, the following parameters are selected for transportation: operating pressure \( P = 2 \text{ MPa} \), operating temperature range from \(-160^\circ\text{C}\) to \(-130^\circ\text{C}\). The phase transition temperature of liquefied natural gas into a gaseous state at this pressure is \( t_{cr} = -107.38^\circ\text{C} \).
As mentioned earlier, a distinctive feature of LNG pipeline transportation is the need to maintain the flow in a single-phase state, which depends on the temperature and pressure changes along the entire length of the pipeline. Based on the selected pumping temperature range, the calculation was performed at its upper boundary, as well as in this case the highest probability of a two-phase flow formation exists. To determine the pressure at the beginning of a pipeline section, it is assumed that the pressure at the end of the section is equal to the LNG saturation pressure. Thus, the pressure at the beginning will be the sum of the pressure drop along the length of the pipe (formula 1) and the pressure at the end of the pipeline section [22]. According to [2], it is recommended to take the minimum value of the pressure in the pipeline above the saturation pressure by 0.5 - 0.7 MPa to ensure reliable operation. Thus, the pressure at the beginning of the section:

$$p_1 = \Delta p + p_s + 0.5.$$  \hspace{1cm} (11)

where $p_s$ – saturation pressure, MPa.

The algorithm of the model is shown in figure 6.

The calculation was carried out according to the initial data indicated in table 2 for the pipeline made of ultra-high molecular weight polyethylene (UHMWPE) and steel AISI 321. The inlet pressure and temperature were 2 MPa and -160 °C, respectively.

| Table 2. Main characteristics of pipeline. |
|------------------------------------------|
| Parameter | Value |
| External diameter of the pipeline, $d_{ext}$, mm | 350 | 351 |
| Internal diameter of the pipeline, $d_{int}$, mm | 286 | 325 |
| External diameter of the pipeline with insulation coating, $d_{ins}$, mm | 410 | 411 |
| Pipeline length, $l$, m | 20000 |
| Pipe roughness, mm | 0,00022 | 0,2 |
| Mass flow rate, $G$, t/pd | 5000 |
| Thermal conductivity of pipeline material, $\lambda_{pipe}$, W/(m·K) | 0,3 | 11 |
| Thermal conductivity of insulation, $\lambda_{ins}$, W/(m·K) | 0,03 |
| Thermal conductivity of ground, $\lambda_{gr}$, W/(m·K) | 1,9 |
| Equivalent depth, $h_0$, m | 2 |
Today nickel-plated steels are the main material for the construction of the mechanisms operating at cryogenic temperatures, but that material is very expensive due to the lack of nickel resources.
At the same time, the production of polymer materials is rising rapidly. Moreover, polymers are becoming more and more widely used in the pipe production. In the oil and gas industry, polyethylene pipelines are widely used in gas distribution networks and fiberglass pipelines in the field conditions [23,24]. Today, the use of UHMWPE pipes as a construction material of slurry pipelines for transporting solid and abrasive substances such as coal, cement, concrete, for pumping sulfur and paraffin-containing oils, as well as for delivering construction and drilling fluids, is developing. Owing to high resistance to chemicals, in particular salts and their solutions, and absence of corrosion, these pipes could find wide application in the oil and gas industry in the development of the North and the coastal shelf. Concerning the LNG pipelines, UHMWPE would make a good construction material due to its low-temperature resistance, long-term service and inertness related to aggressive environments, with high impact strength at cryogenic temperatures (up to -200 °C) [25,26]. Based on this the use of UHMWPE can be an interesting development direction of material science and oil and gas industry.

Figure 7 shows the comparison of pressure drop in an underground LNG pipeline made of steel and UHMWPE. The pressure drop in a steel pipeline is much higher than that of the UHMWPE, which is obviously explained by the higher values of roughness of steel. As you can see from the graph, the pressure drop is almost linear.

As a result of the calculation, graphs showing the change in the LNG with and without the Joule-Thomson coefficient were obtained. The figure 8 depicts that consideration of Joule-Thomson effect leads to a faster increase in the LNG temperature (by an average of 0.8 °C every 1000 m), reaching a difference of more than 2 °C at the end of the pipeline section.

