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Original scientific paper

T-JUNCTION AND TRANSFER OF TRANSIENT MODES IN HYDRAULIC SYSTEMS

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Abstract: A T-junction of a hydraulic system is the point where hydraulic parameters (which are defined by variable pressure and discharge) join or separate. The transmission of the hydraulic conditions distributed by the T-junction connection are numerically analyzed in different conditions which provide insight into the distribution – transfer of hydraulic parameters through the T-junction. Numerical calculations were performed for defining the transient modes and the interaction between the hydraulic parameters in the case of a T-junction with the application of the AFT Impulse software package. The software was chosen as suitable based on previous experience with good alignment between numerical calculations and field measurements. The results from the numerical prediction of the occurrences for different conditions in the T-junction construction showed the influence of simultaneity (interaction and dissipation) of the fluid flow parameters, time delay or parallel flow and counter-flow in the transient modes, which contribute to the technical opinion on the phenomena occurring in a T-junction.

Key words: transient modes; interference; dissipation; fluid flow parameters

Т-ЈАЗОЛ И ПРЕНОС НА ПРЕОДНИ РЕЖИМИ ВО ХИДРАУЛИЧНИ СИСТЕМИ

Апстракт: Т-јазол на хидрауличен систем е точката каде што хидрауличните параметри (кои се дефинирани со променлив притисок и проток) се спојуваат или се одделуваат. Преносот на хидрауличните услови дистрибуирани преку Т-јазолот е нумерички анализиран во различни услови, што дава увид во распределбата – преносот на хидрауличните параметри низ Т-јазолот. Со цел дефинирање на преодните режими и интеракцијата помеѓу хидрауличните параметри во случај на Т-јазол, извршени беа нумерички пресметки со примена на софтверскиот пакет AFT Impulse. Изборот на софтверот е направен врз основа на претходното искуство со добро усогласување помеѓу нумерички пресметки и теренски мерења. Резултатите од нумеричкото предвидување на појавите за различни услови во Т-јазолот покажуваат влијание на истовременоста (интеракција и дисипација) на струјните параметри, временското задоцнување или истонасочно и противнасочно струење во преодните режими, што придонесува кон техничкото мислење за феномените што се случуваат во Т-јазолот.

Клучни зборови: преодни режими; интерференција; дисипација; струјнотехнички параметри

INTRODUCTION

The fluid flow parameters during a transient fluid flow in pipeline systems is a result of a complex set of independently variable parameters. They originate from the physical properties and mechanisms of the kinematics of the surrounding, as well as from the fluid properties at given flow parameters. They are described at unsteady state in a given section of the flow domain [1, 2]. The fluid and its basic physical quantities (density, compressibility, viscosity) are given based on generally known parameters, but the kinematics of their change under different conditions during the fluid flow is a mechanism for which research is still being carried out [3, 4]. The interaction between the surrounding and the fluid medium occurs in conditions of transient flow regimes in pipelines.

Numerical simulation has become the dominant method for analyzing transient flow phenomena. The main challenge in modeling water hammer lies in solving the hyperbolic partial differential equations involved. While the governing equations are available in closed form, no exact analytical solution currently exists. To obtain numerical solutions, several techniques have been employed, most notably the Finite Difference Method (FDM) which can include Lax-Wendroff Scheme and MacCormack Method [5], the Finite Volume Method (FVM), the Finite Element Method (FEM), and the Method of Characteristics (MOC).

