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Study of the Pipeline in Emergency Operation and Assessing the Magnitude of the Gas Leak

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Abstract: Accidents on gas pipelines cause significant damage to the national economy and the economy of the state. Thus, it is necessary to always be prepared for such situations in order to restore the normal operation of the gas pipeline as soon as possible. An important role is played by the execution time of the control actions to localize the accident, pump out the gas, and change the operating modes. It is essential that such control be undertaken, especially if such a situation occurs near a gas-measuring installation for measuring the amount of vented gas. Therefore, the control actions must be error-free in order to quickly stop the non-stationary process, which can lead to undesirable consequences. The paper presents a mathematical model of the operation of the pipeline, developed for the management of the pipeline in an emergency. The analysis of the problem of the occurrence of accidents was carried out, and the effect of liquid on its walls was modeled when the operating mode of the pipeline changed. An example is presented using a numerical model carried out in ANSYS, as well as being analyzed analytically. The results of the calculations are presented, and special attention is paid to the parameters influencing the change in the operating mode of the pipeline.

Keywords: mathematical modeling; parameters modeling; stress state of the pipe; gas transportation; raw materials

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1. Introduction

The pipeline is an integral part of modern society. Pipeline transport is used both in everyday life to supply water [1] or heat [2] and in industry at various stages of production chains, from the extraction of minerals [3] and the transportation of raw materials to the place of processing [4] or finished products to the consumer [5] (Figure 1). Pipeline transport, like any production process, must meet the basic requirements: environmental friendliness [6], economic efficiency [7,8], and safety [9].

Therefore, the control of the pipeline operation and the assessment of its safety using mathematical modeling of the non-stationary mode will allow avoiding emergency situations as a result of economic losses [10] and environmental disasters [11].

Various models of partial differential equations are presented in the literature to describe the behavior of gas inside a pipeline. A description of pipeline operation modes transition from stationary to non-stationary mode, etc. However, in most cases we are talking about the non-stationary operation of the pipeline.

Amaechi, Gillett et al. [12] perform a numerical stress analysis of composite marine risers for deep-water hydrocarbon production applications. The authors use the finite element method to model a composite riser for six load cases. The study provides recommendations on the design of a composite riser. Cramer et al. [13] provide an overview of the main problems that arise in leak detection and describe experiences with the available technologies. They describe the rate of change of the flow and pressure, compensated mass balance, statistical modeling, real-time transient modeling and sounding by acoustic waves. Baqué, [14] presents the Fiber Optic Leak Detection (FOLD) project, the aim of which was to evaluate the ability of a fiber optic sensor to detect a small gas leak in a buried pipe. The paper provides recommendations on the best fiber deployment positions along a pipe, compares the performance of several methodologies, and evaluates the effect of fiber length on detection performance.

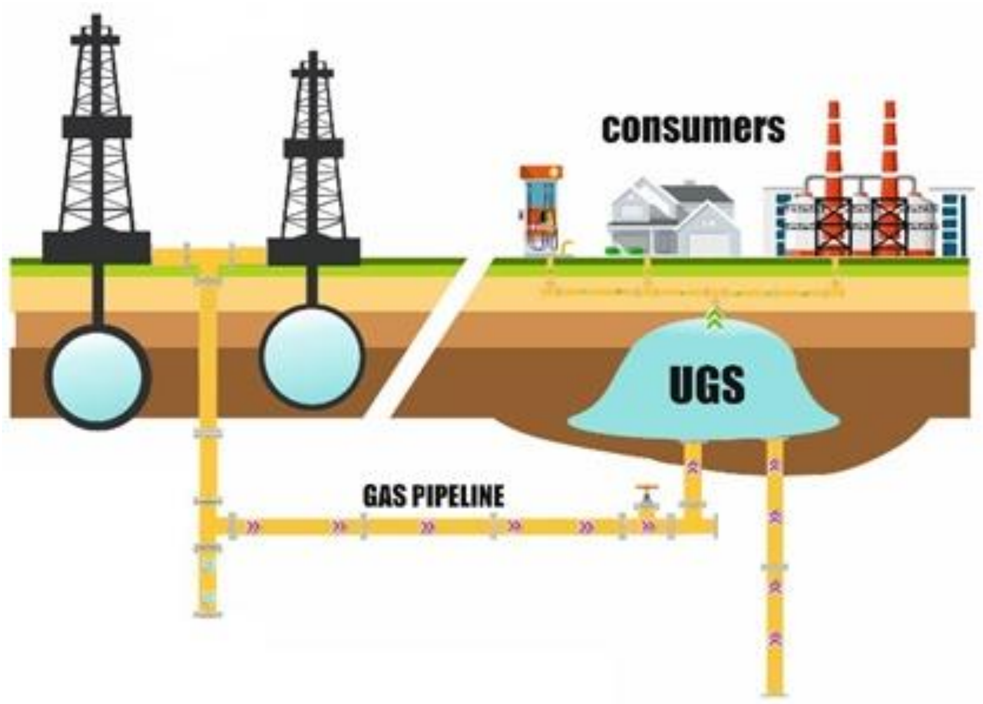


Figure 1. A typical natural gas transportation.

Picksley et al. [15] provide industry guidelines for the integrity monitoring of unbonded coiled tubing, which define a systematic, risk-based approach to coiled tubing integrity management. They also describe the practical implementation of these guidelines on two offshore flexible pipeline systems. Odijie et al. [16] review the engineering of semi-submersible stabilized columns that are used to design and develop drilling and production platforms for offshore deep-water operations. The paper provides an overview of the movement and structural adaptations of semi-submersible vehicles. The type and formation of dry-type semi-submersibles are discussed. It also explains their dynamic behavior and comparative advantages in different operating modes.

