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Developing the model of non-stationary processes of motion and discharge of single- and two-phase medium at emergency releases from pipelines

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Abstract. The system of equations describing gas dynamic processes with extremal gradients of velocity, temperature, concentration and pressure in pipeline systems is presented. The proposed model most completely takes into account the actual processes in pipeline systems transporting various media. The model is formulated in one-dimensional approach. However it takes into account the multidimensional effects affecting the flow, including the development of non-equilibrium processes. These multidimensional effects are due to the branching pipeline, diameter change, valve shut down. This model can be used for modeling an emergency situation, that includes single- and two-phase mediums release.

1. Introduction

Trunk pipelines are used to transport liquid or gaseous products (typically hydrocarbon raw materials) over distances of hundreds or even thousands of kilometres. The great length of piping systems and their large diameter (up to 1200 mm) requires presence of up to several hundred or even thousand tons of product in a pipeline system. It is obvious, that such a huge mass of products can produce a considerable damage if this mass is released in case of accident.

On the other hand, there are a lot of events producing considerable changes in flow through creating large gradients. Examples of such actions are:

- changes in pump operation;
- shut down of valves;
- releases through pressure relief systems;
- rupture of the pipeline;
- heating of the transported product;
- injection of a product with different composition or temperature into the pipeline system;
- cavitation etc.

As a result, gradients of different nature (velocity, temperature, concentration and phase) may appear in the pipeline. These gradients can initiate various processes, provoking a new mode of operation in the pipeline system.

Thus, the pipeline system can be treated as a system, turning in its functioning from one state to another through series of gas dynamic processes. These processes may cause stress that could destroy the pipeline, releasing hundreds or even thousands tons of its content into the environment.

So modelling pipeline systems as real (non-idealized) ones is an urgent task and appropriate models for this description are needed. However, in most cases the pipelines are described in significantly simplified interpretation. Typically the simplified model is used for modelling a pipeline. This system of equations describes an isothermal single component flow in the relief, taking into account the losses due to friction against the walls [1,2]. This approach narrows the range of consideration of real-life situations, many pipeline systems and modes of their operation can not be modelled in the framework of models of the type [1,2].

In this paper the system of equations, describing the behavior of a pipeline system with velocity, temperature, concentration, pressure and phase gradients, is presented. This system of equations allows to simulate a wide range of practical problems.

2. Mathematical model

2.1. Main assumptions

To describe the flow in the pipeline we propose to use the following scheme for one-dimensional stationary equations expressing conservation laws in one-velocity approximation for all transportable components. It is assumed that all the parameters are averaged over the cross section. It is believed that there is no flow rotation.

It is assumed that the pipe system has arbitrary branched configuration (with looping, by-pass from the output to the output of the pump, etc.). The mixture of N different substances with a mass fraction Y_m ($\sum_{m=1}^{N} Y_m = 1$) is transported in the pipeline system. It is assumed that the components of the mixture do not react and do not fall down onto the inner surface of the pipeline.

We consider flow under head gradient, when the tube cross section is blocked by the transported medium completely, i.e. gravity-fed areas (shallow water flow) are not considered.

2.2. Conservation equations

System of equations using assumptions stated above, is as follows.

The law of mass conservation (continuity equation)

$$\frac{\partial(\rho \cdot A)}{\partial t} + \frac{\partial(\rho \cdot A \cdot w)}{\partial x} = M_k - M_0 \tag{1}$$

The law of individual components conservation:

$$\frac{\partial(\rho \cdot A \cdot Y_m)}{\partial t} + \frac{\partial(\rho \cdot A \cdot Y_m \cdot w)}{\partial x} = Y_{mk} M_k - Y_m M_0 + \frac{\partial}{\partial x}\left(\rho \cdot A \cdot (D_m + D_{turb}) \cdot \frac{\partial Y_m}{\partial x}\right) \tag{2}$$

Conservation of momentum:

$$\frac{\partial(\rho \cdot A \cdot w)}{\partial t} + \frac{\partial(\rho \cdot A \cdot w^2)}{\partial x} = I_k - I_0 - A \cdot \frac{\partial p}{\partial x} - A \cdot g \cdot \rho \cdot \frac{\partial z}{\partial x} - \frac{\pi}{2} \cdot \left(\frac{\lambda}{2 \cdot R} + \xi_l\right) \cdot \rho \cdot w \cdot |w| \cdot R^2 \tag{3}$$

