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Increase of the technogenic and ecological safety of the natural gas transportation due to displacement of explosive mixtures with nitrogen

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ABSTRACT

Purpose: To ensure technological and environmental safety it is proposed to use the technology of purging pipeline with compressed nitrogen.

Design/methodology/approach: The purpose of the calculation is: to get the graph of the concentration distribution (in volume fraction) of nitrogen and natural gas components depending on the distance from the injection point of nitrogen and the duration of the purge process, to determine of parameters of a non-stationary process, and to establish the optimal parameters of the purging process under conditions of the given flow chart.

Findings: In the process of displacement of natural gas, the velocity of the front of nitrogen is one of the main quantities that significantly affect the quality of displacement. To assess the actual technological schemes for transporting natural gas, it is necessary to select the velocity of displacement of explosive mixtures.

Research limitations/implications: This technology should be implemented in the conditions of a nitrogen pressure higher than 0.25 MPa.

Practical implications: Most favourable conditions for the complete displacement of air and subsequent replacement of nitrogen with natural gas were observed for pressures higher from 1.0 to 1.5 MPa.

Originality/value: Complex calculations of the volume of air displaced with nitrogen and natural gas in the process of filling the pipeline were conducted in the research. Boundary conditions on the concentration of the mixture of nitrogen and natural gas were identified.

Keywords: Environmental impact, Modelling numerical method, CNG vessel, Gas dynamics, Explosive mixtures, Natural gas displacement, Non-stationary processes, Sequential gas pumping

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Underwater pipelines, LNG and CNG vessels are used for offshore transportation of natural gas. At the present stage of development of the gas industry Ukraine faces the problem of development of technologies of transporting gas in compressed form (CNG), which is in our opinion, the most relevant option in areas of high traffic hazards. The bases of this technology of natural gas transportation are specially equipped vessels. Scientists of Ivano-Frankivsk National Technical University of Oil and Gas have proposed the technology of transportation of compressed natural gas on containerships, equipped with standard 20-or 40-foot sea containers with storage tanks for compressed [1-4].

When transporting compressed gas by the container vessels it is very important to ensure technological and environmental safety, safety and minimization of environmental pollution in the process of the first filling of movable pipeline with natural gas.

When putting the pipelines on gas-carriers to transport compressed natural gas into operation, the question of the choice of rational method of purging arises. In fact, we need to solve the complex problems associated with the displacement of the air, water, soil, dust and the like from the pipeline. The application of the classical method, i.e. passing the cleaning pig, in terms of LNG-vessel is technologically impossible.

According to current view on environmental safety and considering the economic component of the process, the use of natural gas to displace the air is irrational. This is due to emissions of large amounts of natural gas into atmosphere that, given the need for compliance with international environmental law, is invalid. Piping purging by air is possible only at the stage of pneumatic tests or cleaning of the pipeline from the water after hydraulic tests. Final commissioning of the pipeline will require replacement of the existing air with natural gas.

Purging of the pipeline is one of the most important stages [5-7]. In the zone of contact of air and natural gas a mixture of both is formed. To avoid serious consequences associated with ignition of gas mixture, the process of displacement of air should be low rate. However, reducing the speed of the sequential movement of air and gas causes an increase in volume of the mixture and, consequently, sharp increase in the required purge gas, especially in large-diameter gas pipelines.

To reduce the gas flow during purging of a pipeline in some cases it is advisable to apply "moving plugs" of non-combustible gases (nitrogen, carbon dioxide), which are injected into the pipeline before supply of natural gas. The use of a buffer gas plugs eliminates the possibility of formation of an explosive mixture in the pipeline and provides for high speed purging, thus providing high quality purging, drastically reduced gas losses and monetary costs associated with the putting of the gas pipeline into operation. Use of buffer gas plugs while purging requires the solution of the problem of reciprocal mixing of three different gases in the pipeline: air, inert gas and natural gas [8-15].

To ensure technological and environmental safety it is proposed to use the technology of purging pipeline with compressed nitrogen. Nitrogen is used to create an inert atmosphere during production, transportation and storage of flammable products, as well as before the first injection, after conducting repair works and for the abandonment of pipelines.

To produce nitrogen, nitrogen plants are used, which are of three types: portable mobile and stationary. Since an issue of technological and environmental safety in transportation of natural gas by containerships is considered, we will focus on the mobile nitrogen stations, mounted in 20- or 40-foot offshore containers: series NDA or TGA (12 m x 2.5 m x 2.5 m; weight – 40 tons). Their advantages are: simplicity of operation, ability to work in open areas at temperature from -60º to +45ºC, ease of transportation by any means of transport, etc.