Sheng et al. [17] compare open source software to meet the requirements of the TALOS hydrodynamic simulation and wave energy converter optimization based on a numerical simulation. Reda et al. [18], in the article, describe an example of damage to the coating of field joints when crossing an existing pipeline with a 132 kV submarine cable with an outer diameter of 191 mm. An in situ investigation of the damages showed that they were caused by the lateral displacement of the cable under the action of hydrodynamic forces. The authors offer some recommendations for the safe design and construction of cable crossings, as well as proposals for the development and standardization of the relevant requirements for the design of underwater crossings.

The aim of this study is to introduce a mathematical model into the developed gas network simulator based on the operation of the gas pipeline to evaluate various operation scenes, taking into account the mentioned features of the regime change. A mathematical model was developed to integrate simplified models derived from input data based on typical pipeline operating conditions. The analysis of the problem of the occurrence of accidents was carried out, and the effect of the liquid on its walls was modeled when the operating mode of the pipeline changed. The results of calculations are presented, and special attention is paid to the parameters influencing the change in the operating mode of the pipeline. The paper continues in Section 2 with the materials and research methods. The equivalence of the equations of motion is described. Section 3 presents the application examples, locating the leak and assessing the magnitude of the gas leak. The reason for the inaccuracy of the existing mathematical model, which consists of neglecting the growth of the gas-dynamic resistance of the medium to the movement of a gas jet at a high linear velocity and the decrease in the density of the gas into the jet due to its expansion in the pipe, is discussed. Section 4 provides the algorithm for obtaining the solution of a system. Section 5 includes the discussion and conclusion.

2. Materials and Methods

2.1. The Proof of the Equivalence of the Equations of Motion

Mathematical modeling of non-stationary mode [19] was performed using the developed algorithm based on a simulation method [20,21] for calculating non-stationary gas movement in pipelines [22,23]. The accident data allowed establishing the boundary conditions and determining the initial pressure distribution and mass flow rate of natural gas [24].

Taking into account the above basic tasks, which are set in the design and operation of gas pipelines [25,26], you can bring basic solutions to obtain the necessary data [27]. The gas reserve in the pipeline [28] (Figure 1) at any time can be calculated using the non-isothermal, non-stationary system of Equation (1) for any type of boundary conditions [29]:

$$\begin{cases} \frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}\left(\rho v^2\right) + \frac{\partial P}{\partial x} + \rho g \sin\alpha + \frac{1}{2d}\lambda\rho v|v| = 0 \\ \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \\ \frac{\partial}{\partial t}\left(\rho\varepsilon^n + \rho\frac{v^2}{2} + \rho g H\right) + \frac{\partial}{\partial x}\left(\rho v\left(\frac{v^2}{2} + h^n + gH\right)\right) = \frac{4}{d}K_0(T - T_0), \end{cases} \quad (1)$$

All hydraulic calculations are based on the theoretical formula for the mass flow rate G for a steady isothermal flow regime:

$$G = \frac{\pi}{4}\sqrt{\frac{p_1^2 - p_2^2}{\lambda z R T_0 L}D^5} \quad (2)$$

where p_1 and p_2 are pressure at the beginning and at the end of the pipeline with length L, internal diameter D; λ is coefficient of hydraulic resistance; z is the gas compressibility factor; R is the gas constant of the transported gas; T_0 is the ambient temperature (assumed to be constant). p_1 and p_2 are selected, taking into account the characteristics of the installed equipment at the beginning and at the end of the pipeline, while ensuring the necessary strength of the pipes.

When designing and operating gas pipelines, the concept of «mass flow» is almost never used; instead, a «volume flow rate» normalized to standard conditions is used.

This expense is also called «commercial». Based on the equation, volumetric (commercial) flow rate can be expressed:

$$Q = \frac{G}{\rho_{stc}} = \frac{GRT_{stc}}{\rho_{stc}} = \frac{GRT_{stc}}{\Delta\rho_{stc}} \quad (3)$$

where ρ_{stc} is the gas density under standard conditions (Pst, Tst); R is gas constant of air; Δ is relative density of gas in air $\left(\Delta = \frac{\rho_{gas}}{\rho_{air}};\ \rho_{air} = 1.206\right)$.

If we transform Equation (2),we can obtain:

$$Q = K\sqrt{\frac{p_1^2 - p_2^2}{\lambda z \Delta T_0 L} D^5} \quad (4)$$

where $K = \frac{\pi}{4} \cdot \frac{T_{st}}{p_{st}} \sqrt{R}$.

The pressure P at a distance x from the beginning of the pipe is determined by the formula:

$$P = \sqrt{P_1^2 - \left(P_1^2 - P_2^2\right)\frac{x}{L}} \quad (5)$$

The line described by Equation (4) is a parabola, the gradient of which increases along the length of the gas pipeline.

The greatest number of accidents is created on the linear part of gas pipelines. In addition to blockage of the gas pipeline as a result of the formation of hydrates, freezing of water plugs, etc., leaks are possible. The location of damage to the linear part of the gas pipeline can be determined using the "three points" method: the line of change in the square of pressure is built from pressure measurements, and the place of its rupture will indicate a gas leak or damage to the pipeline. However, only major damage to the gas pipeline can be detected in this way. The accuracy of the «three points» method is not high and is completely determined by the accuracy of graphic constructions (Figure 2).

