Simulation of compression waves/shock waves propagation in the branched pipeline systems with multi-valve operations

S I Sumskoi¹, A M Sverchkov², M V Lisanov² and A F Egorov³

¹National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye shosse 31, Moscow 115409, Russia
²CJSC Scientific technical center of industrial safety problems research, Block 14, Perevedenovsky Pereulok 13, Moscow 105082, Russia
³D. Mendeleyev University of Chemical Technology of Russia

E-mail: sumskoi@mail.ru

Abstract. With the help of the developed model and numerical method the task has been solved concerning the transmission of the compressive wave complex in the branching pipeline system when several shut down valves operate. It is shown that for branches of the pipeline the highest peak of pressure can be achieved in them under the asynchronous operation of the shutdown valves, but not under the simultaneous operation of all valves, as it has been assumed in previous studies.

1. Introduction
The shock waves/compression waves (SW/CW) can have a negative impact and cause destructions. Typically, the SW/CW attenuate during their propagation and their damage effects decrease. A significant factor of the waves’ attenuation is the SW/CW divergence in multidimensional space, when the flow is divergent. However, in practice, there are flows that do not have significant multidimensional effects, leading to the attenuation of SW/CW. In this case, the SW/CW can propagate over long distances, with maintaining its damage potential. Since such flows take place in real technical devices and structures the methods are needed for modelling the pressure wave’s propagation processes.

The most famous example of the weak attenuating pressure waves’ propagation is the flow in pipeline systems known as water hammer. The problem about the SW propagation under the explosion in the tunnel system, for example, in mine workings may serve as another example. Both of these tasks in a fairly accurate approximation can be set and resolved in the one-dimensional formulation, naturally, taking into account the multidimensional effects, if any.

This article presents results for solving the task of water hammer in the pipeline system. The task is considered in the one-dimensional non-stationary formulation taking into account the realities such as the change in the diameter of the pipeline and its branches.

2. Calculations of water hammer: operation of two valves
Let us consider the following model configuration of the branching pipeline system (see Fig. 1). From the beginning of the pipeline (point A) to the branching point (point O) the pipe with the length of 20 km has a diameter of 1 m. At the point O the pipeline is diverged into two identical pipes with the length of 20 km and the diameter of $1/(2)^{1/5}$ m each, i.e. the cross-sectional area of the two branched...
pipes equals to the cross-sectional area of the main pipe. All pipes have the same roughness - 0.3 mm, and are laid on a flat terrain. The pressure at the beginning of the pipeline is 10 atmospheres. The pressures in the end of each branched pipeline equal 3 atmospheres. There are two valves in the end of each pipeline. These valves completely stop the flow within 0.1 seconds.

![Diagram of branching pipeline system]

**Figure 1.** The scheme of branching pipeline system.

The following scenario of the valves actuation is considered. Initially the valve №2 triggers, and then, after a while, the valve №1 operates. When making calculations the time count starts from the beginning of the valve №2 closing. It was assumed when making calculation that the speed of disturbance propagation coincides with the speed of sound and is 1300 m/s.

Obviously, the operation of the two valves can result in a substantial increase in pressure in the pipeline system, as the CW from the valve № 1 will be propagated through the liquid, where the pressure increase has occurred as a result of the valve №2 closing.

To solve this problem we used the physical model and numerical method offered in [1, 2]. The shutdown of valves may happen simultaneously or with a certain degree of asynchrony. In this regard the question arises: which of the options of the valves shutdown will be the most dangerous relating to the maximum peaks of the pressure? To answer this question the calculations have been made with different variants of operation of valves. The general scheme of the flow stopping looked as follows. At first the valve shuts down in the main section, and then, with some time delay, the valve shuts down in the branch. The calculation results in the form of distribution of the maximum achievable values of the pressure in the main pipeline and in the branch pipeline are shown in the Fig. 2 (a-e). The Fig. 2 a) shows the profiles for the cases of the second valve shut down with delay in 1, 2.5 and 5 seconds; Fig. 2 b) - 10, 15, 20, 25 and 30 seconds; Fig. 2 c) - 35, 40, 45 and 50 seconds; Fig. 2 d) - 60, 70, 90 and 110 seconds; Fig. 2 e) – 240 seconds. Each of these figures shows the profiles of the maximal pressure reached in the pipeline system when only one valve (red lines) operates and when simultaneous operation of two valves (yellow line) takes place.

From Figure 2 a) it is clear that for a small time delay the pressure profiles in branches are close to the pressure, reached in the case of simultaneous operation of valves. At that for 1 second delay the deviations are observed only in the zone of the branching. As for the deviations themselves, they are small: in the main pipe the pressure decreases, and it increases in the branch. As the time delay grows the difference in pressures is becoming more visible, and the pressure growth in the branch is more significant than the drop of the pressure in the main pipe: so for 5 second delay (brown lines) the pressure drop in the main pipe is about 1.5 atmosphere (brown solid line in comparison with the yellow line); whereas as the pressure growth in the branch is greater than 5 atmospheres (dashed brown line in comparison with the yellow line). When the time-synchronization grows the decrease in the maximal peaks of the pressure achieved at the beginning of the pipeline is also observed.

With the growth of the time delay the mentioned trends are kept also for the time interval of 10-30 s in the shut down delay of valves. As can be seen from Fig. 2 b), the maximum pressure, achieved in the main pipeline, continue to decrease, tending to the pressure level characteristic for the case of operation of only one valve (solid black line comes close with a solid red line). At the same time the
pressure in the branch increases significantly: under the 30 second delay the maximum pressure (black dotted line) exceeds the pressure in the case of simultaneous valve shut down (yellow line) by about 10 atm.