The law of energy conservation:

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$$\frac{\partial}{\partial t}\left(\rho\cdot A\cdot\left(\varepsilon+\frac{w^2}{2}\right)\right)+\frac{\partial}{\partial x}\left(\rho\cdot A\cdot w\cdot\left(\varepsilon+\frac{w^2}{2}\right)\right)=$$
$$E_k-E_0+\frac{\partial}{\partial x}\left(\rho\cdot A\cdot\sum_{m=1}^{N}\varepsilon_m\cdot\left(D_m+D_{turb}\right)\cdot\frac{\partial Y_m}{\partial x}\right)+$$
$$-\frac{\partial(A\cdot p\cdot w)}{\partial x}-A\cdot w\cdot g\cdot\rho\cdot\frac{\partial z}{\partial x}-\frac{\pi}{2}\cdot\left(\frac{\lambda}{2\cdot R}+\xi_l\right)\cdot\rho\cdot w^3\cdot R^2 \tag{4}$$
$$+Q\cdot A+\frac{\partial}{\partial x}\left(\left(k+k_{turb}\right)\cdot A\cdot\frac{\partial T}{\partial x}\right)-\Theta\left(T,T_{sur}\right)$$

here t – time, g – the acceleration of gravity, k – the coefficient of thermal conductivity, k_{turb} – the coefficient of turbulent heat transfer, x – distance from the pipeline beginning, p – pressure averaged over the cross section of the pipe, z –leveling mark track, w – velocity averaged over the cross section of the pipe, ε – specific internal energy, ε_m – specific internal energy of the m-th component, ξ_l – local friction losses, λ – the friction coefficient, which depends on the flow regime in the pipe (Reynolds number $\mathrm{Re}=\frac{wD}{\nu}$), ν – kinematic viscosity ($\nu = \mu/\rho$), μ – dynamic viscosity of transported product (in general, depending on the temperature of the transported medium), π – a number equal to 3.14 ..., ρ – density averaged over the cross section of the pipe, A – cross sectional area of the pipeline, D – inner diameter of the pipeline, D_m – the diffusion coefficient of the m-th component of the transported product; D_{turb} – the coefficient of turbulent diffusion, E_0 – the intensity of the energy loss with the release of the transported product at the site of the accident, E_k – flow rate of additional energy in/out of k-th pipeline, I_0 – intensity of the loss of momentum with the release of the transported product at the site of the accident, I_k – flow rate of additional momentum in/out of k-th pipeline, M_0 – intensity of the loss of mass with the release of the transported product at the site of the accident, M_k – flow rate of additional mass in/out of k-th pipeline, Q – intensity of heat exchange with the environment (heating of the transported product), R – the inner radius of the pipe, T – temperature, T_{sur} – soil temperature, Y_m – mass fraction of m-th component, Y_{mk} – mass fraction of m-th component in flow of mass in/out of k-th pipeline, $\Theta(T,T_{sur})$ – the function of heat exchange with the ground.

If a product is transported at a constant temperature (an isothermal process) the equation (4) can be neglected. However, in some cases in the pipeline system thermal nonequilibrium can occur. Then it is necessary to solve the equation (4) to:

- take into account the transportation of initially pre-heated products;
- take into account additional injection of products with different temperature in the pipeline;
- take into account the variation of the soil temperature;
- take into account the change in temperature when boiling of unstable liquids or gas expansion in rarefaction waves takes place.

It should also be noted that in the general case, the value ε_m in equation (4) consists of two parts: elastic energy and heat energy (in the presence of a liquid phase). But in the case of transporting of fluids through pipelines elastic energy is small and can be neglected in ε_m. Accordingly, equation (4) can actually be considered as a heat balance equation.

2.3. Initial and boundary conditions

The equations (1)-(4) are supplemented by initial and boundary conditions. As the boundary conditions the pressure is set on the inlet and outlet of the pipeline, this pressure corresponds to the pressure of the pumps or vessel at the ends of the pipeline. As an initial data the parameters are set for the stationary pumping, which can be obtained analytically from the solution of the system (1)-(4).

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In a more general case, boundary conditions are set by specifying more complex dependency parameters corresponding to real devices located at the ends of the linear section. This approach considers boundaries of the following types:

- presence of diverse valves in various stages of closing at the ends of the pipeline;
- pumps/compressors (or group of pumps/compressors) taking or injecting the transported product;
- safety relief valve;
- interconnections with other pipelines of different diameters;
- pipeline branching;
- presence of release on the site of the accident;
- presence of a vessel at a pipe inlet or outlet.