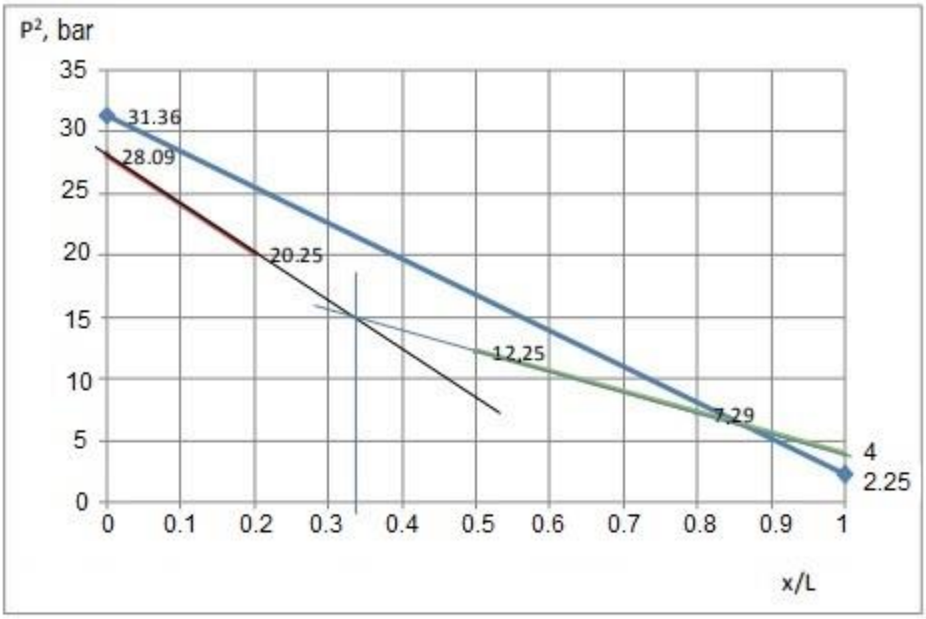


Figure 2. Determining the location of pipeline damage using the «three points» method.

2.2. Simplified Model

Technological problems [30,31] are solved by simulating gas flow parameters associated with solving the following system of differential equations [32,33]:

$$\begin{cases} h^n = \varepsilon^n + \frac{P}{\rho} \\ h^n = \frac{1}{M} h(P, T) \\ \rho = \rho(P, T) \end{cases} \quad (6)$$

where ρ is the density of natural gas, kg/m^3; υ is gas velocity at the considered point of the pipeline, m/s; P is the absolute gas pressure at a given point of the pipeline, bar; α is the angle between the generator tube and the horizontal, radian; d is the internal diameter of the pipe, mm; λ is the coefficient of hydraulic drag of the pipeline section; ε^n is specific internal energy of gas, J/kg; g is gravitational acceleration, m/s^2; H is height of the gas pipeline point above sea level, m; h^n is the specific enthalpy of gas, J/kg; K_0 is average on the site the coefficient of total heat transfer from gas to the environment, W/m^2·K; T is gas temperature at a given point of the pipeline, K; T_0 is design ambient temperature, K; M is the molar mass of gas, kg/mol; h is the molar enthalpy of gas, J/mol.

To simplify the solution of the system [34], it was assumed that the gas flow in the pipeline is stationary [35]. Under certain conditions of modeling at steady state, this solution gives good results [36,37]. However, there are many situations where these conditions lead to inaccurate results. Fluctuations in gas consumption [38], as well as disruption of valves [39], compressors, pressure regulators, or any other equipment of gas pipelines [40] cause changes in the mode of gas movement [41].

The mathematical model [42] of the onshore gas pipeline [43], which has the form of a one-dimensional, non-stationary [44], non-isothermal model of gas transportation through the onshore pipelines [45], was proposed and investigated in the report [46,47]. With a constant cross-section of the pipeline without inflow and outflow of gas [48] through the side surface, the system of equations of this model is written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial z} = 0, \tag{7}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial\left(p + \rho v^2\right)}{\partial z} = -\rho g \frac{d\tilde{y}}{dz} - \lambda \rho \frac{v|v|}{2D}, \tag{8}$$

$$\frac{\partial(\rho e)}{\partial t} + \frac{\partial}{\partial z}\left(\rho v\left(e + \frac{p}{\rho}\right)\right) = \frac{4\alpha}{D}(T^* - T) - \rho v g \frac{d\tilde{y}}{dz}, \tag{9}$$

$$e = \varepsilon + \frac{v^2}{2}, i = \varepsilon + \frac{p}{\rho}, \tag{10}$$

$$p = Z_\rho R_g T, Z = 1 + 0.07 \frac{p}{p_c T_c}\left(1 - 6\frac{T_c^2}{T^2}\right), \tag{11}$$

$$i = \int_{T_0}^{T} C_{p0} dT + RT(Z - z_2^*)\left(1 - \frac{p_0}{p}\right), \tag{12}$$

$$z_2^* = 1 + 0.84 \frac{T_c^3}{T^3} \frac{p}{p_c}. \tag{13}$$

where t is the time; z is the coordinate along the axis of the pipeline; $\rho(z, t)$, $p(z, t)$, $T(z, t)$, $v(z, t)$ is the density, pressure, temperature, and velocity of the gas averaged over the cross-section of the gas pipeline; $e(z, t)$, $\varepsilon(z, t)$, $i(z, t)$ are the specific total energy, the internal energy, and the enthalpy of the gas; D is the diameter of the pipeline; $\tilde{y}$ is the ordinate of the point z of the pipeline axis; $\tilde{y} = z\sin(\varphi)$, φ is the angle between the axis of the pipeline and the horizontal plane, the derivative $\frac{d\tilde{y}}{dz}$ on the descent negative, on the rise is positive; $\lambda = \lambda\ (Re, k)$ is the coefficient of hydraulic resistance; $Re = \rho v\ D/\mu$ is the Reynolds number; μ is the coefficient of dynamic viscosity of a gas; k is the coefficient of relative roughness; α is total heat transfer coefficient through the side surface of the pipeline; T^* is the ambient temperature; Z is the compressibility factor of the gas; R_g is the gas constant; p_c, T_c is critical pressure and gas temperature; c_{p0} is the mass density of the heat capacity at constant pressure.

