

## Simulation of systems for shock wave/compression waves damping in technological plants

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**Abstract.** At work of pipeline systems, flow velocity decrease can take place in the pipeline as a result of the pumps stop, the valves shutdown. As a result, compression waves appear in the pipeline systems. These waves can propagate in the pipeline system, leading to its destruction. This phenomenon is called water hammer (water hammer flow). The most dangerous situations occur when the flow is stopped quickly. Such urgent flow cutoff often takes place in an emergency situation when liquid hydrocarbons are being loaded into sea tankers. To prevent environment pollution it is necessary to stop the hydrocarbon loading urgently. The flow in this case is cut off within few seconds. To prevent an increase in pressure in a pipeline system during water hammer flow, special protective systems (pressure relief systems) are installed. The approaches to systems of protection against water hammer (pressure relief systems) modeling are described in this paper. A model of certain pressure relief system is considered. It is shown that in case of an increase in the intensity of hydrocarbons loading at a sea tanker, presence of the pressure relief system allows to organize safe mode of loading.

### 1. Introduction

During a pipeline system operation the pumps can stop and the valves can shut down. As a result, the flow in the pipe slows down and compression waves appear. This phenomenon is called water hammer [1, 2].

The water hammer can have various negative impacts [3]:

- first, high pressure, which can destroy the wall of the pipeline;
- secondly, large pressure impulse (pressure action for a certain time) affects various structural elements, that leads to the flange damage and a leak appearance;
- thirdly, the rate of pressure rise; the difference in the loading rates of different parts of the pipeline can lead to excessive loads that results in pipeline displacement, the destruction of its mountings;
- fourth, the pressure oscillations resulting from the water hammer negatively affect the pipeline if cyclical pressure increase/decrease takes place.

The most dangerous situations occur when the flow is stopped quickly. This rapid flow cutoff often takes place in an emergency at sea terminals when liquid hydrocarbons are loaded into sea tankers. The special loading lines are used for this loading. When an accident takes place, it is necessary to stop the loading quickly. An urgent cutoff prevents hydrocarbon releases into the



environment. For this purpose, various kinds of valves are used to cut off the flow and to stop further loading. At sea terminals there are several types of valves to ensure safety (during shipment, for example) [3]:

- safety valves (ball valves or butterfly type valves) are located on the route of a loading pipeline; if there is any threat of spills, they quickly cut the flow off;
- safety valves are located in the drift stender, they quickly cut off the flow directly to a tanker (stender - special pipeline connection to the hinge ensures the supply of oil/oil products from the pier to the tanker); these valves can be triggered automatically when the threat of separation tanker from the dock at high wind load, the wave rolling;
- ship valves are located on the tanker; they are triggered when the staff of the tanker immediately arises an urgent need to stop the loading (such as overflow tanks).

All of these valves are fast. Time of complete shut-off is between 3-5 seconds to 8-30 seconds. This quick cutoff is necessary that, on the one hand, does not create more pollution in marine waters: huge penalties are charged for water pollution. On the other hand, the rapid cutoff of release to the environment is necessary to prevent the appearance of large amounts of fire and explosion hazard substance near such a valuable object as a marine tanker: the larger the volume of release, the higher the probability of a tanker accident, and the sequences of tanker accident are already really catastrophic.

Thus, the closing of the safety valves is extremely fast (for 3-30 s), much faster than in the trunk pipelines: there complete valve closing takes up to a few hundred seconds. Obviously, the faster the flow is stopped, the more intense is pressure growth and situation became more dangerous. Pressure rise in the pipeline can be estimated by using Zhukovsky formula [1], which is obtained by solving the problem of stopping the flow with velocity  $u$  on a rigid wall. When the instantaneous flow stopping takes place, pressure, according to the formula of Zhukovsky, increases by an amount  $\Delta p$ :

$$\Delta p = c\rho\Delta u \quad (1)$$

here  $c$  - the velocity of propagation of the disturbance in the liquid medium,  $\rho$  - flow density,  $u$  - flow velocity.

From (1) it follows that for characteristic values of  $c = 1300$  m/s and  $\rho = 900$  kg/m<sup>3</sup>  $u=1$  m/s flow stopping leads to pressure rise on 1170000 Pa, i.e. almost 12 atm.