For example, for a closed valve zero velocity is a boundary condition.

The system (1)-(4) describes the flow in one linear sector. In the case of a branched pipeline system when the individual linear sectors are combined in a specific sequence, the system of equations (1)-(4) is recorded for each linear sector. The boundary conditions at the connection of two linear sectors are set in such a way that the flows of mass and impulses could be correctly transferred from one sector to another (according to the conservation equations).

The considered model takes into account the following factors:

- non-stationary processes;
- variable cross-section of the pipeline;
- convective motion of the medium;
- appearance and circulation of the waves at a stop/start up of the pumps, closing valves;
- presence of friction on the pipe wall;
- gravity force effect on the flow, when the pipeline's route goes along complex terrain.
- taking away/injection of mass, momentum and energy out/into the pipeline system;
- loss of mass, momentum and energy in the system due to release of the product at rupture point;
- molecular and turbulent diffusion of individual components of the mixture along the axis of the pipeline;
- heating of the transported product;
- molecular and turbulent transport of heat;
- heating of the product transported by the pipeline to the ground (via the pipe wall).

Some of physical processes are not taken into account in the equations (1)-(4), because these processes have a negligible effect. For example, in equation (3) we don't consider turbulent viscosity in the direction of fluid flow. This is due to the fact that the velocity gradient along the axis of the flow in the absence of a shock wave is very insignificant, so the action of turbulent viscosity is also low.

The system of equations (1)-(4) enables to describe the motion of the liquid, gaseous or two-phase medium, in the latter case for different phases equilibrium velocity approximation is used.

2.4. Closer equations

The system of equations (1)-(4) is not closed, it includes the value for which you need to specify methods of calculation: pressure, friction coefficients , the laws of heating and heat exchange with the soil, source (and boundary) terms - M_0, M_k, I_0, I_k, E_0, E_k..

The closure of system (1)-(4) is carried out by different means for different mediums in various phase states.

For example, to calculate the pressure it is necessary to know the equation of state - the relationship between pressure, density and specific internal energy: In the most general case, this relationship can be obtained by thermodynamic calculation (solution of UV task).

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This approach is versatile and can be used for both liquid and gaseous, and two-phase media. In the latter case, the solution of UV-problem is especially attractive, since it will determine not only the pressure but also the ratio of gas and liquid phases, as well as their composition.
In the case of transportation of liquid, neglecting the elastic component of the energy for the calculation of the pressure and temperature, one can use the following equation:

- the relation between pressure, density and temperature (equation of state):

$$P_c - P_0 = c^2(\rho - \rho_0) - c^2 \rho_0 \varsigma (T_0 - T), \tag{5}$$

- equation for termal part of energy:

$$\varepsilon_m = C_v T \ , \tag{6}$$

here ρ_0 – density at standard conditions p_0=101325 Pa, T_0=293 K, ς –coefficient of volume expansion, C_v – average specific heat/.
In a similar way (i.e. taking into account the phase states) other physical quantities in the system (1)-(4) are calculated. For liquids closer assumptions about these variables, can be found in [3].

3. Calculation of water hammer flow without and with mass release

A typical example of a flow in the pipeline system is water hammer - appearance and propagation of a high pressure wave in a pipeline. In this case the pipeline system can evolve through several states.
Let us consider the following example of a pipeline system. There is a 2 km long pipeline to pump liquid product. The vessel with 2 atmospheres pressure is placed at the inlet of the pipeline The vessel with 1.5 atm pressure is placed at the end of the pipeline. The first vessel is raised above the second to the height of 200 m. The tube diameter is 500 mm. The density of the product is 860 kg/m^3 and the viscosity of the transported product is 10^{-4} m^2/s. The valve is installed at the end of the pipeline (before the vessel). The time of the complete flow shutdown is 3 seconds. The perturbation propagation velocity is taken equal to 1200 m/s, and the velocity of sound in the liquid is taken equal to 1250 m/s for this system.

This pipeline is a realistic model, for example, for a process like a sea tanker loading from a shore tank.