Figure 9 shows differences of LNG temperature for a pipeline made of UHMWPE and AISI 321 steel.
Thus, the use of polymer materials for the construction of pipelines is advantageous due to the possibility of their transportation over longer distances without construction of additional pumping and cooldown stations.

4. Conclusion

A model for calculating the main pumping parameters (pressure drop and temperature) of liquefied natural gas during its flow through an underground process pipeline was proposed, which took into account the change in the thermodynamic and hydraulic parameters of LNG along its entire length. This model allows the calculation to be performed in the absence of initial parameters such as inlet pressure and pipeline diameter.

It should be noted that in order to ensure the LNG pipeline transportation safety, a condition was added to the model to prevent a two-phase flow formation. The temperature should be lower than the boiling point LNG at the given pressure and operating pressure exceeds saturation pressure of LNG by at least 0.5 MPa.

The analysis of the Joule-Thomson coefficient inversion influence on the temperature changes along the length of the LNG pipeline was conducted. The inversion curve passes through the maxima of the isotherms, coinciding with the saturation line to point A (154 K, 1.24 MPa), after which its direction changes, reaching the maximum value at the level of point M (335 K, 54.2 MPa). Considering the LNG inversion curve, it can be seen that the value of the Joule-Thomson coefficient is negative and the fluid will heat up during movement. As a result of calculations, it was found that taking into account the Joule-Thomson coefficient leads to an increase in the growth rate of the LNG temperature, on average by 0.8 °C for every 1000 m, and given the exponential law of the temperature change in the pipeline, this value will grow faster with the increase of pipeline length, reaching a maximum at the final point (in this case, a difference of 2 °C).

Based on the obtained results, a comparative analysis of temperature and pressure changes in a UHMWPE pipeline and the commonly used cryogenic steel AISI 321 was carried out. It was found that the temperature rise rate in a UHMWPE pipeline is lower than in a similar made of steel. However, the difference in pressure drop during pimping is the most indicative, that being confirmed by the fundamentals of hydraulics and, first of all, by different roughness of pipes and the ability of polymers to self-lubricate.

According to the analysis, it was found that to maintain LNG within the required temperature and pressure range, the distance between the intermediate cooldown and pressure stations for pipelines made of polymer materials is greater than for steel pipes.

The proposed UHMWPE pipes are used only for oil pipeline transportation and have not found wide application due to the relative novelty of the material. However, due to the scarcity of nickel resources...
and the resulting high cost of cryogenic steels, the use of polymer materials, such as UHMWPE, capable of operating at cryogenic temperatures down to -180 °C, may be a good solution. The areas of application of the obtained results can be process lines at small and medium-scale LNG plants and terminals.

References

[1] Madison J and Kimmel H 2010 Pressure Induced Isenthalpic Oscillations with Condensation and Evaporation in Saturated Two-Phase Fluids International Journal of Physical and Mathematical Sciences 4(9) 1235-40 http://doi.org/10.5281/zenodo.1072806

[2] Rachevsky B S 2009 Liquefied Hydrocarbon Gases (Moscow: Neft and Gas)

[3] Safonov V S 2017 Justification of operating parameters of technological pipelines of LNG complexes taking into account industrial safety requirements Vestsi gazovoy nauki 1(29) 83-99

[4] Gu Y, Ju Y L, Chen J and Shi Z J 2012 Experimental investigation on pressure fluctuation of cryogenic liquid transport in pitching motion Cryogenics 52(10) 530-7 https://doi.org/10.1016/j.cryogenics.2012.07.003

[5] Takatoshi T, Mitsuo M, Masanori A, Kensuke U, Michitsugu M and Yuzuru Y 1999 The coalescence mechanism of multiple slug bubbles J Nucl Sci Technol 36(8) 671-82 https://doi.org/10.1080/18811248.1999.9726254

[6] Das R and Pattanayak S 1995 Bubble to slug flow transition in vertical upward two-phase flow of cryogenic fluids. Cryogenics 35(7) 421-426. https://doi.org/10.1016/0011-2275(95)93575-K

[7] Zhang L, Lin W S, Lu X S and Gu A Z 2004 Geysering inhibiting research for single feeding-line in cryogenic propellant transfer system Cryogenics 44(9) 643-8 https://doi.org/10.1016/j.cryogenics.2004.03.007