As for the existing technologies of production of nitrogen, it is necessary to pay attention to the most common membrane, adsorption and cryogenic technologies of obtaining nitrogen from atmospheric air. Using membrane technology, it is possible to produce nitrogen with a concentration of 95-99,999% at performance of 1-1000 Nm^3/hr. The basic principle of membrane technology is the difference in the permeation rate of gas components through the membrane. The driving force for gas separation is the difference in partial pressures on opposite sides of the membrane. The main advantages of membrane technology are that the membranes can withstand shock and vibration, are chemically inert to moisture and lubricants, operate in a wide temperature range from -40ºC to +60ºC, and their operational life is 15-20 years.

In the case of purging pipeline with nitrogen we are dealing with the physical process of sequential pumping of two different sorts of gases that differ in their physical and thermo-physical properties. The issue of sequential pumping of gases is studied less, than sequential pumping of all sorts of liquids. This is primarily due to limited use of technology of sequential pumping of gases. The main issue of any sequential pumping of gases or liquids is determination of the volume of mixture created in the process of pumping, distribution of different components concentration and determination of optimal regimes of pumping. Such regimes, under which the amount of the resulting mixture is minimal, are considered optimal. Furthermore, a condition regarding maximum oxygen content in the mixture should be considered. Air displacement can be considered as successful if the oxygen content in the gas which exits from the pipeline, does not exceed 0.02% (according to the existing technical conditions as for the quality of natural gas.

Statement of the problem consists, primarily, in forming the original data and the calculated model of the process of purging the pipeline with nitrogen. To select the source data, we use the developed technological scheme of the pipeline. Based on the characteristics of the technological scheme of the pipeline, to simulate the process of nitrogen purge let us consider a specific element of the pipeline with a total length of serially connected sections of 6700, 13400 m and inner pipe diameter of 690 mm, which allows to carry 500 thousand m^3 or 1 million m^3 of natural gas in a compressed state. Provide for putting block valve station DN250 at the end of the pipeline. Simulation of the purging of the pipeline will be held for different values of pressure and temperature of nitrogen and the duration of the purge process. The purpose of the calculation is: to get the graph of the concentration distribution (in volume fraction) of nitrogen and natural gas components depending on the distance from the injection point of nitrogen and the duration of the purge process, to determine of parameters of a non-stationary process, and to establish the optimal parameters of the purging process under conditions of the given flow chart.

2. Methodology of research

When calculating the volume of the mixture for the sequential pumping of the gases it is assumed that the effective diffusion coefficient - is a constant value along the length of the pipeline [12]. However, in our opinion, this assumption can be justified only for pipelines of short length or with slight pressure differences. In the case of CNG technology, the use of such assumptions can lead to significant error.

The problems of sequential pumping of gases must be solved considering changes in gas density along the length depending on the gas pressure and temperature and, consequently, velocity change of gas along the pipeline. The differential equation of one-dimensional turbulent diffusion in terms of a variable effective diffusion coefficient has the following form [5]

$$\frac{\partial K_b}{\partial t} = \frac{\partial}{\partial x}\cdot\left(D_{ef}\cdot\frac{\partial K_b}{\partial x}\right) - v\cdot\frac{\partial K_b}{\partial x} \qquad (1)$$

where K_b – concentration of gas moving behind, x – the distance from the beginning of the moving coordinate system, D_{ef} – the effective diffusion coefficient, v – flow rate.

For a moving coordinate system which moves with the velocity of the gas flow, this equation takes the following form [5,16]

$$\frac{\partial K_b}{\partial t} = \frac{\partial}{\partial x}\left(D_{ef}\cdot\frac{\partial K_b}{\partial x}\right) \qquad (2)$$

The main difficulty of this calculation is to determine the effective diffusion coefficient. In isothermal gas flow, the effective diffusion coefficient is determined by the following dependencies [5,17,18]

$$D_{ef} = \frac{\nu_{0avr}\cdot\left[\frac{1}{\Pr} + 28.7\cdot\left(\mathrm{Re}\cdot\sqrt{\lambda}\right)^{0,755}\right]\cdot P_{n.c}\cdot T}{T_{n.c}\cdot P_x}, \qquad (3)$$

where ν_{0avr} – the average coefficient of kinematic viscosity of a 50% mixture of gases, reduced to normal conditions, m^2/s; $\Pr$ – Prandtl diffusion criterion; Re – the average value of Reynolds criterion; λ - the coefficient of hydraulic resistance of the pipeline; $P_{n.c}$ – pressure under normal conditions, Pa; T – gas temperature, K; $T_{n.c}$ – temperature under normal conditions, K; P_x – the gas pressure in the pipeline at a distance x from the beginning, Pa.