Pal et al. [6] review recent advancements in numerical methods for modeling water hammer, focusing on one-dimensional approaches like FDM, MOC and FVM. Although MOC has been the most widely used method, especially in one-dimensional transient flow modeling, the authors highlight the advantages of FVM for accurate transient flow simulations, especially in complex scenarios like fault detection. Henclik [7] presents a numerical approach to modelling water hammer phenomena incorporating fluid–structure interaction (FSI) using a four-equation model solved via MOC. The study emphasizes the influence of viscoelastic pipe supports, formulating boundary conditions as differential equations of junction motion, which are solved concurrently with MOC compatibility equations. Numerical simulations, validated against experimental data from a laboratory pipeline model with complex support systems demonstrate that appropriately designed supports can significantly reduce pressure surges by absorbing and dissipating energy. Prica et al. [8] developed a numerical model to simulate condensation-induced water hammer in two-phase flows. Utilizing MOC, the model accounts for the direct condensation of steam on subcooled liquid and tracks the interface between steam and water columns. The model is validated through application to a laboratory test case. Ani and Khayatzadeh [9] developed a general computer program for analyzing pipelines with pumps, valves, surge tanks, air chambers, etc., based on FDM and MOC coupling. The accuracy of their program is validated by comparing numerical results to available exact analytical solutions. Kandil et al. [10] investigated the impact of different pipe materials on water hammer intensity and frequency in pressure pipelines by integrating experimental testing and numerical modeling. A numerical model based on MOC was developed and validated using data from a custom experimental setup equipped with pressure sensors and strain gauges. The research evaluated five pipe materials under various flow rates and pressures. Fast Fourier Transform (FFT) analysis revealed different frequency responses of each material, showing that more viscoelastic materials mitigate water hammer effects compared to rigid materials like steel. Deviations between experimental and numerical results were attributed to differences in pipe rigidity. Toumi and Sekiou [11] employed MOC and a mixed scheme for simulating transient flow. The results revealed that for each slow closing time, there is a unique convex law that effectively reduces maximum overpressure. Furthermore, the evolution of the optimal pressure at the valve is governed by two models: exponential and linear.

The literature review shows that the Method of Characteristics (MOC) is the most widely adopted approach which is extensively used in engineering applications to simulate water hammer effects especially in case of problems with relatively simple geometries and boundary conditions, like valve closures or pump failures.

Understanding transient flow behaviour in complex pipeline networks is essential for the safe and efficient design of hydraulic systems. The transient state of the junction element is considered in this paper, since different states are possible at this nodal point that can be achieved during the pipeline operation, i.e., it is possible for one branch of the junction to have inflow or outflow or no flow through it. On the other hand, the part of the pipeline where redistribution of flow to the branches occurs is in the junction. From a hydraulic point of view, the junction is a place in the pipeline where the influence of the surrounding is minimal or none from aspect of transient states of the fluid, but the hydraulic conditions are more dominant since a pressure wave is distributed or two pressure waves are superimposed. In particular, T-junctions present critical points where pressure wave interactions can lead to amplified loads, potentially compromising system integrity. Thus, in this paper, the MOC is selected as a numerical approach for defining the transient states at T-junction in pipelines through a one-dimensional model of analysis along the flow. The presence of a specific pipeline components (reservoir, valve, pump, accumulator, etc.) is given through appropriate mathematical boundary models to describe their influence and specificity. The junction model as a boundary condition is developed on the following assumptions: the head in the junction is constant for all its branches, while the pressure wave propagation towards the junction has a positive sign of the characteristic function C for a branch with fluid flow velocity in the same direction as the pressure wave propagation speed and vice versa [1, 2, 4, 12]. This research uses AFT Impulse with the MOC to simulate and analyze transient flow in a T-junction. The goal is to quantify how the length ratio between parallel branches influence wave intensity, timing and oscillation patterns, thereby improving predictive capabilities for transient behaviour in branched pipeline systems.

MODEL SETUP

The conditions for transient states transmission in a pipeline with a T-junction that connects three branches were numerically analyzed. The fluid flows from a tank with a constant level through a pipeline and is evenly distributed into two horizontal parallel branches positioned at the same elevation.

Two models of parallel branches were considered: a pipeline with branches of same length (with 1:1 length ratio) and a pipeline with parallel branches whose length ratio is 1:2. The length of the shorter branch of the pipeline model 1:2 is the same as the length of the branches of the 1:1 model. By assigning different lengths to the branches, it is ensured that the pressure wave induced by opening/closing the flow in the branch is present in the junction at different times.

a) *Model with length of branch 1:1*

b) *Model with length of branch 1:2*

Fig. 1. Schematic of the models for T-junction

Technical parameters of model

Basic technical parameters for the models considered are:

- the water level in the reservoir is constant, set at 100 m height relative to the T-junction,
- the supply pipe (made of steel) to the T-junction (section 3) is 200 m long and has a diameter of DN600 and a wall thickness of 4.5 mm,
- the short branch has a total length of 1500 m, set with 150 m step,
- the longest branch length is 3000 m, set with 150 m step,
- at the ends of the branches, the flow is set at constant value of 0.1 m^3/s.