The flow in this pipeline occurs due to both pressure gradient and gravity. The pressure profile for the steady-state flow is shown in figure 1. The flow shut down at the end of the pipeline is the event triggering the appearance of non-equilibrium. A high pressure area is formed before the valve, then this area extends over the entire pipeline. The dynamics of such pressure increase is shown in figure 2 (lines 1-8). As a result, the system goes into a new state, corresponding to hydrostatic equilibrium. Thus, the proposed model allowed us to simulate a nonequilibrium process initiated by the closing of the valve.

As one can see in figure 2, relatively high pressure can be achieved during non-equilibrium transformations in the system and its transition to a state of rest (up to 84 atm). The distribution of the maximum pressure achieved is shown in figure 2 (line “max pressure”). Special relief valve is used to prevent the high pressure rise. This is another element of the pipeline system, which may contribute to the development of non-equilibrium process. The results of solving the problem stated above are presented in figures 3-4. These calculations take into account the presence of the relief valve, that is located 500 meters to the end of the pipeline. The diameter of the relief valve is 100 mm. Figure 3 shows pressure profiles at different time points (line 1-8) and the maximum pressure profile achieved (line “max pressure”) if the valve is activated, when pressure reaches 5 atmospheres. Figure 4 shows the same profiles if the valve is activated, when pressure reaches 10 atmospheres.. As one can see in figures 3 and 4, the working pressure has minor effect on the pressure reached in the pipeline. This is due to the rapid increase in pressure. As a result the relief release starts at about the same time, so there is practically no difference in the data presented in figures 3 and 4.

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It is clear in figures 2-4 that the presence of the relief valve considerably reduces the pressure that can be reached in the pipeline. Thus, a relief valve can be regarded as a controller of non-equilibrium by creating other non-equilibriums.

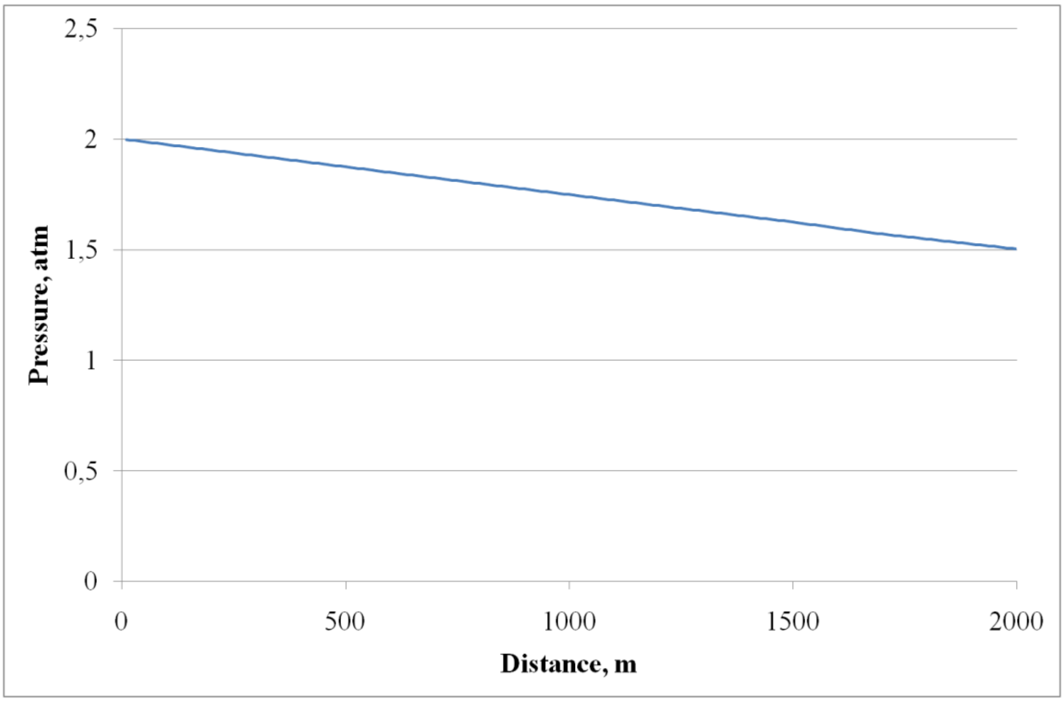

Figure 1. Pressure vs. distance at stationary state.