It is impossible to use the dependence (3) for the calculation of complex systems with consideration of non-stationary processes of gas transportation due to a significant averaging of the parameters of the mixture (viscosity, Prandtl criterion and Reynolds criterion, gas temperature). In addition, in the stationary transportation processes they use one parametric equation of real gas state of Clapeyron-Mendeleev, in which the deviation of the properties of real gas from ideal one is taken into account using the factor of gas compression, which, in our opinion, is substantially limited for complex systems operating in a wide range of pressures and temperatures, taking into account the nonstationary processes of motion. In world practice Soave-Redlich-Kwong, Benedict-Webb-Rubin, Peng-Robinson, and other equations, are widely used which characterize the dependence of the gas density on pressure and temperature in two or three parametric form. In the work the most suitable for the specified range Soave-Redlich-Kwong equation (4) was applied [18,19]. When calculating the mixture of gases, the classic rule of mixing phases is used

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)}, \qquad (4)$$

where P – absolute pressure, Pa; T – absolute temperature, K; V – molar volume, m^3/mol; R = 8.31441 J/mol·K – universal gas constant; a, b – constant values, depending on the properties of the matter. The coefficients of the state equation a *and* b for a single gas component depend on the critical pressure and temperature of the component, eccentricity factor of substance molecules according to such dependencies.

$$a(T) = a_{cr} \cdot \alpha(T), \tag{5}$$

$$a_{cr} = \Omega_a \cdot \frac{R^2 \cdot T_{cr}^{2,5}}{P_{cr}}, \tag{6}$$

$$b = \Omega_b \cdot \frac{R \cdot T_{cr}}{P_{cr}}, \tag{7}$$

$$\alpha(T) = \left(1 + m\left(1 - \left(\frac{T}{T_{cr}}\right)^{0.5}\right)\right)^2, \tag{8}$$

$$m = 0.480 + 1.574 \cdot \omega - 0.176 \cdot \omega^2, \tag{9}$$

where Ω_a and Ω_b – the coefficients that constitute 0.42748 and 0.08664 respectively; T_{cr} – critical temperature of the gas component, K; P_{cr} – critical pressure of the gas component, Pa; ω – eccentricity factor of the substance.

In the process of technological calculations, several technological limitations were adopted. According to the existing normative documents the volume fraction of oxygen in natural gas must not exceed 0.02% (in molar fractions), thus the process of replacement of air with nitrogen and later with natural gas had been being carried out until, the requirement of normative documents on the oxygen where fulfilled.

To determine the maximum permissible oxygen concentration of the gas based on the availability of nitrogen we use the Le Chatelier principle. Explosive limit of technical gases, which consists of a mixture of combustible components and contains no ballast impurities, is determined from the dependencies:

$$l = \frac{100}{\frac{a_1}{l_1} + \frac{a_2}{l_2} + \ldots + \frac{a_n}{l_n}}, \tag{10}$$

where l – upper or lower limit of explosiveness of gas mixture, which consists of n components, %; $a_1, a_2, \ldots, a_n$ – the content of combustible components in the gas mixture, %; $l_1, l_2, \ldots, l_n$ – upper or lower explosion limits of certain combustibles, %.

However, under actual conditions of the process of substitution of the nitrogen with natural gas, one should determine concentration limits of the explosive mixtures containing ballast components (carbon dioxide and nitrogen). Thus, the following dependence was used:

$$l_{bal} = \frac{\left(1 + \frac{a_{bal}}{(1 - a_{bal})}\right) \cdot 100}{100 + \frac{l \cdot a_{bal}}{(1 - a_{bal})}}, \tag{11}$$

where a_{bal} – the total content of the ballast components (nitrogen and carbon dioxide), %.

3. Results and discussion

Boundary conditions were adopted based on the concept of the technology of compressed gas transportation by gas carriers, and operating requirements for the gas quality. The maximum pressure of the process of substitution did not exceed the working pressure of the system. Based on the requirements of normative documents regarding the quality of natural gas, a mixture of natural gas and nitrogen in the final stages of displacement is considered suitable for supply to consumer when the maximum nitrogen content in natural gas does not exceed 5 % (molar fraction).

Simulation of the replacement process was carried out at an absolute pressure of nitrogen in the 0.3, 0.5, 1.0 and 1.5 MPa (absolute pressure). The temperature of the nitrogen at the beginning of the pipeline was considered in accordance with the conditions of the equipment to produce nitrogen within 25°C. The simulation was performed with the release of air from the pipeline DN700 with a length of 6700 m and with a maximum operating pressure of 20 MPa. The replacement of nitrogen with natural gas was carried out at a pressure of 2.5 MPa (absolute pressure) and a temperature of 20°C.