The conditions under which the numerical calculations were performed are:

- Fluid-water.
- The time duration of opening/closing the flow in the branch is 2 seconds.
- The law of change of flow is linear.
- Number of divisions-steps of calculation nodes is 5 m.
- Calculation time is set for 20 seconds.
- During the calculations, in the first second, the stationary state conditions of the pipeline system are set, and then the changes follow.

Numerical calculations were performed using the commercial software package AFT-Impulse.

Scenarios for calculated cases

Transient regimes in the T-junction are considered under conditions of positive pressure wave (flow closure), negative pressure wave (flow opening), as well as with the combined action of pressure waves. The different scenarios considered for the 1:1 model and for the 1:2 model are given in Table 1 and Table 2, respectively. Junctions J15 and J26 represent the ends of the parallel branches where the flow either closes or opens. For every scenario, the original state of the branch (opened/closed) is given, so as the time for completing the action of opening/closing at the respective branch end. The corresponding symbol for the resulting change, which is used in the graphical presentation of the results, is given in the second column of the tables.

Table 1

Scenarios of numerical calculations for a model with the same length of branches (1:1)

Scenario		J15			J26		
Number	Symbol	Start	Time	End	Start	Time	End
1	Zs-Zs	open	2 sec	closed	open	2 sec	closed
2	Zs-Xs	open	2 sec	closed	closed	no action	closed
3	Xs-Zs	closed	no action	closed	open	2 sec	closed
4	Os-Os	closed	2 sec	open	closed	2 sec	open
5	Xs-Os	closed	no action	closed	closed	2 sec	open
6	Os-Xs	closed	2 sec	open	closed	no action	closed
7	Os-Zs	closed	2 sec	open	open	2 sec	closed
8	Zs-Os	open	2 sec	closed	open	2 sec	closed

Table 2

Scenarios of numerical calculations for a model with different branch lengths (1:2)

Scenario		J15			J26		
Number	Symbol	Start	Time	End	Start	Time	End
1	Zs-Zl	open	2 sec	closed	open	2 sec.	closed
2	Zs-Xl	open	2 sec	closed	closed	no action	closed
3	Xs-Zl	closed	no action	closed	open	2 sec	closed
4	.+s-Zl	open	no action	open	open	2 sec	closed
5	Zs-+l	open	2 sec	closed	open	no action	open
6	Os-Ol	closed	2 sec	open	closed	2 sec	open
7	Zs-Ol	open	2 sec	closed	closed	2 sec	open
8	Os-Zl	closed	2 sec.	open	open	2 sec	closed
9	.+s-Ol	open	2 sec	open	closed	2 sec	open
10	Os-+l	closed	2 sec	open	open	2 sec	open
11	Xs-Ol	closed	no action	closed	closed	2 sec	open
12	Os-Xl	closed	2 sec	open	closed	no action	closed

RESULTS AND DISCUSSION

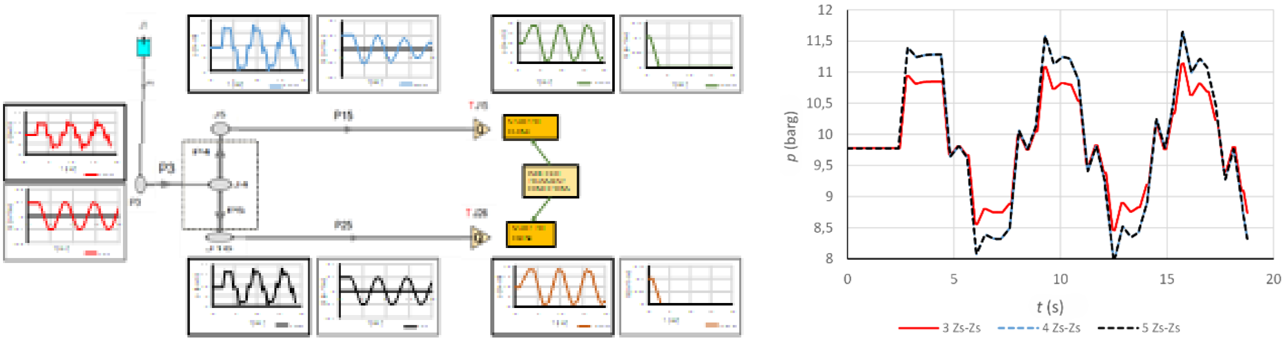
The results of the calculations for the transient modes are analyzed primarily for the pressure distribution in the T-junction, by defining the pressure change in section 3 (supply pipeline to the junction), section 4 and section 5 (branches from the junction). The results are given in the form of diagrams which show the pressure and flow change in each individual section, as well as a comparative diagram for the pressure distribution. In addition, the pressure and flow change diagrams at the point where the transient mode is induced in the pipeline system are given. The branch from which the transient mode is induced in the system is given on the comparative diagrams with a dashed line.