The mathematical model for the offshore gas pipeline is presented in the work [49,50], shows the calculation of non-stationary gas-dynamic processes [51] in the gas pipeline at the underwater crossing through the sea [52]. The simplified versions of this model are given, which are used in papers [53–55]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial z} = 0, \tag{14}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial\left(p - \rho g y + \rho v^2\right)}{\partial z} = -\lambda \rho \frac{v|v|}{2D} - g y \frac{\partial \rho}{\partial z}, \tag{15}$$

$$\frac{\partial}{\partial t}\left(\rho\left(\varepsilon - g y + \frac{v^2}{2}\right)\right) + \frac{\partial}{\partial z}\left(\rho v\left(i - g y + \frac{v^2}{2}\right)\right) = \frac{4\alpha}{D}\left(T^* - T\right), \tag{16}$$

$$i = \varepsilon + \frac{p}{\rho} \tag{17}$$

$$p = p(\rho, T), \varepsilon = \varepsilon(\rho, T), i = i(\rho, T) \tag{18}$$

The proof of the equivalence of the equations of motion of the mathematical model for the onshore gas pipeline and the mathematical model for the offshore gas pipeline can be converted as follows:

$$\begin{gathered}\frac{\partial \rho v}{\partial t} + \frac{\partial\left(p+\rho v^2\right)}{\partial z} - \rho g \frac{dy}{dz} - g y \frac{\partial \rho}{\partial z} = -\lambda \rho \frac{v|v|}{2D} - g y \frac{\partial \rho}{\partial z} \rightarrow \frac{\partial \rho v}{\partial t} + \frac{\partial\left(p+\rho v^2\right)}{\partial z} =, \\ = \rho g \frac{dy}{dz} - \lambda \rho \frac{v|v|}{2D} = -\rho g \frac{dy}{dz} - \lambda \rho \frac{v|v|}{2D},\end{gathered} \tag{19}$$

The equations of motion in these mathematical models are the same.

A mathematical model of the distribution of natural gas along the length of the pipeline has been obtained, which makes it possible to calculate the fields of gas concentrations during its interaction with air. The mathematical model includes three-dimensional non-stationary equations of continuity, momentum, and mass transfer, averaged by Reynolds of the Navier–Stokes equations.

3. Application Examples

3.1. Locating the Leak and Assessing the Magnitude of the Gas Leak

During normal operation, the pressure at the beginning and end gas pipeline P_1 = 56 bar and P_2 = 15 bar. After some time, the instruments showed the following pressure values: P_1 = 53 bar, P_2 = 20 bar; the distance x/L = 0.2, 0.5, 0.8; $P_{0.2}$ = 45 bar; $P_{0.5}$ = 35 bar and $P_{0.8}$ = 27 bar. It is necessary to determine the location of the leak and make an assessment of the magnitude of the gas leak.

3.2. Model Verification Solution

Let us denote the pressure on the graph by squares (Figure 2). The point of intersection shows the location of the damage x/L = 0.34 and the pressure at the location of the damage:

$$P_1 = \sqrt{15} = 38.7 \text{ bar} \tag{20}$$

Let us determine the pressure in the section x/L = 3.4 bar in normal mode using Equation (5):

$$P_{3.4} = \sqrt{56^2 - \left(56^2 - 15^2\right)3.4} = 46.3 \text{ bar} \tag{21}$$

Assuming the invariance of the flow regime, based on the flow formula, the relative flow rate Q_1 in the section up to the point of pipe damage will be:

$$\frac{Q_1}{Q_0} = \sqrt{\frac{p_1^2 - p_2^2}{p_1^2 - p_{3.4}^2}} = \sqrt{\frac{53^2 - 38.7^2}{56^2 - 46.3^2}} = 11.5 \tag{22}$$

where Q_0 is consumption of gas in the pipeline before damage.

The same conditions determine the flow rate in the area after the damage site:

$$\frac{Q_2}{Q_0} = \sqrt{\frac{p_1^2 - p_2^2}{p_{3.4}^2 - p_2^2}} = \sqrt{\frac{38.7^2 - 2^2}{46.3^2 - 15^2}} = 7.57 \tag{23}$$

The leakage in the pipe will be:

$$Q_{leak} = Q_1 \cdot Q_2 = (11.5 - 7.57) = 3.93Q_0 \quad (24)$$

3.3. Model Verification and Solution

Solving the non-stationary problem, taking into account phase transitions in the spectrum of temperature and pressure changes, the temperature dependences of the thermal conductivity coefficient and the condensate content were used. An onshore gas pipeline with output parameters is considered as an example in (Table 1) and (Figure 3).

Table 1. The main parameters of the gas pipeline for operating conditions.

Pressure, (bar)	Nominal Pipe Size, (in)	Wall Thickness, (in)	Temperature Difference, (°C)
75	55.9″	0.85″	35

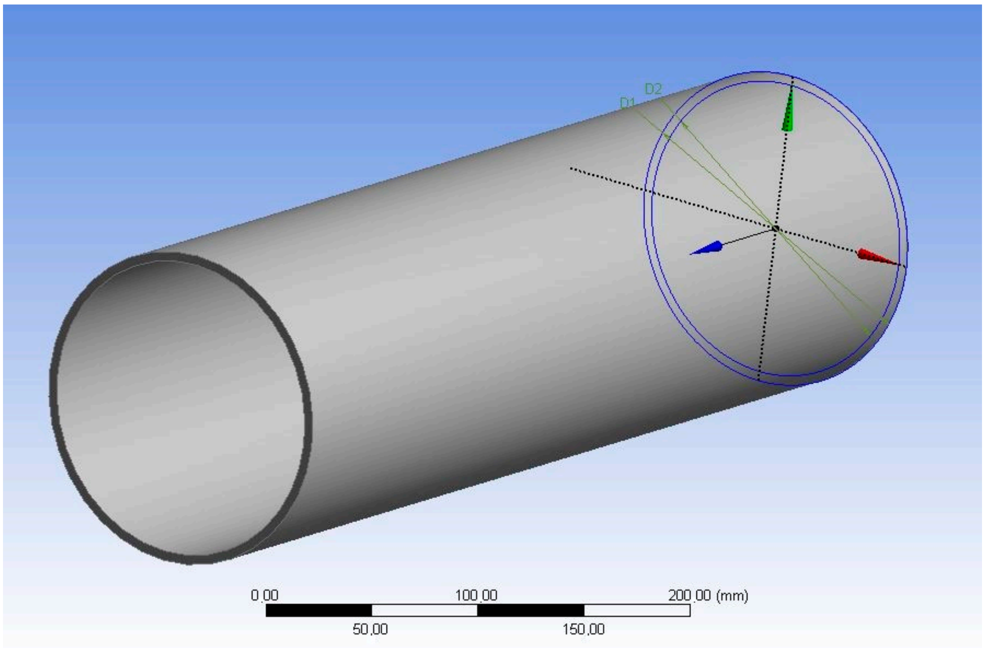


Figure 3. Pipe model.