The replacement was carried in two stages: the replacement of air (the control of the oxygen content during the replacement) and the replacement of nitrogen (the control of the nitrogen content during the replacement). The duration of the first stage was near four minutes and the duration of the second stage was near two minutes. So short duration of the second stage is dealing with short length of the pipe and replacement with the high pressure of the natural gas (2.5 MPa).

In Figure 1 the dependency graph of nitrogen and oxygen concentration change at first stage of replacement when the nitrogen pressure is 0.3 MPa is provided. In Figure 2 the dependency graph of methane and nitrogen concentration change at second stage of replacement when nitrogen pressure is 0.3 MPa and natural gas pressure is 2.5 MPa is provided. In Figure 3 the dependency graph of the nitrogen concentration changes at second stage of replacement when the nitrogen pressure is 0.3 MPa is provided.

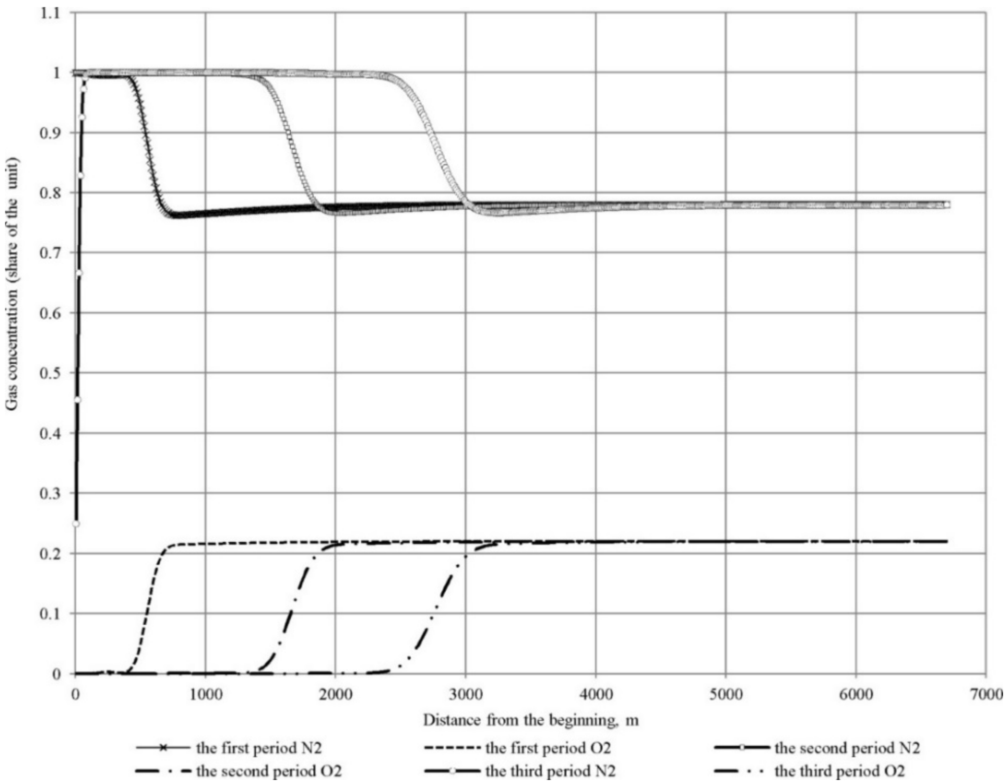

Fig. 1. Dependence of nitrogen and oxygen concentrations changes at the first stage of replacement when the nitrogen pressure is 0.3 MPa