It should be noted that flow velocity in pipelines is about 1-2 m/s, so for water hammer hypothetical pressure increase should not exceed 12-24 atmospheres. In practice, because of the slow response valve that growth is significantly lower. This increase in pressure can be compensate by increasing the strength of the pipe. If strength characteristics of the pipe can not ensure the integrity of the systems require special protection against water hammer.

Velocity of oil and oil products while loading in marine terminals can reach 4-5 m/s. If the valve shuts down quickly, the pressure may increase to tens of atmospheres (50-60 atmospheres or more). In this case, almost always a system of protection against water hammer (SPAWH) is necessary.

The general principle of SPAWH is to take away part of oil or oil products from the pipeline, when a water hammer is developed. This enables the pressure reduction, accordingly.

There are various types of safety devices:

- bursting discs;
- air caps;
- spring valve;
- gas spring valve.

As mentioned above, the general principle of SPAWH operation is to take away all the excess liquid phase from the pipeline, commonly this liquid phase is placed into a special vessel.

Safety valves may have a significant effect on the flow and, above all, reduce the pressure, preventing unacceptable loads. It is therefore extremely important to have an accurate and reliable model to describe the operation of a pipeline system containing safety valves.

In this paper, the approach, that allows to consider the work of the pipelines in the presence of safety valves on them, is proposed. This approach is based on the model of isothermal flow of weakly compressible liquid.

## 2. Mathematical model

In the isothermal approximation the motion of the fluid in the tube of variable cross section is described by the system of following equations for one-dimensional non-stationary flow:

Continuity (mass conservation)

$$\frac{\partial(A \cdot \rho)}{\partial t} + \frac{\partial(\rho \cdot A \cdot u)}{\partial x} = -M_0, \quad (2)$$

Momentum conservation

$$\frac{\partial(A \cdot \rho \cdot u)}{\partial t} + \frac{\partial(A \cdot \rho \cdot u^2)}{\partial x} = -I_0 - A \cdot \frac{\partial p}{\partial x} - A \cdot \frac{\lambda(Re)}{2 \cdot D} \cdot \rho \cdot u \cdot |u| - A \cdot g \cdot \rho \cdot \beta, \quad (3)$$

Link between the pressure and density (equation of state)

$$p - p_0 = c^2(\rho - \rho_0) \quad (4)$$

here  $\rho$ ,  $p$ ,  $u$  – density, pressure and velocity of the fluid, averaged according to the cross section;  $t$  – time;  $x$  – the distance from the start of the pipeline;  $\lambda(Re)$  – the coefficient of friction as a function of the Reynolds number  $Re = Du/\nu$ ;  $A$  – cross sectional area of the pipeline,  $D$  – the diameter of the pipeline,  $g$  – acceleration of gravity power;  $\beta$  – sine of the angle of inclination of the route, which is determined by the elevations points of the pipeline  $h(x)$ ,  $\nu$  – kinematic viscosity;  $\rho_0$  – density of the fluid at pressure  $p_0$  and transportation temperature (usually  $p_0 = 101325$  Pa),  $c$  – the speed of sound in the fluid,  $I_0$  – intensity of the loss of momentum with the release of the transported product at the site of relief valve,  $M_0$  – intensity of the loss of mass with the release of the transported product at the site of relief valve.

In this paper to determine the  $\lambda(Re)$  the dependence of Colebrook - White is used [4], relation friction coefficient  $\lambda$  with Reynolds number  $Re$  and the characteristics of the pipeline (diameter  $D$  and roughness  $k$ )

$$\frac{1}{\sqrt{\lambda(Re)}} = -2 \lg \left[ \frac{2,51}{Re \sqrt{\lambda(Re)}} + \frac{k}{3,71 \cdot D} \right], \quad (5)$$

here  $k$  – the size of the pipeline roughness.

The function of mass release  $M_0$  is a function of several parameters and especially:

- the pressure at which relief valve starts working  $p_r$  (the pressure of relief valve opening); this pressure is set by adjusting the relief valve;
- the time delay in the opening of the relief valve  $\tau_r$ ; time from start of opening of the valve to the start of flow through relief valve; the existence of this time lag is due to the inertia of process of valve opening, in fact, this is the time it takes to rupture a disk or to compress spring, etc.; in practice, it ranges from several tens of milliseconds to a few seconds;
- the dependence of the flow rate through the relief valve as degree of relief valve opening; usually in practice flow rate dependent on the ratio of overpressure to the pressure that relief valve starts working.