The soil temperature on the surface is constant at 6 °C. The volumetric heat capacity and specific heat capacity of soils at different soil moisture and density were compared with independent estimates using the obtained theoretical ratios [56]. The thermophysical properties of the soil are given in (Table 2).

Table 2. Thermal properties of the soil.

Characteristic	Frozen Soil, (Sand)^1 (Clay)^2	Thawed Soil, (Sand)^1 (Clay)^2
Thermal conductivity, kJ kg^{-1} °C^{-1}	(0.83–1.67)^1 (1.17–2.25)^2	(1.09–3.04)^1 (1.13–1.98)^2
Thermal diffusivity, MJ m^{-3} °C^{-1}	1.48–3.54	1.56–3.51
Specific heat of condensate, MJ m^{-3} °C^{-1}	1.44	1.35
Soil moisture	0.410	0.410

Sandy soil had higher thermal diffusivity than clay soil. By definition, thermal diffusivity is the ratio of thermal conductivity and volumetric heat capacity [56]. Beyond a certain bulk density, higher values of moisture content increased thermal conductivity less rapidly in the case of clay and more rapidly in the case of sand. Increasing water content in sand perhaps completed water films around the larger sand particles than silt and clay, thus increasing the contact area between sand particles, which caused the thermal conductivity to increase rapidly. In addition, the differences in mineralogy and sand, silt, and clay fractions could be the primary reasons that sandy soils often have a higher thermal conductivity and diffusivity than clay soils [56].

The equation has been verified for the three-dimensional non-stationary of continuity, momentum, and mass transfer, averaged by Reynolds of the Navier–Stokes equations, which is used in the mathematical model for the onshore gas pipeline under the conditions of non-stationary processes of compressible gas flow, which has been performed. The next step is to calculate the stress state of the pipeline.

The published results of solving the problem using several ANSYS calculation models of thermal interaction are compared below (Figure 4). Comparative analysis showed that all considered models give similar results (a,b).

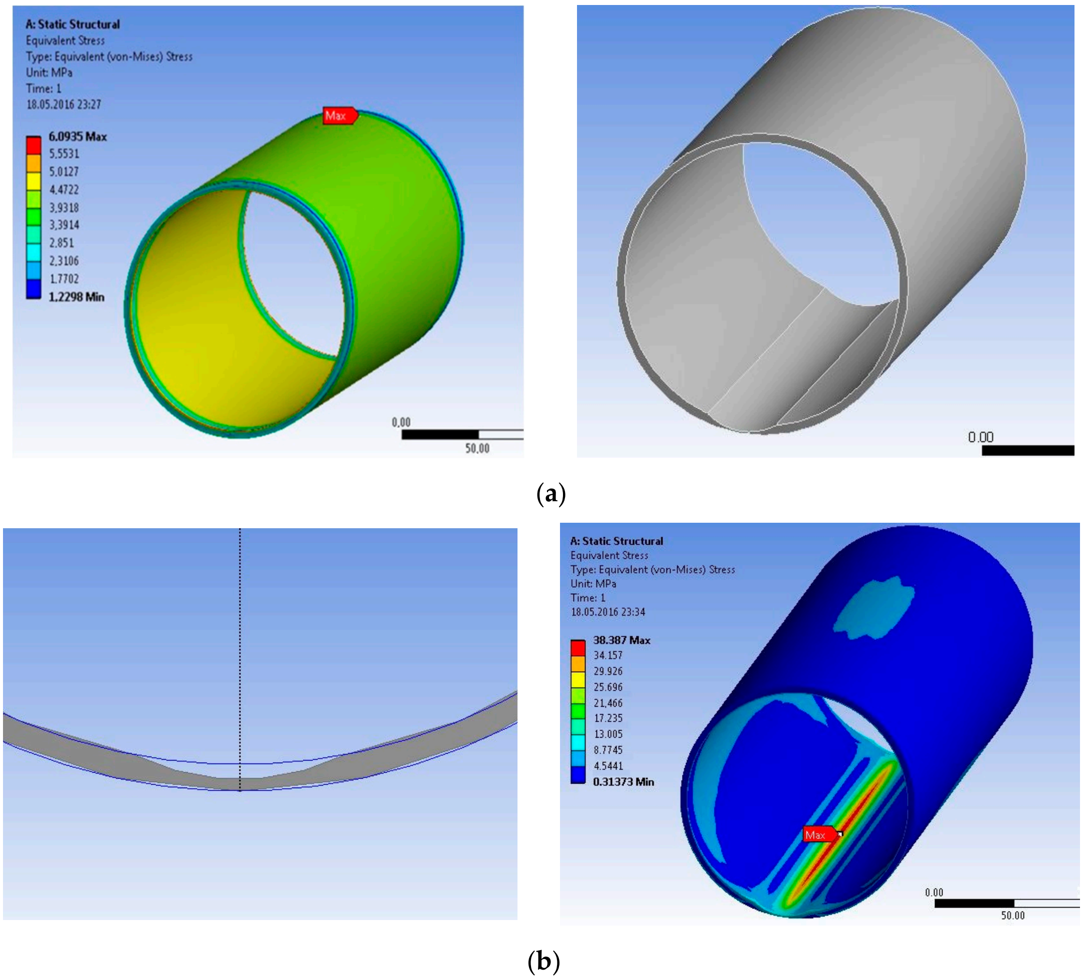


Figure 4. The stress state of the pipe, showing: (**a**) Before stress; (**b**) After stress.