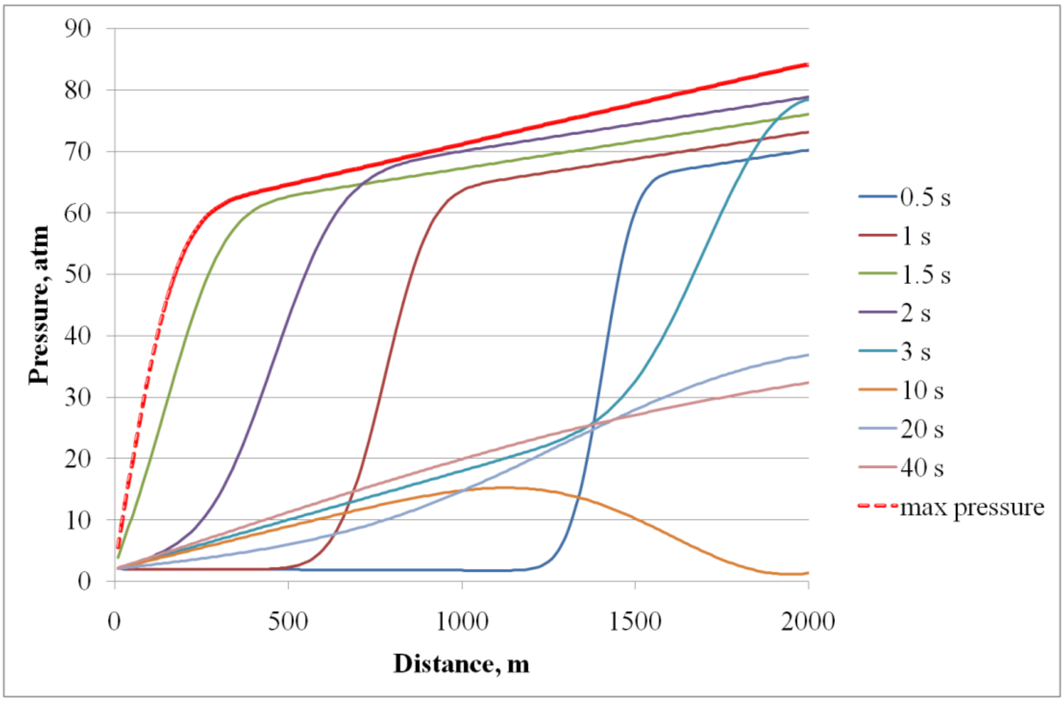

Figure 2. Pressure vs. distance at different time points after valve closing starts: 1 – 0.5 s; 2 – 1 s; 3 – 1.5 s; 4 – 2 s; 5 – 3 s; 6 – 10s; 7 – 20 s; 8 – 40 s (in the absence of pressure relief system).