The most simple and rather accurate approximation for discharge rate calculation is the use of the Bernoulli formula. The outflow velocity  $U_0$  through relief valve was calculated using such Bernoulli formula:

$$U_0 = \sqrt{2 \frac{p - P_0}{\rho}}, \quad (6)$$

here  $p$  – pressure in pipeline at relief valve location,  $\rho$  - liquid density,  $P_0$  – outer pressure. The equation (6) is used when  $p$  more  $p_r$  it true during the time period longer than  $\tau_r$ . The mass rate through  $S_0$  square relief valve can be found as:

$$F = \alpha S_0 U_0 \rho, \quad (7)$$

here  $\alpha$  — coefficient equal 0,6.

The pulse rate through  $S_0$  square relief valve can be found as the product of the mass ejected from the pipeline and the liquid velocity within the pipeline.

The equations (2) - (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 vessels 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 (2) - (4). When the flow is cut off by the valve the zero speed is set as a boundary condition.

Godunov type method [5, 6] was used to solve equations (2-7).

### 3. The calculation results and discussion

#### 3.1. The flow calculation without safety system

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<sup>3</sup> and the viscosity of the transported product is 10<sup>-4</sup> m<sup>2</sup>/s. The valve is installed at the end of the pipeline (before the vessel). The time of the complete flow shutdown is 0,1 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.

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. The results of calculations of the same problem, but in the presence\ absence of pressure relief system are presented below in sections 3.2-3.4.

The following variations in the safety system are considered below:

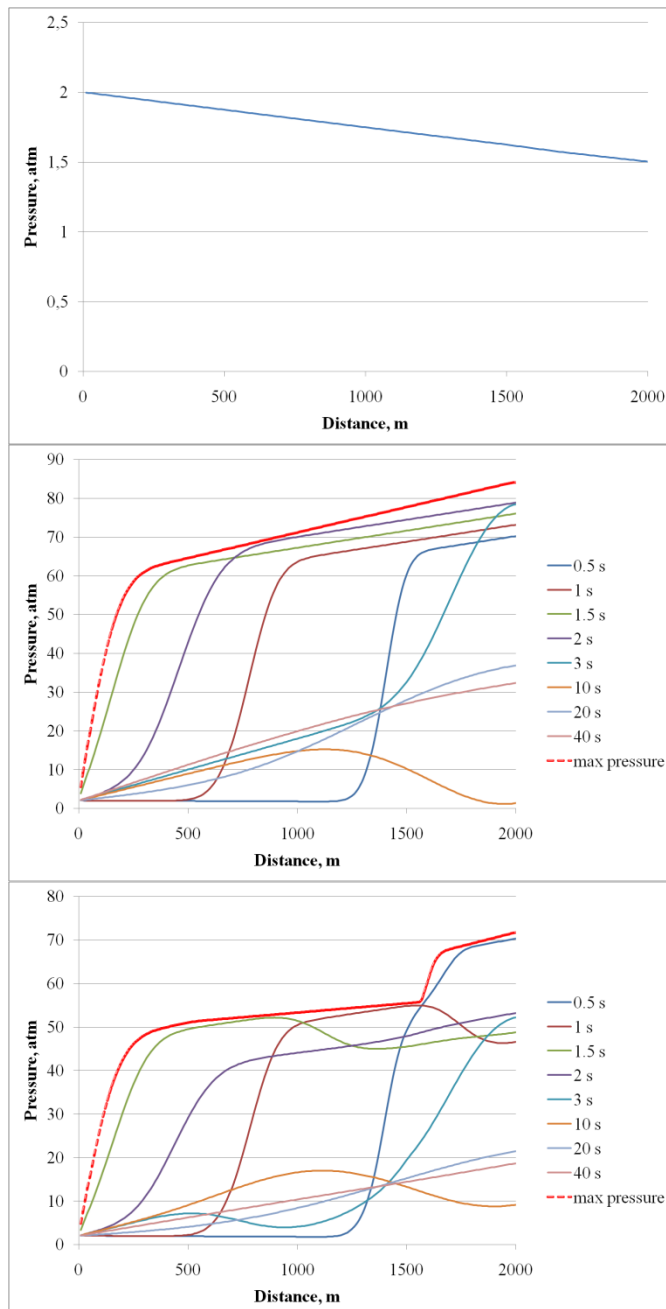
- different pressure of safety valves operations;
- various placements of safety valves;
- different diameter of relief valves.