Effects of a positive pressure wave

Unsteady flow with the positive pressure wave is ensured by closing the parallel branches, i.e., by stopping the flow. The cases of pressure distribution in the T-junction during simultaneous closing of the parallel branches and the case when the flow is closing in only one branch while the other is already without flow are considered.

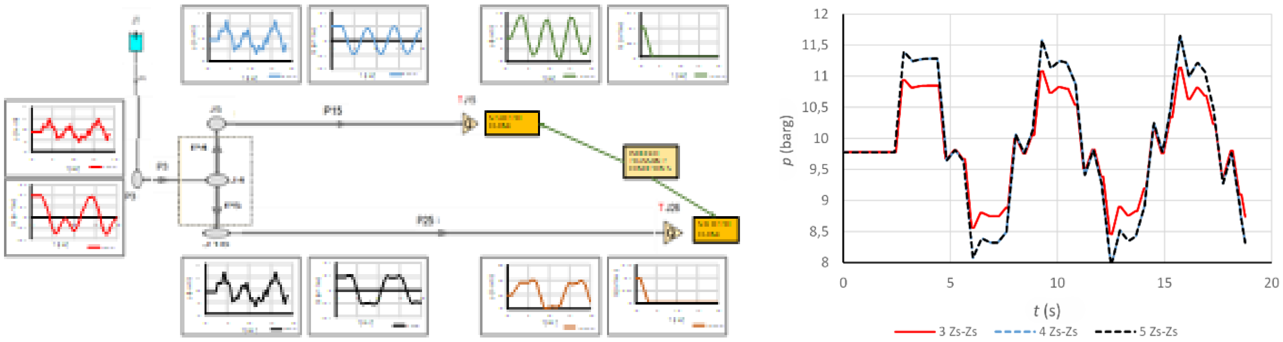
Simultaneous closure of branches

The transitional states in the pipe system in the T-junction zone under conditions of simultaneous closure of the flow in the branches are given in Figure 2 and Figure 3.



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 2. Pressure wave distribution at T-junction – 1:1 model: same time closing of both branches



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

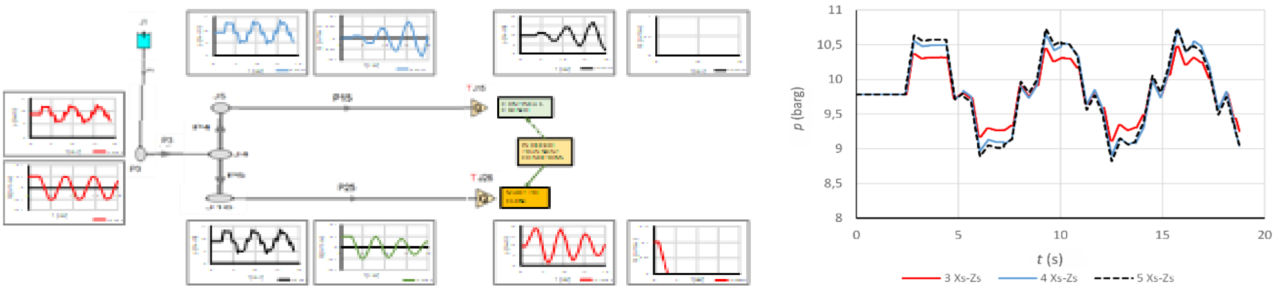
Fig. 3. Pressure wave distribution at T-junction – 1:2 model: same time closing of both branches

For the 1:1 model, the two positive pressure waves from the branches model propagate toward the T-junction and arrive simultaneously where they are superimposed in a more intense pressure increase due to constructive interference. The pressure wave is distributed to the supply pipeline with reduced amplitude because it propagates in the opposite direction of the water velocity, causing partial cancellation and energy dissipation.