[8] Mao H, Li Y, Wang L, Wang J and Xie F 2020 Investigation of appearance and intensity of geyser phenomenon in a vertical cryogenic pipe International Journal of Heat and Mass Transfer 150 119390. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119390

[9] Leskong A A and Churkin G Yu 2018 Normative support and issues of industrial security of cryogenic pipelines for liquefied natural gas offloading Vestsi gazovoy nauki 2(34) 135-40

[10] Voronov V A, Karyakina E D and Akhmerov E V 2019 Analysis of technical solutions in transport and storage of liquefied natural gas. Journal Internatynal Academy of Refrigeration 3(72) 15-22 https://doi.org/10.17586/1606-4313-2019-3-15-22

[11] Bahadori A 2014 Thermal Insulation Handbook for the Oil, Gas, and Petrochemical Industries 1st edition (Oxford: Gulf Professional Publishing) pp 303-321. https://doi.org/10.1016/b978-0-12-800010-6.00004-6

[12] Peng D and Robinson D B 1976 A new two-constant equation of state Ind. Eng. Chem. Fundamen. 15(1) 59-64 https://doi.org/10.1021/i160057a011

[13] Reid R C, Prausnitz J K M and Poling B R 1987 The Properties of Gases and Liquids 4th edition (New York: McGraw-Hill)

[14] Lurie M V 2017 Theoretical Foundations of Pipeline Transportation of Oil, Oil Products and Gas (Moscow: Nedra)

[15] Grunicheva Y V, Kurbatova G I and Popova Y A 2011 Nonstationary nonisothermal flow of gas mix in offshore gas pipelines. Math Models Comput Simul 3 751-8 https://doi.org/10.1134/S2070048211060032

[16] Vasilyeva M A and Volchikhina A A 2018 J. Phys.: Conf. Ser. 1118 012047 https://doi.org/10.1088/1742-6596/1118/1/012047

[17] Włodek T and Łaciak M Selected thermodynamic aspects of liquefied natural gas LNG pipeline flow during unloading process 2015 AGH Drilling, Oil, Gas 32(2) 275-87 https://doi.org/10.7494/drill.2015.32.2.275.

[18] Kudryashov B B, Litvinenko V S and Serdvyukov S G 2002 The reliability of thermal analysis of cross-country gas pipelines Tech. Phys. 47 375–379. https://doi.org/10.1134/1.1470580
[19] Suleymanov V A 2020 Calculation of the Joule-Thomson coefficient values using the Lee-Kesler-Ploker EOS: a case of natural gas transportation through subsea gas mains Vesti gazovoy nauki 1(42) 23-31
[20] Maytal B and Pfromhauer J M 2013 Miniature Joule-Thomson Cryocooling: Principles and Practice (New York: Springer). https://doi.org/10.1007/978-1-4419-8285-8
[21] Marič I 2005 The Joule–Thomson effect in natural gas flow-rate measurements Flow Measurement and Instrumentation 16(6) 387-95 https://doi.org/10.1016/j.flowmeasinst.2005.04.006
[22] Voronov V A and Ivanik S A 2019 Peculiarities of flow of liquefied natural gas in pipelines Youth Technical Sessions Proc. June 23-28 2019 Saint Petersburg ed V Litvinenko (London: CRC Press) pp 126-132. https://doi.org/10.1201/9780429327070
[23] Willoughby D A, Woodson R D and Soverland R 2002 Plastic Piping Handbook (New York: McGRAW-HILL)
[24] Nikolaev A K and Coello Velazquez A L 2017 Modeling of fiberglass pipe destruction process Zapiski Gornogo Instituta 223 93-98. https://doi.org/10.18454/pmi.2017.1.93
[25] Galibeev S S, Khayrullin R Z and Arkhireev V P 2008 Ultra-high molecular weight polyethylene trends and prospects Bulletin of Kazan Technological University 2 50-5
[26] Selyutin G E, Gavrilo Y U, Voskresenskaya E N and Zakharov V A 2010 Composite materials based on ultra high molecular polyethylene: properties, application prospects Chemistry for Sustainable Development 18 301-14