#### 3.2. The flow simulation in the presence of safety system. (different pressure of the safety valves operations)

As noted above, one of the basic settings for the safety valve operation is the opening pressure of the valve, that is the pressure at which the valve opens and the discharge through it begins. The influence of this pressure is considered in this section.

The results of solving the problem stated above (see sec. 3.1) 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

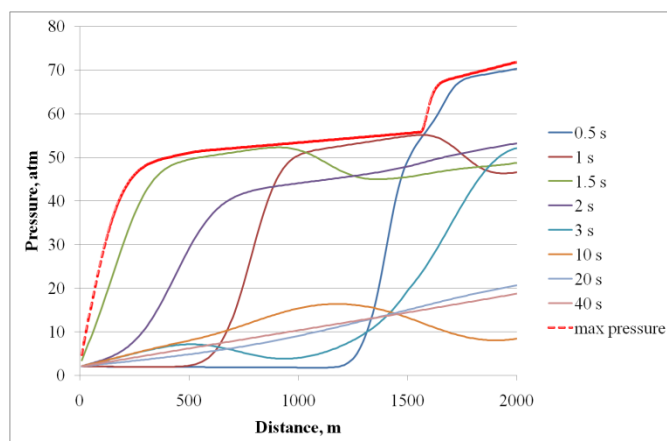
the pipeline. The diameter of the relief valve is 100 mm. Figure 3 shows pressure profiles at different time points (line 1-8) and the maximum pressure profile achieved (line “max pressure”) if the valve is activated, when pressure reaches 5 atmospheres. Figure 4 shows the same profiles if the valve 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.



**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, the relief system is placed at 1500 m, the relief valve diameter is 100 mm).



**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 – 10 s; 7 – 20 s; 8 – 40 s (the working pressure of the relief system is 10 atm, the system is placed at 1500 m, the relief valve diameter is 100 mm).

### 3.3. The flow simulation in the presence of safety system. (various placements of safety valves;)

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. It should be noted that the distribution of the maximum pressure achieved in the pipe can be clearly divided into two areas: before the safety valve and after one. The safety valve helps to reduce the pressure in the most powerful way (compared to the case of safety valves absence) in the upstream region (0-1500 m in figure 3, 4). The pressure decreases much less in the downstream area (1500-2000 meters from the location of the valve). This comes from the fact that the downstream section pressure may grow longer time to open the valve than the upstream section pressure, i.e. the valve is closed when the downstream pressure begins to increase and it opens (or is opened already), when the pressure in the upstream point begins to rise. Thus, the mass discharge will contribute to reducing the pressure growth rate in the upstream section. In this connection it is clear, that the displacement of the safety valve towards the closed end of a pipeline (shift downstream) is able to increase the area of intensive pressure reduction. For example, when the safety valve is moved to the mark of 1700 m, this area naturally expands up to 1700 meters. This fact is confirmed by the results of the calculations shown in figures 5, 6. These figures show the pressure profiles for different moments of time after the valve closing, as well as the maximum pressure reached in the process. Figure 5 shows the results of calculations for the case when the safety valve is placed at a distance of 1,700 meters, and figure 6 shows the one, placed at a distance of 1900 m from the start of the pipeline. The calculations in figures 4-6 deal with a safety valve with a diameter of 100 mm. This valve opens when the pressure in the pipeline is equal of 10 atm.

As one can see in figures 4, 5 and 6, the displacement of the safety valves downstream extends the zone of strong pressure decrease (it lies upstream of the valve). It is interesting to note that the value of maximum pressure reached at the end valve is only slightly sensitive to the displacement of the safety valve. As one can see in figures 4, 5 and 6, the pressure at 2000m (at the end valve) is about 70 atm. The pressure in the vicinity of the relief valve in upstream direction is just slightly changed: in all the three cases, it is about 55 atm.