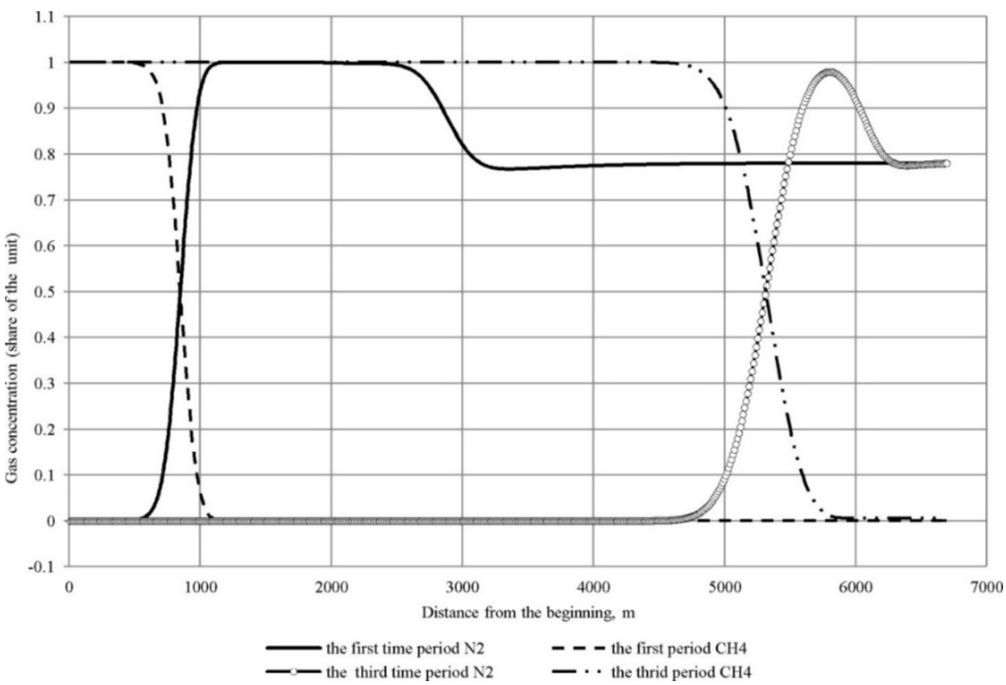

Fig. 2. Dependence of methane and nitrogen concentrations changes at the second stage of replacement when the nitrogen pressure is 0.3 MPa

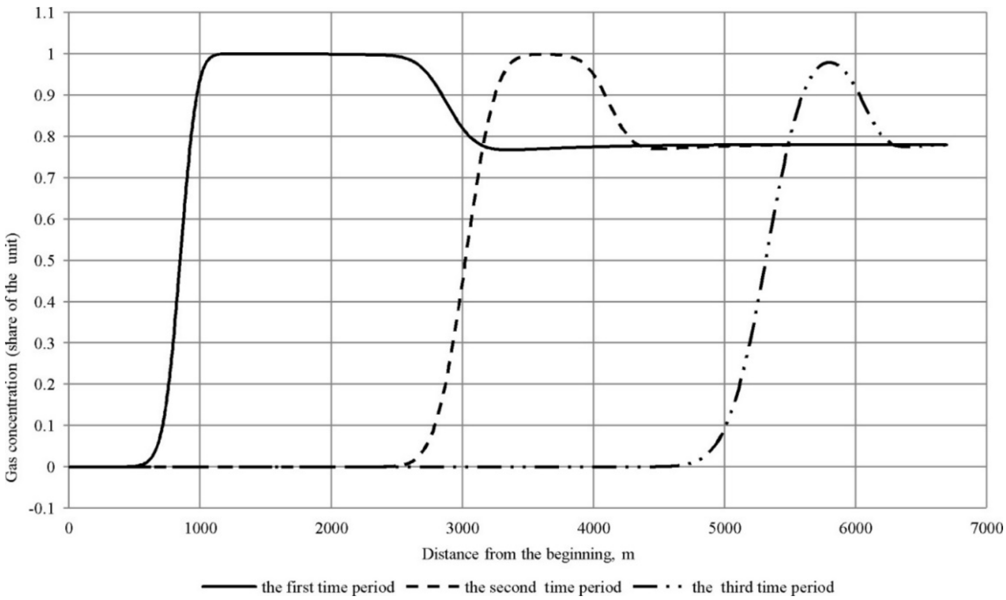

Fig. 3. Dependence of the nitrogen concentration changes at the second stage of replacement when the nitrogen pressure is 0.3 MPa