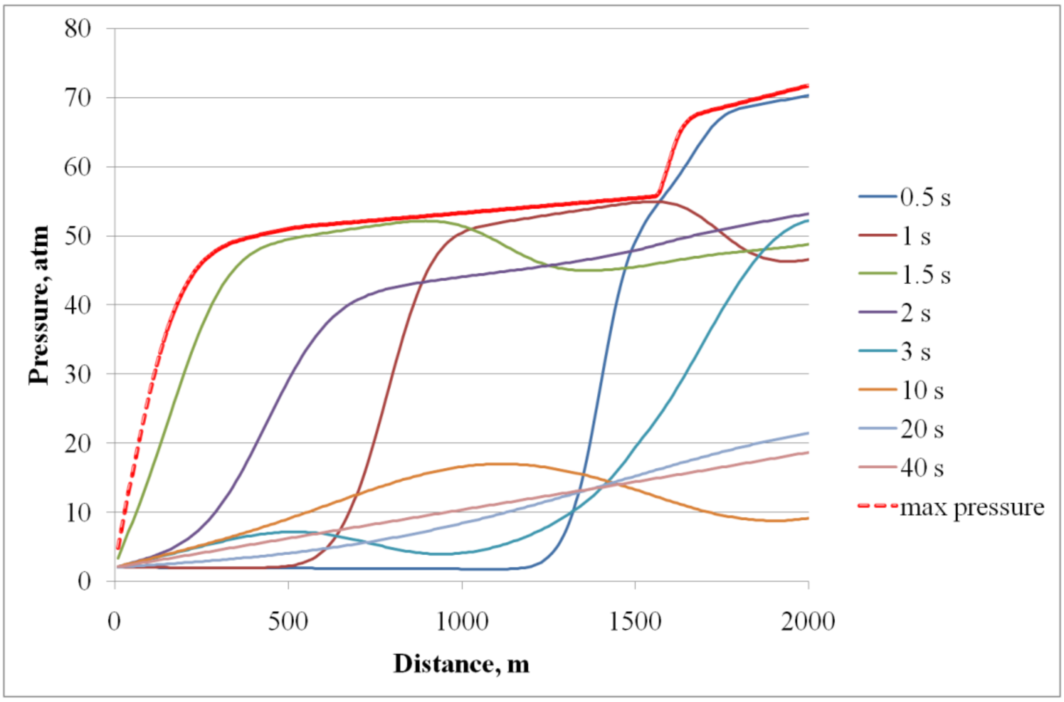

Figure 3. Pressure vs. distance at different time points after valve closing starts: 1 – 0.5 s; 2 – 1 s; 3 – 1.5 s; 4 – 2 s; 5 – 3 s; 6 – 10s; 7 – 20 s; 8 – 40 s (the working pressure of relief system is 5 atm).

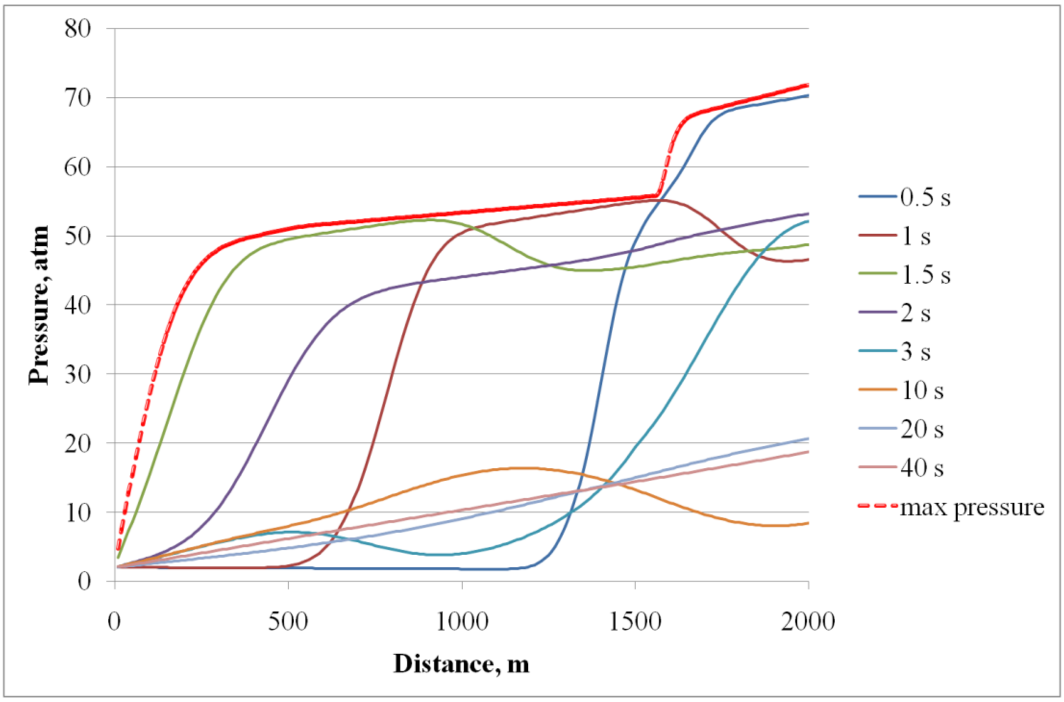

Figure 4. Pressure vs. distance at different time points after valve closing starts: 1 – 0.5 s; 2 – 1 s; 3 – 1.5 s; 4 – 2 s; 5 – 3 s; 6 – 10s; 7 – 20 s; 8 – 40 s (the working pressure of relief system is 10 atm).

4. Conclusion

To describe the motion of fluids (gas, liquid or two-phase) in the pipline system of arbitrary configuration a mathematical model was suggested. This model can be used to describe any operation regime of a pipeline system including emergency releases. The model takes into account all the fundamental physical processes occurring in the pipeline. Also it takes into account basic technical characteristic of pipelines. The proposed model allows to simulate real processes of transportation by a pipeline taking into account appearance of different type gradients (velocities, temperatures, concentrations).

The behaviour of a pipeline system in case of water hammer flow was modelled taking into account mass release.

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