It should also be noted that when the safety valve is moved, the flow pattern is still low-sensitive to the opening pressure of the safety valve. This is confirmed by comparing figures 7 and 6, where corresponding pressure lines are virtually indistinguishable (while one safety valve opens at 10 atm (figure 6), the other one - at 5 atm (figure 7)) for the same safety valve position (1900 m from the start of the pipeline) and the same diameter of the safety valve (100 mm). One can argue that in the case of closer position of safety valve to the closed pipeline end (figure 6, 7), the pressure difference is less noticeable than in the case of larger valves removal from the end of the pipeline (figures 3, 4).

### 3.4. The flow simulation in the presence of safety system. (various release area of safety valves;)

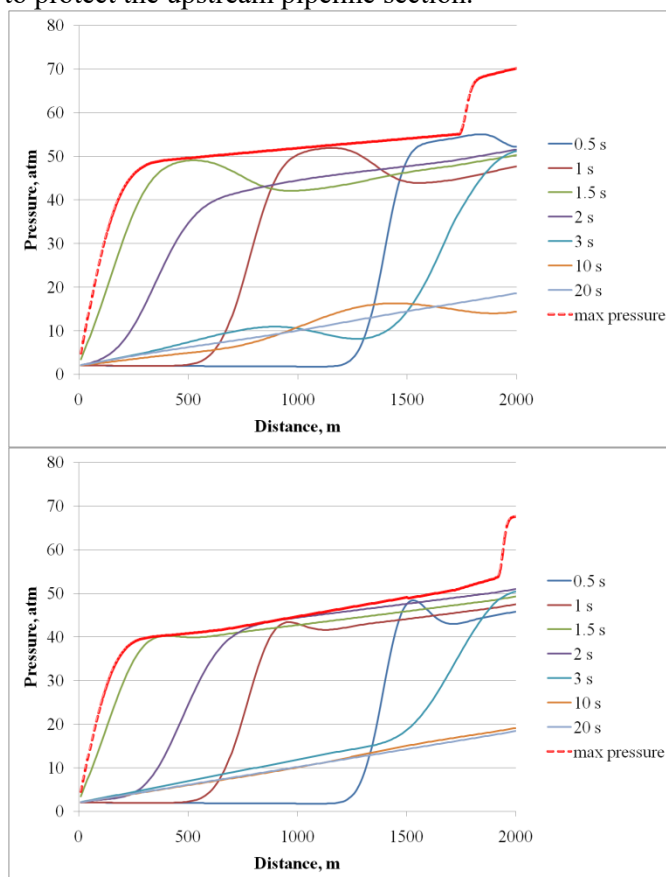
As one can see from the calculations, the results of which are presented in sections 3.1-3.3, no starting pressure, nor the location of the relief valve does not allow considerably reduce the pressure for a given diameter of discharge hole of the relief valve (100 mm under consideration in this article

configuration). It is clear that this result is mainly due to high-speed of valve cut-off operation - 0.1 s. At longer cut-off importance discussed in Sections 3.2-3.3 factors is likely to grow.

However, it seems appropriate, as before, assuming the fast opening relief valve, explore another factor - the influence of cross-sectional area of the relief valve. Obviously, the increase in the area of the relief valve hole through which fluid is discharged, will lead to higher discharge rate, at least immediately after the opening of the valve until the pressure in the pipeline has not much changed.