Therefore, the model makes it possible to obtain correct calculation results when changing temperature fields and pressure in the pipeline operation.

The next step is to calculate according to the algorithm (Figure 5).

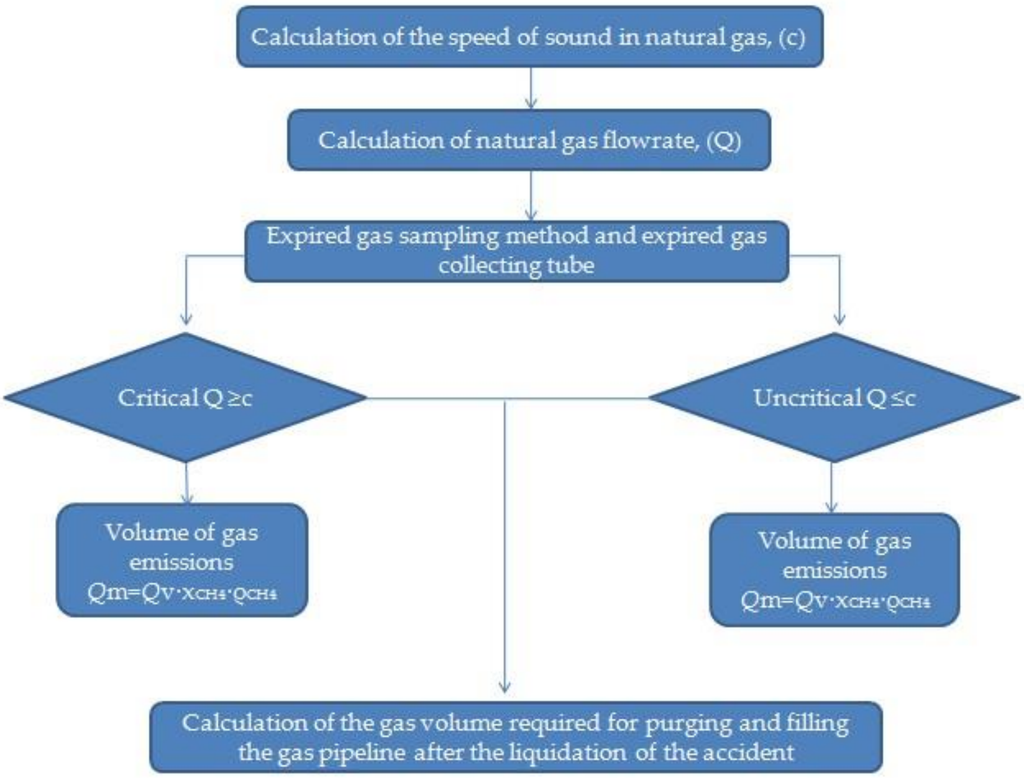


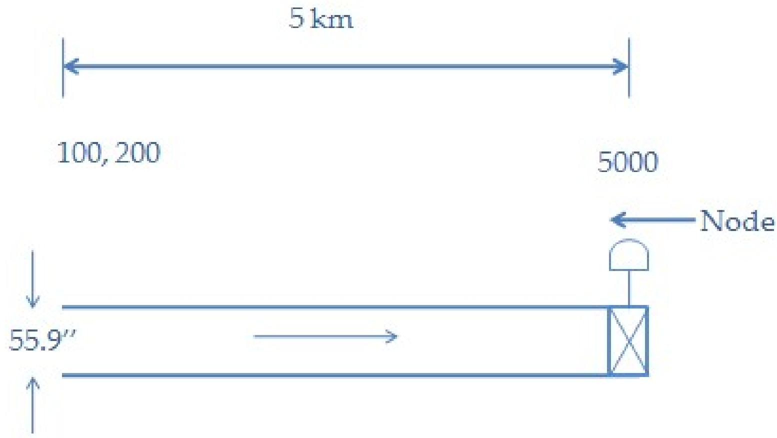
Figure 5. Algorithm for calculating the volume of emergency gas emissions where Qm is the mass rate, expressed in (kg) per time unit; Qv is the volumetric rate, expressed in (m^3) per time unit; x_{CH4} is the methane share in the natural gas composition (in %), typical for a particular gas system, subject to reporting; ρ_{CH4} is the density of methane (i.e., 0.715 kg/m^3 in normal conditions; i.e., at 0 °C and 1 bar).

When obtaining the solution of a non-stationary system of equations with boundary conditions, such as pressure at the beginning of the pipeline, mass flow at the end of the pipeline, in the following order:

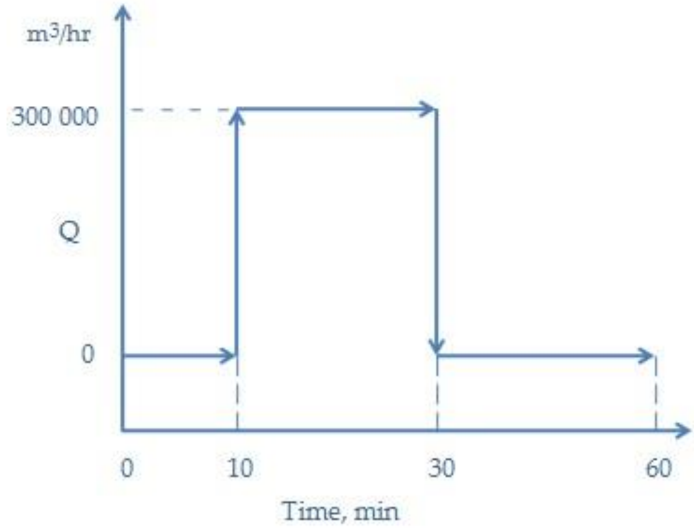
1. We have to the build a grid by coordinate and time, set the distribution of flow and pressure at the initial moment of time.
2. Obtainthe initial approximation for pressure and flow at time dt.
3. Check the initial approximation, whether it is a solution to the system of Equation (6).
4. If the solution obtained satisfies the system of Equation (6), then the iterations stop; otherwise, the next approximation is carried out until the iteration process is completed.
5. We have to the build a solution for the next time step.