For the 1:2 model, in the T-junction, the positive pressure waves from the shorter branch arrives earlier due to the reduced propagation path and its influence is transmitted to the longer branch. At the same time, the pressure wave generated within the longer branch is still propagating toward the junction. The superposition of the two positive pressure waves occurs along the branch with higher length. This amplified wave then reflects back toward the T-junction, where its delayed arrival causes a secondary pressure rise.

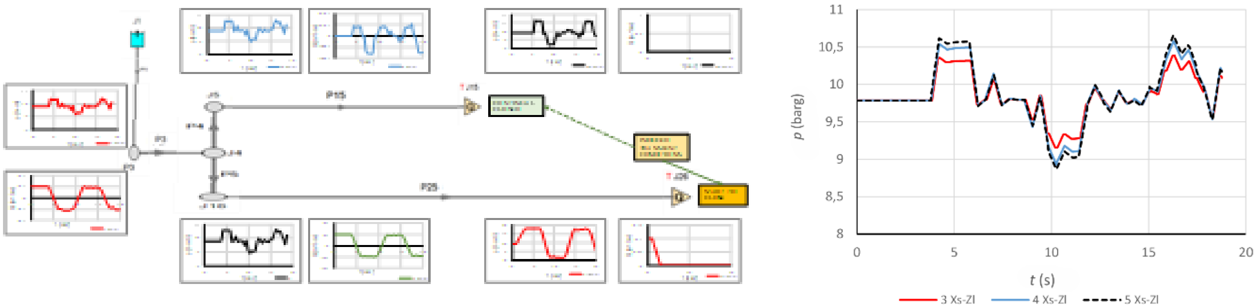
Closing one of the branches, the other one is closed (no flow)

Transitional states in the pipe system in the T-junction zone under conditions of flow closure in one of the branches are given in Figure 4 for the 1:1 model and in Figure 5 and Figure 6 for the 1:2 model.



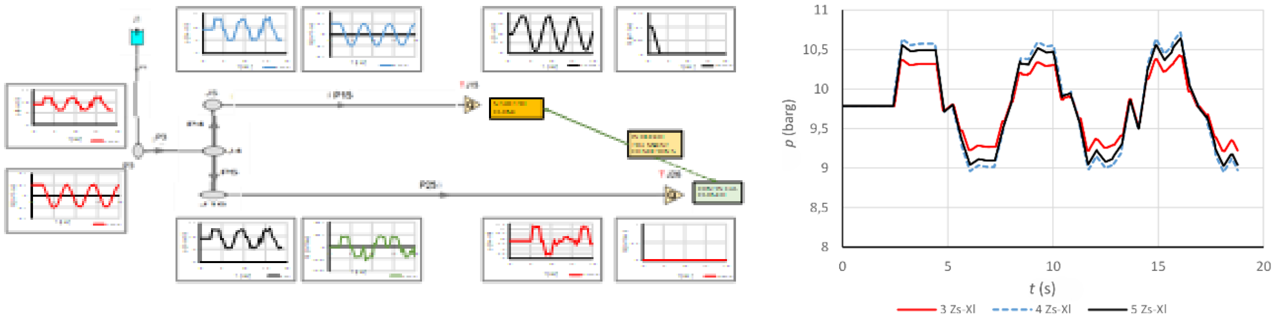
a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 4. Pressure wave distribution at T-junction – 1:1 model: closing one branch



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 5. Pressure wave distribution at T-junction – 1:2 model: closing one branch (longer)



a) Pressure wave distribution at T-junction and initiation b) comparative diagram

Fig. 6. Pressure wave distribution at T-junction – 1:2 model: closing one branch (shorter)

For the 1:1 model, a positive pressure wave from only one of the branches enters the T-junction, which is partially transmitted into both the closed branch and the supply pipeline (section 3). Due to the hydraulic symmetry of the system, i.e. equal lengths, diameters and boundary conditions, the wave transmission pattern remains the same regardless of which branch is closed. The pressure wave transmitted through the T-junction has the highest intensity, as it carries the primary energy from the initiating disturbance.