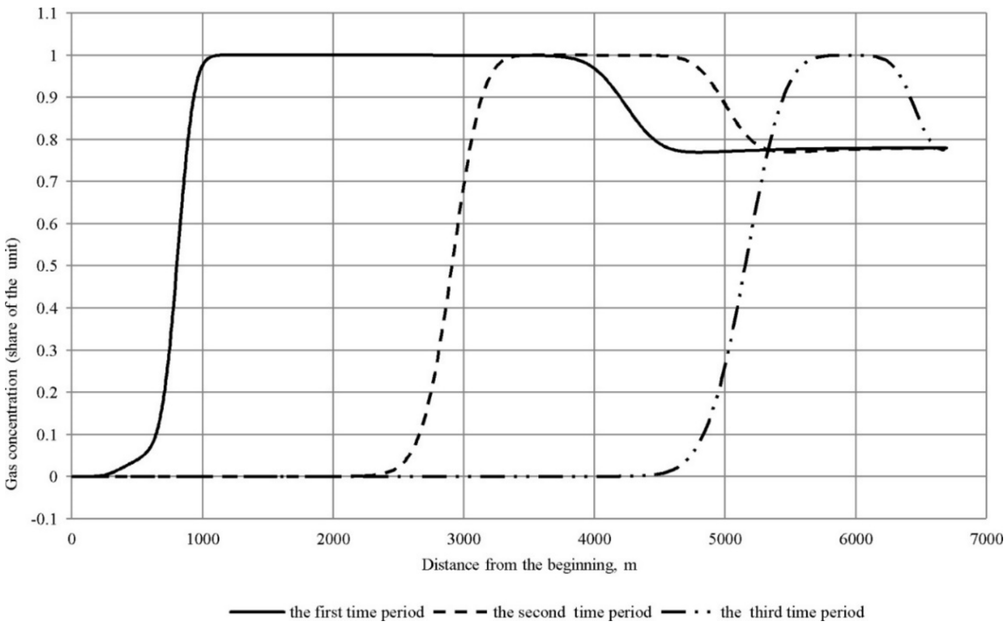

Fig. 4. Dependence of the nitrogen concentration changes at the second stage of replacement when the nitrogen pressure is 0.5 MPa

Nitrogen concentration does not reach 100% while flowing throughout the length of the pipe under the pressure of 0.3 MPa, according to the results of calculation. In Figure 4 the dependency graph of the nitrogen concentration changes at second stage of replacement when the nitrogen pressure is 0.5 MPa is provided. Figure 4 shows that 100% nitrogen concentration is reached during the second stage of replacement. High nitrogen concentration (100% by molar share of the unit) ensures zero natural gas emissions during the replacement.

In Figure 5 the dependency graph of nitrogen and oxygen concentration change at first stage of replacement when the

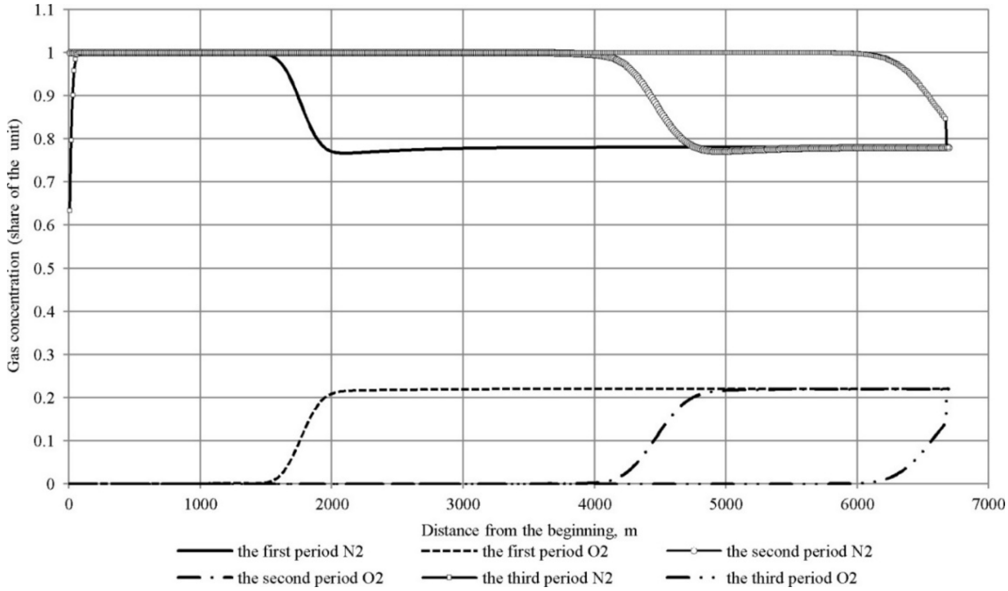

Fig. 5. Dependence of nitrogen and oxygen concentrations changes at the first stage of replacement when the nitrogen pressure is 1.5 MPa