The algorithm of the system is based on the equations of unsteady gas motion, continuity, and energy, using the equation of state of a real gas, which forms a closed system. When studying the response of the system to a sudden cessation of gas supply by shutting off a linear crane, it may occur in the case of an accident on a single-line gas pipeline, consisting of two main nodes—input and output. These nodes simulate compressor stations.

The comparison uses the system described by Kiuchi (1994). This system is modeled as a simple straight line 5 km in length, having a diameter 55.9″ inches, and holding a gas of molecular weight 18.0 at a pressure of 50 bar as shown in (Figure 6).



(**a**)



(**b**)

Figure 6. Pipe and boundary condition for flow through the valve: (**a**) before the valve; (**b**) after the valve.

As the outlet valve opens, and the outflow increases from zero to 300,000 m^3/h, flow rate m^3/h is shown in the standard condition (100 kPa, 288.15 K) while the inlet pressure is maintained at 50 bar. The mathematical model of the system is based on the equations of unsteady gas motion, continuity, and energy, using the equation of state of a real gas, which forms a closed system. Mathematical model created for the linear section of the pipeline length L = 5 km, at the beginning of which gas is taken off at a constant mass flow rate $m = 50\frac{kg}{s}$.

4. Results

Analyzing Figures 7 and 8, we can draw the following conclusions. The assumptions underlying the dependence of the mass flow rate when gas flows out of the tank through a hole in a thin wall have a significant impact on the results of the process simulation, because the real mass flow rate is significantly different from the calculated one.

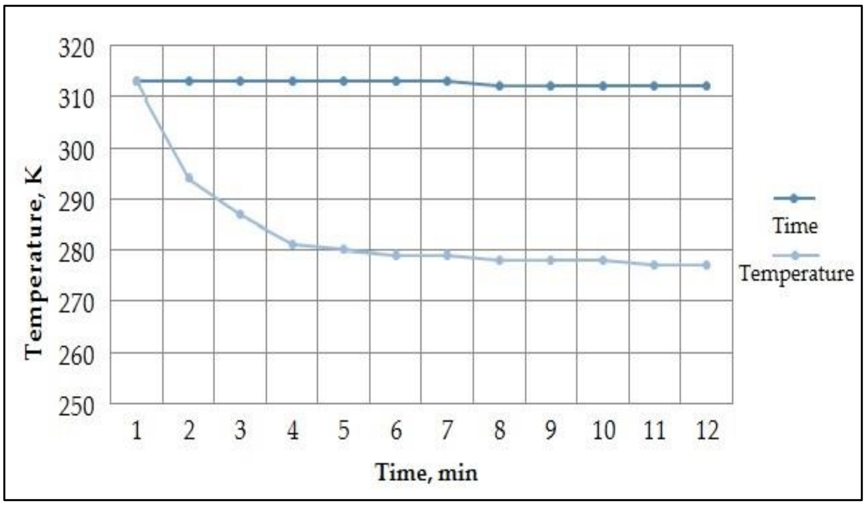


Figure 7. Gas Temperature Change Graph.

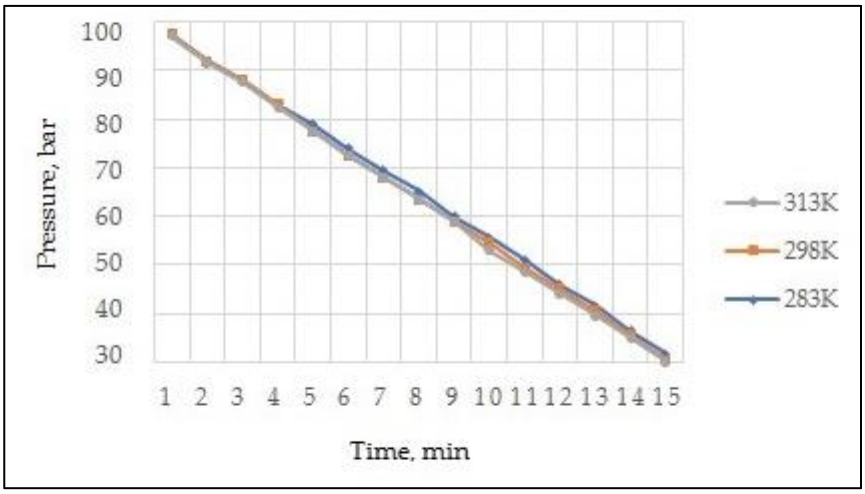


Figure 8. Pressure change in pipeline.

When the absolute pressure in the receiver changes from 10 bar to 5 bar (the end of the critical outflow zone), the flow coefficient changes from 0.776 to 0.709 at the temperature in the 288 K receiver. An increase in the gas temperature in the receiver leads to a more significant deviation of the actual flow rate from the theoretical one. Then, at a temperature in the 283 K receiver and a pressure of 10 bar, the flow coefficient is 0.776, and as the temperature rises to 298 K, it drops to 0.756, and as the temperature rises further to 313 K, it drops to 0.738 (Figure 9).

Thus, one of the reasons for the inadequacy of the mathematical model is the neglect of the growth of the gas-dynamic resistance of the medium to the motion of the gas jet with a high linear velocity and the decrease in the density of the gas into the jet due to its expansion. This method of calculation is simple in its solution, because it depends in general only on minor changes in the load of gas-pumping units, while ensuring that the main condition of the optimization problem is fulfilled, maintaining the general established operating mode of the main gas pipeline.