For the 1:2 model, a positive pressure wave enters the T-junction from either the long or the short branch. In both cases, the wave is partially transmitted into the closed pressure branch and the supply pipeline (section 3). The pressure wave transmitted through the T-junction has the highest intensity, regardless of which branch closes. The difference in these two cases is in the periodicity of the transient modes, that is, due to the different branches lengths, the pressure wave propagation time is different resulting in variations in the timing of wave reflections and superpositions, which directly affect the frequency and phase of the pressure oscillations in the system.

The analysis of the branch with zero flow (closed end) given in Figure 7 shows that its length does not influence the initial phase of the transient response. However, as unsteady conditions develop over time, the difference in branch length leads to variations in the timing of wave reflections resulting in a non-uniform pressure distribution in the T-junction. The transient response of the pipeline system differs in the case of simultaneous closure of both branches and the closure of only one branch, as shown in Figure 8. When both branches are closed, the pressure wave intensity at the T-junction is higher due to the superposition of compression waves arriving from both sides. In contrast, closing only one branch results in a lower pressure peak, as the wave energy is not reinforced by a second incoming wave.

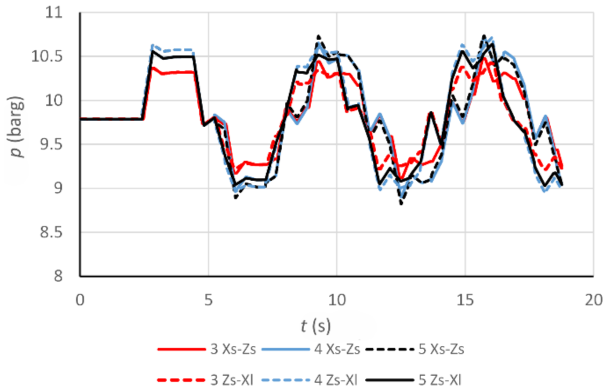


Fig. 7. Comparative diagram of pressure wave distribution at T-junction – 1:1 model and 1:2 model: closing one branch (shorter)

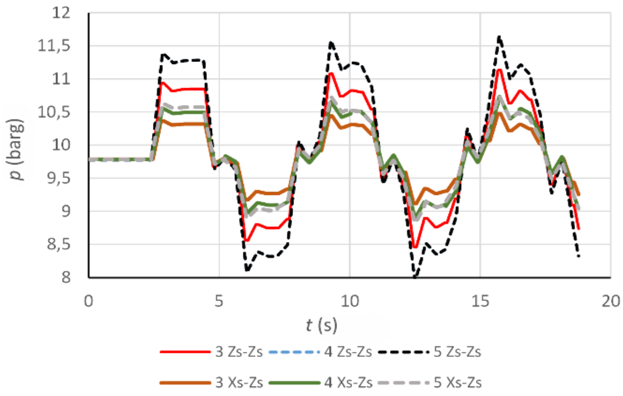


Fig. 8. Comparative diagram of pressure wave distribution at T-junction – 1:1 model: closing one branch vs. closing both branches

Effects of a negative pressure wave

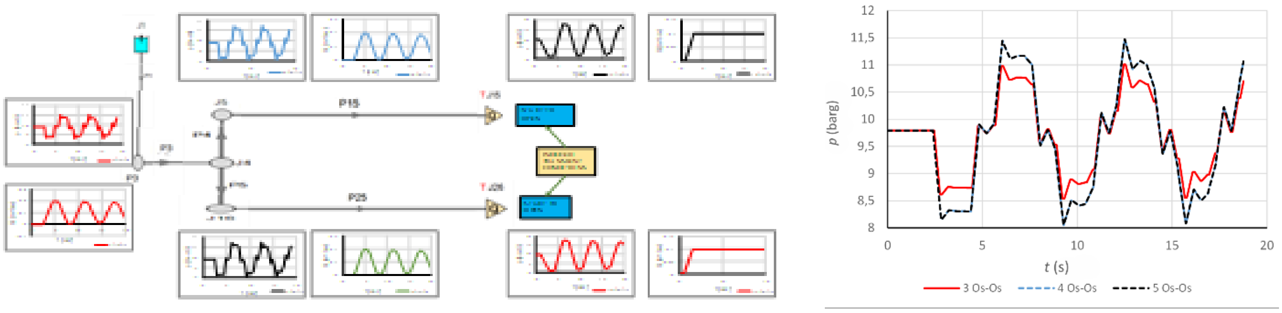
Unsteady flow with a negative pressure wave is ensured by opening the parallel branches, that is, establishing a flow in the branch. The cases of pressure distribution in the T-junction during the simultaneous opening of the parallel branches and the case when the flow is established only in one branch while the other is without flow (closed) are considered.