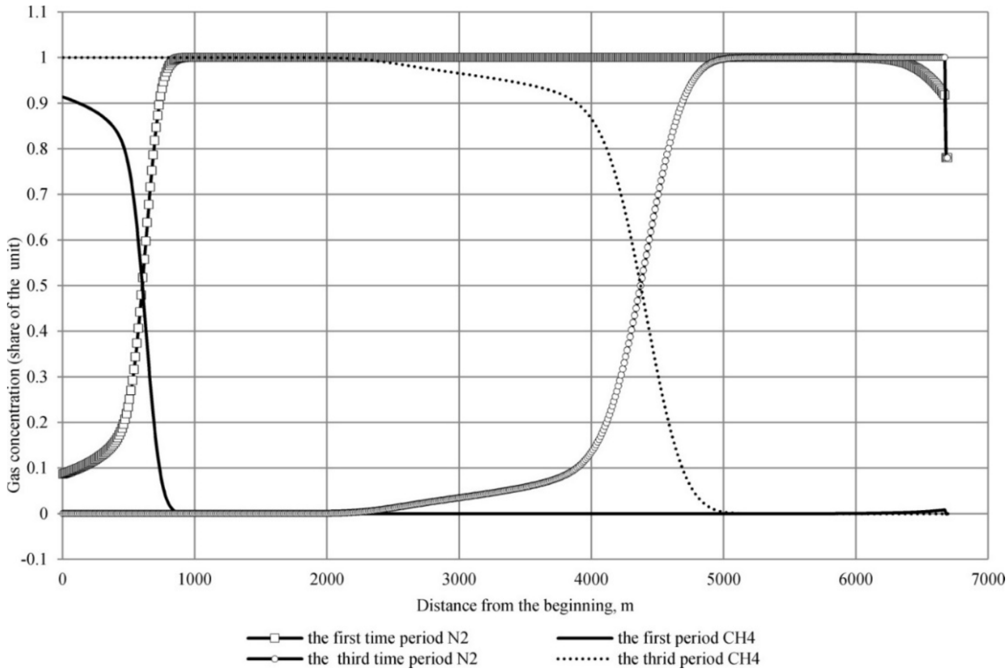

Fig. 6. Dependence of methane and nitrogen concentrations changes at the second stage of replacement when the nitrogen pressure is 1.5 MPa

nitrogen pressure is 1.5 MPa is provided. In Figure 6 the dependency graph of methane and nitrogen concentration change at second stage of replacement when the nitrogen pressure is 1.5 MPa and the natural gas pressure is 2.5 MPa is provided. The minimum nitrogen pressure during the replacement of the air should be greater than 0.5 MPa (for pipes up to 7 km in length).

There were also made calculations of the duration of non-stationary regime in the work.