Figure 2. The maximal peaks of the pressure achieved inside the main pipeline and in the branch under operation of two valves with a time difference of 1, 2.5 and 5 s (a); 10, 15, 20, 25 and 30 s (b); 35, 40, 45 and 50 s (c); 60, 70, 90 and 110 s (d); 240s (e). All figures also show the maximum pressure when only one valve operates and when simultaneous operation of two valves takes place.
At 30 second delay on the response time of the second valve, as it is seen in Fig. 2 b) and c), the maximal peaks of the pressure, achieved inside the main pipe, are at the minimum level, and in the branch – at the maximum level. This may be explained by the fact that for 30 with a little over seconds the compression wave, generated at the moment of closing the first valve (valve #2), succeeds, on the one hand, to reach the start of the pipeline and to begin unloading the tube of the main section up to the branching point, and, on the other hand, to achieve the second valve (valve #1, in the branch) and by this pressing the liquid in this section of the branch up to the highest values. As a result of this, the second compression wave, generated when the second valve (valve #1) operates, will be propagated along the maximum compressed liquid in the branch and among the most unloaded liquid in the main section.

As can be seen from Fig. 2 b) and c), the further increase in the time-synchronization causes the growth of the maximum pressure attained in the main section, and, in the opposite, they decrease in the branch. This is reasoned by the fact that now the first compression wave passes through the branch, and the pressure decreasing begins in it, respectively, in the branch the second compression wave propagates among the less compressed liquid. Owning to this factor starting with approximately 50-55 seconds the maximal peaks of the pressure in the main section after the branching point start exceeding the maximal pressure in the branch (see line “50 s” in Fig. 2 c) and green line “60 s” Figure 2 d).

In case of delay in the activation of the second valve for more than 50 seconds the maximal peaks of the pressure, achieved in the main section downstream to the branch point, firstly fall down (to 60 s), then increase somewhat (to 90 s) and then fall again (to 110 s) (see Fig. 2 d)-e). In the end, starting with a certain value of time delay, the maximum achievable pressure comes to a certain level, which is not affected by a further increase in the delay time until the second valve actuates. Similar oscillations and stabilization on the some stationary level of maximum achievable pressure are observed also for the sections after the branching points (see Fig. 2 d) to e).

The maximal achievable peaks of pressure corresponding to the situation when these peaks of the pressure do not change due to the time delays are shown in Fig. 2 e), for example, with the delay of 240 seconds. At the same time, as shown in Fig. 2 e), for large delays in the activation of the second valve the maximal achievable pressure up to the branching point exceed a little bit the corresponding values for the case of only one valve shut down, and the maximum pressure reached in the areas after the branching point, slightly exceed the pressure in the case of simultaneous operation of valves.

If we analyze the received results shown in Fig. 2, we can draw the following conclusion: for different sections of the pipe the greatest danger (i.e., the greatest growth of the pressure) is implemented in a variety of scenarios. This implies that when calculating the branching of pipelines one cannot be limited by the single scenario of closing valves.

Most often, for example in [3], the scenario of simultaneous shut down of all valves is considered as the most dangerous scenario. The safety of marine shipping terminals is analyzed in this formulation in [3]. According to the results presented in this paper, such scenario is the most dangerous only for the section before the branching point. This is reasoned by the fact that in this case, when the waves are simultaneously propagating, the maximum compression is reached in this waves; and the desynchronization in valve shut down allows to start the unloading of the separate sections and, accordingly, the value of maximal achievable pressure decrease. For the sections after the branching points the situation with a simultaneous closing of the two valves is, as it may seem paradoxical, the best option, as in this case for all sections the maximum pressure is the least one; in all other cases, and it can be clearly seen from Fig. 2, in the sections after the branching point there is always the area where the greater peaks of the pressure are achieved (and sometimes very much significantly) than the maximum pressure for the simultaneous valve shut down.

It is clear that in the case of varying diameters and lengths of pipelines even more diverse range of situations may develop. In this connection, the important conclusion should be made – the analysis of loads on the branching pipeline in the event of water hammer phenomenon should be carried out across the entire spectrum of possible scenarios of closing valves.
3. Conclusion
The paper proposes to apply the Godunov Type Method for the calculation of water hammer in branched pipeline systems. The possibility to disseminate this method among the branched pipeline systems has been successfully demonstrated.

The problem of the water hammer under different variants of the valves operation for the model system with one branch and valves at the ends of the pipeline system has been solved. The numerical modeling results show that in the given case the maximum load on the main pipeline (from its start to the point of branching) occurs at the simultaneous closing of the valves.

And in the pipelines after branching point the maximum loads on the pipeline under the water hammer happen not at the simultaneous operation of the shutdown valves at the ends of the pipeline, but at some delay in the shutdown of valves at the ends.

It should be noted that even a small desynchronization in the operation time of valves can lead to a significant growth of the pressure in the branches compared to the case of simultaneous operation of valves. Moreover, the case of simultaneous operation of valves in the considered system provides the smallest increase in pressure in the branches comparing to any asynchronous option of closing the valves.

With that in mind, one can make an important methodological conclusion: when making the analysis of branching systems to determine the maximal peaks of pressure on the branching sections it is needed to consider the spectrum of events associated with the different options of closing valves.

The proposed method of calculating of the liquid medium motion can be used (with appropriate modification) and for other tasks, similar topology. The dissemination of this methodology to the problem of shock waves in tunnels or the flow in the blood vessels seems to be of current concern.

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