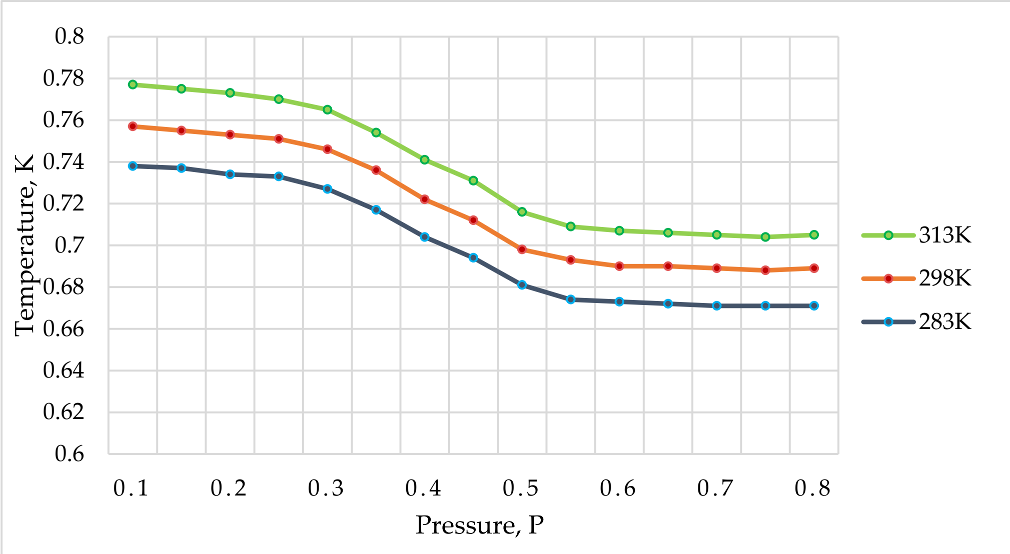


Figure 9. Change in gas consumption coefficient depending on pressure and temperature.

5. Discussion

As a result of the study, analytical dependencies were obtained that make it possible to assess the safety margins of pipelines, taking into account the internal pressure, its changes due to the unsteadiness of the gas-pumping mode, the regulation of the pumping mode, the geometric characteristics of pipes and their connections, and the mechanical properties of the pipe metal. The analysis showed that under the conditions of non-stationarity of the transfer mode without its regulation, the level of mechanical stresses in the pipe wall in a number of cases exceeds the standard values.

The analysis of the influence of the parameters of the regulation of the pumping mode, the geometric characteristics of pipes, and their connections on the level of mechanical stresses and safety margins of pipelines is carried out.

Under the same loading conditions, the greatest stresses arise in the cross-sections of the pipeline connection with equipment with absolute rigidity for deformation. The analysis showed that in a number of non-stationarity cases, the stress level and safety margins do not meet the regulatory requirements. Changing the pipeline performance due to the use of the main pumping units equipped with a drive that regulates the pump shaft speed ensures smooth changes in the internal pressure, a significant decrease in the maximum stresses in the pipe wall, and an increase in the safety margin.

For real conditions, a smooth change in the pumping mode makes it possible to increase the safety margins of the pipeline in the section of its connection with the equipment from 1.2 to 2.4 times. At the same time, with an increase in the length of the pipeline section, on which there is a change in the pumping mode with internal pressure, the speed of the movement of the pumped product, there is a decrease in the level of the stress state of the pipeline. The presence of a rational length in the section of smooth change in the pumping mode of the product was revealed, more than which there is no significant reduction in the highest stresses and an increase in safety margins. An increase in safety margins reduces the risk of an accident and increases the safety of the gas pipeline operation. The regulation of the product-pumping mode under conditions of non-stationary technological parameters by pumping units equipped with a variable drive ensures the safety of the gas pipeline operation at an acceptable level.

6. Conclusions

This study focuses on dynamic modeling and the modeling of a gas pipeline network as a result of a change in the operating mode. Pipelines, and more generally long tubular structures, are major oil and gas industry tools used in exploration, drilling, production, and transmission. The high pressures and elevated temperatures, the high ambient external pressures, the large forces involved during installation, and generally the hostility of the environment can result in a large number of limit states that must be addressed [57]. Various methods are used in pipeline installations, and it is necessary to take into account the effect of stresses on the pipeline walls on the stability of the soil during installation [58].

The resulting mathematical model can be used for any calculation of the change in the operating mode of a steel pipeline currently used, and the formula takes into account the coefficients of hydraulic friction, density, pressure, temperature, gas velocity, etc.

The practical application is as follows: One of the ways to provide gas to the consumer in the required quantity is the use of the last section of the gas pipeline as a storage tank. The nature of the operation of the last section of the gas pipeline has its own characteristics. This is due to the fact that the last compressor station operates at a constant capacity mode, and the gas consumption at the end of the last section coincides with the city's gas consumption schedule (in the absence of underground gas storages and other storage tanks). During periods when the city's gas consumption has less productivity in the last compressor station (almost coinciding with the average daily productivity), the gas is accumulated in the gas pipeline itself. In this case, the pressure at the compressor station outlet slightly increases to the value P_1, and the pressure at the end of the gas pipeline can reach its maximum values of P_2. During the period of the highest gas consumption, the missing gas is compensated by the accumulated gas and the withdrawal of an additional amount of gas with a decrease in pressure at the end of the gas pipeline to P_2. In this case, the pressure of the compressor station will decrease to P_1. Using the method of successive changes in the stationary state of the gas into a non-stationary one, it is possible to obtain the storage capacity of the last section gas pipeline using a mathematical model and algorithm.

Numerical equations with derivatives and the integration of these equations into an algorithm were proposed. Only the implementation of the mathematical model and the construction of the algorithm were explained in detail, because this was the goal of the project. Solutions in this article show that the change in pressure, temperature, and gas constant parameters cannot be neglected, because there is a significant pressure drop at the outlet when using different values of these coefficients. As a further study, it is proposed to use the developed algorithm in the developed program of the gas pipeline accident library to simulate various operating conditions in order to gain deeper knowledge about such systems. The implementation of such a program is a very powerful tool to test the various management strategies proposed for pipeline-compressor station systems.

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