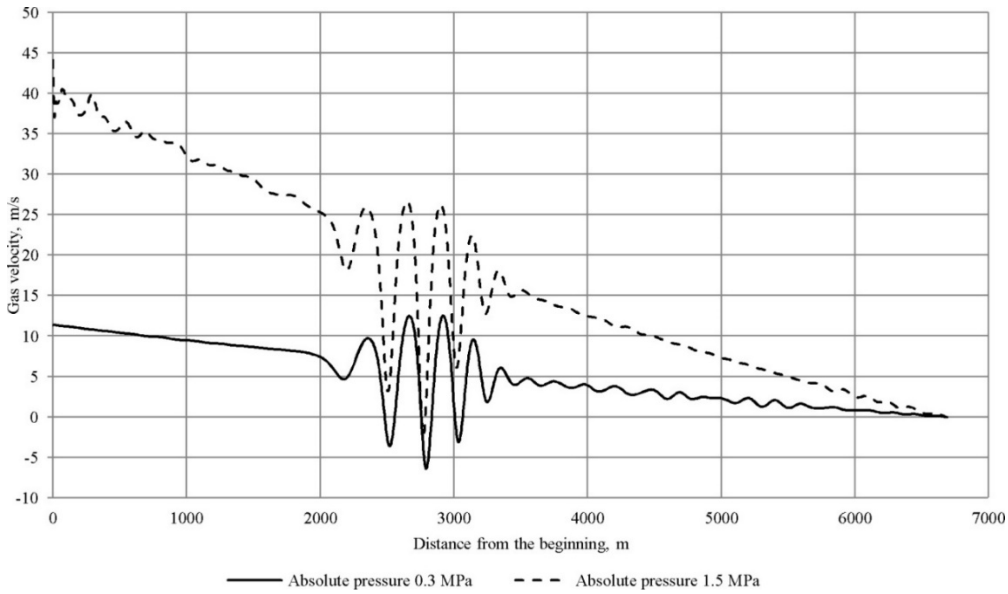

Fig. 7. Dependence of gas velocity at the first minute of the replacement

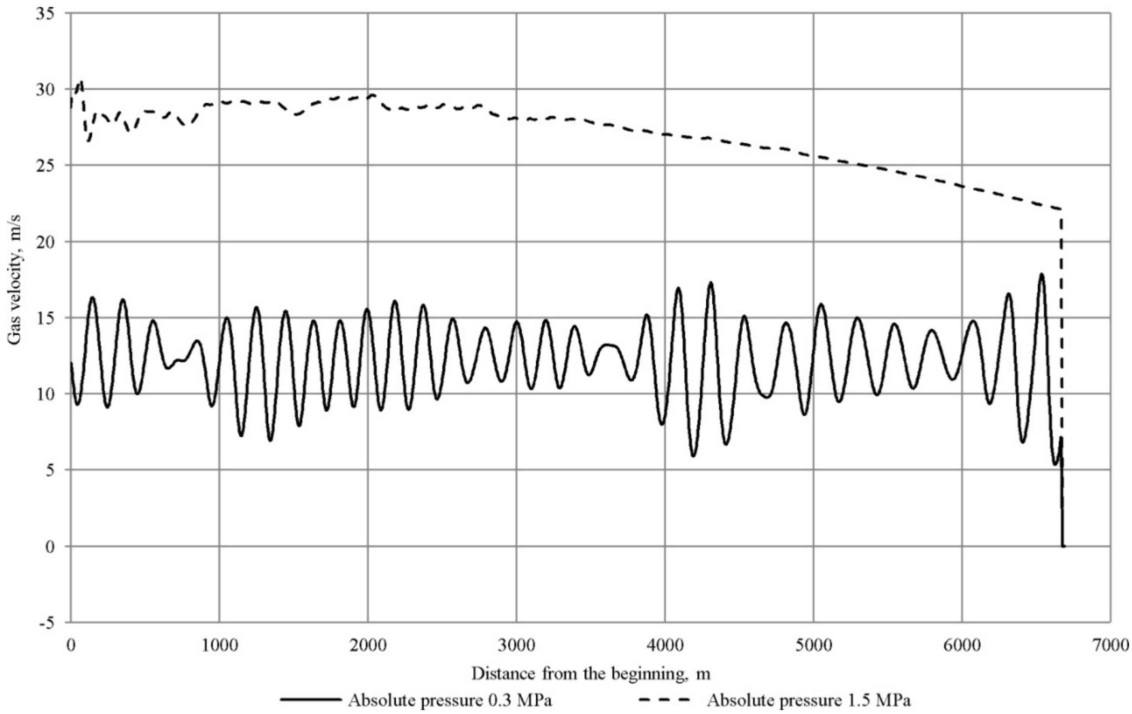

Fig. 8. Dependence of gas velocity at the third minute of the replacement

In Figure 7 the dependency of the velocity of the gas on the first minute of the replacement (for different pressure of the replacement) is provided. In Figure 8 the dependency of the velocity of the gas on the third minute of the replacement (for different pressure of the replacement) is provided. The duration of the non-stationary process increases at the low-pressure replacement.

The results of the calculation of non-stationary processes of replacement can be used in studies on the reliability and durability of gas pipelines [20-24]. The specifics of this calculation are presented in several works [25-28], however, in our opinion, for a more accurate calculation of the reliability and durability of pipelines it is necessary to take into account the pressure temperature and speed fluctuations during non-stationary processes [28-30].

To determine the length of the mixture of natural gas and nitrogen zone, the following boundary conditions were used. A mixture in which the concentration of natural gas was higher than 20% of the lower explosive limit of the mixture (including ballast components) was considered safe. The mixture was considered suitable for supply into a gas pipeline to consumers, if the concentration of nitrogen was less than 5% (molar fraction). Based on the same assumptions, the length of the mixture under different conditions of displacement was determined. The smallest length of the mixture was observed under conditions of low displacement pressure of nitrogen (0.5 MPa).

However, under these conditions, the steady nitrogen and natural gas front was formed solely in the conditions of purging short pipeline sections (up to 5000 m). When purging long sections, the process of releasing the pipeline should have been made at higher pressures.

Therefore, the most favourable conditions for the complete displacement of air and subsequent replacement of nitrogen with natural gas were observed for pressures higher from 1.0 to 1.5 MPa. In our opinion, this technology should be implemented in the conditions of a nitrogen pressure higher than 0.25 MPa. This limitation, on the one hand, will stick to the safety requirements of the process, on the other – minimize the cost of nitrogen compression before it is injected into the system.

4. Conclusions

The pressure of nitrogen in the process of displacement should be in the range of 1.0 to 1.5 MPa, under the conditions of further filling of pipeline with natural gas with an absolute pressure of 2.5 MPa, with the aim of forming a stable nitrogen displacement front and avoiding active mixing with natural gas.

In the process of displacement of natural gas, the velocity of the front of nitrogen is one of the main quantities that significantly affect the quality of displacement. To assess the actual technological schemes for transporting natural gas, it is necessary to select the velocity of displacement of explosive mixtures. Air displacement can be considered as successful if the oxygen content in the gas which exits from the pipeline, does not exceed 0.02% (by volume fraction).

The mixture of nitrogen and natural gas supplied to the consumer must contain no more than 5% (by volume fraction) of nitrogen, for the purpose of compliance with the quality requirements as for natural gas. Such technological parameters of the process can guarantee zero natural gas emissions and ensure process safety parameters of the process.

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