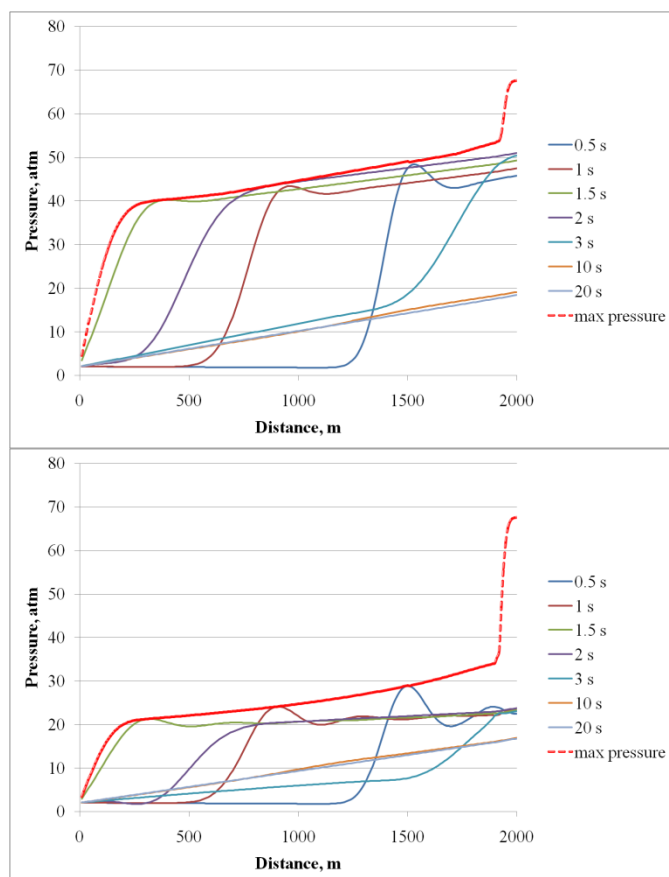
Figures 8 and 9 show the pressure profiles for case of discharge through the relief valve 200 mm, that starts to operates at 10 bar (previously we consider a case for 100 mm). Figure 8 shows the profiles of pressure for relief valve, located at 1,900 meters from pipeline inlet, and figure 9 at 1500 meters.

Figures 8 and 9 show us that increasing in the area of the relief valve hole substantially reduces the pressure in the pipeline section from its beginning to the place of installation of the relief valve. According to the obtained results, the magnitude of reduction of pressure is about 20 atm, as for the case of the relief valve at 1500 m (Figures 4,9) and for the case of the relief valve location at 1900 m (Figures 6,8). Thus, increasing the cross-sectional area of the relief valve is an extremely efficient way to protect the upstream pipeline section.



**Figure 5.** 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 the relief system is 10 atm, the relief system is placed at 1700 m, the relief valve diameter is 100 mm).

**Figure 6.** 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 the relief system is 10 atm, the relief system is placed at 1900 m, the relief valve diameter is 100 mm).



**Figure 7.** 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, the relief system is placed at 1900 m, the relief valve diameter is 100 mm).

**Figure 8.** 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, the relief system is placed at 1900 m, the relief valve diameter is 200 mm).

However, as one can see from Figures 6 and 8, 4 and 9, an increase in discharge capacity of the relief valve has practically no effect on the value of the pressure attained in the area downstream from the safety valve. In our opinion this is due to the rapid, for 0.1 s, the time of closing the valve at the end of the pipeline.

It should also be noted that the investigated above (section 3.2-3.3) the effect of the pressure that relief valve starts to work takes place for the case of increasing valve capacity (the area of discharge hole) also.

#### 4. Conclusion

The paper examines the approaches to the modeling of systems of protection against water hammer (SPAWH). A model of SPAWH is described. The results of calculations of piping systems with SPAWH are presented. It is shown that SPAWH allows under certain conditions to reduce the pressure in the case of water hammer.

The article presents the results of calculation of the effects of water hammer in the single pipeline in the presence of relief valve.

In the case of fast-acting valves and the appearance of water hammer in the pipeline the influence of three factors on the pressures achievable in the pipeline is considered: a pressure relief valve, its location and flow when it is reset.

It was shown that the presence of the relief valve in the pipeline divides this pipeline into two parts with different character of pressure rise:

- upstream, with a significant reduction in the pressure;
- downstream, with a weak reduction in pressure.

At displacement of relief valve downstream the first zone length is increased, and the second region is reduced. The magnitude of the decrease in pressure in each of these two sections weakly depends on the opening pressure of the safety valve and on relief valve location (for the case of rapid response valve at the end of the pipeline). It is interesting to note that the value of maximum pressure



reached at the end of the valve in the pipeline is slightly sensitive to the displacement of the relief valve.

The biggest influence on the value of the pressure reduction in the water hammer has a relief area of a relief valve. The more its area, the greater the pressure drop. However, a noticeable reduction in pressure occurs only in the upstream section.

Thus, in case of the valve at the end of the pipeline urgent cut-off, it is almost impossible to reduce water hammer pressure and to protect the section between this end valve and the relief valve against water hammer: This is because the response time of the SPAWH is much more, than the pressure rise time. On this basis, it must be concluded that the safety of the end section can be ensured only by proper choice of the time of end valve shutdown, primarily by the time increase.

## 5. Acknowledgments

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