Simultaneous opening of the branches

The transient states in the pipe system in the T-junction zone under conditions of simultaneous opening of the flow in the branches are given in Figure 9 and Figure 10.

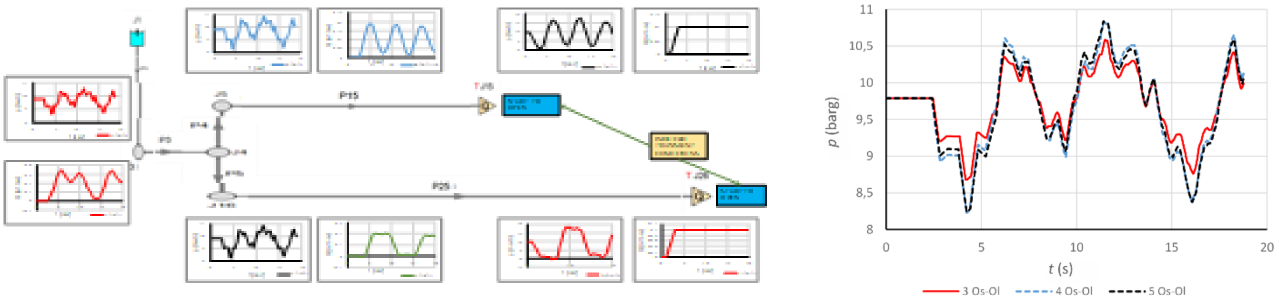
For the 1:1 model, the two negative pressure waves (rarefaction waves) from the branches arrive simultaneously at the T-junction, where they are superimposed in a more intense increase in pressure, which is distributed to the supply pipeline with reduced intensity. The pressure distribution of the pressure wave towards the supply pipeline (section 3) is of reduced amplitude because it propagates against the direction of the water velocity which leads to partial attenuation due to momentum opposition and energy dissipation.

For the 1:2 model, in the T-junction the negative pressure wave from the shorter branch arrives first due to its shorter propagation path and its influence is transmitted to the longer branch. The superposition of the two negative pressure waves occurs along the length of the longer pipe and that effect is perceived in the T-junction after a delay.



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 9. Pressure wave distribution at T-junction – 1:1 model: opening at same time both branches



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

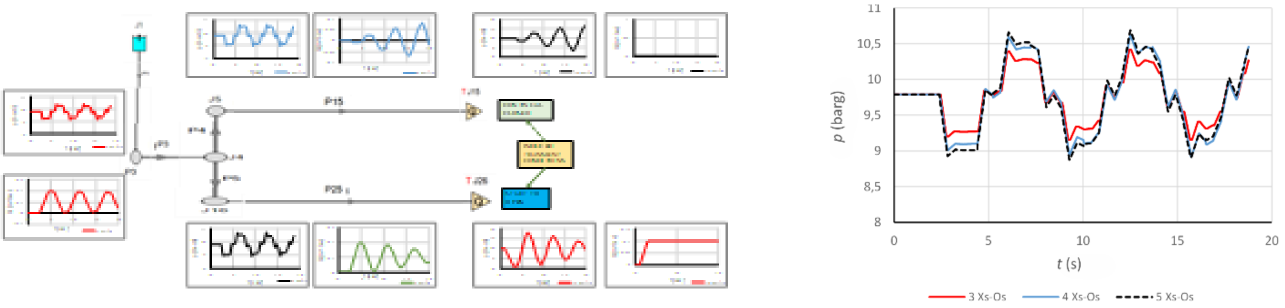
Fig. 10. Pressure wave distribution at T-junction – 1:2 model: opening at same time both branches

Opening one of the branches, the other is closed (no flow)

The transient states in the pipe system in the T-junction zone under conditions of flow opening in one branch are given in Figure 11 for the 1:1 model and in Figure 12 and Figure 13 for the 1:2 model.

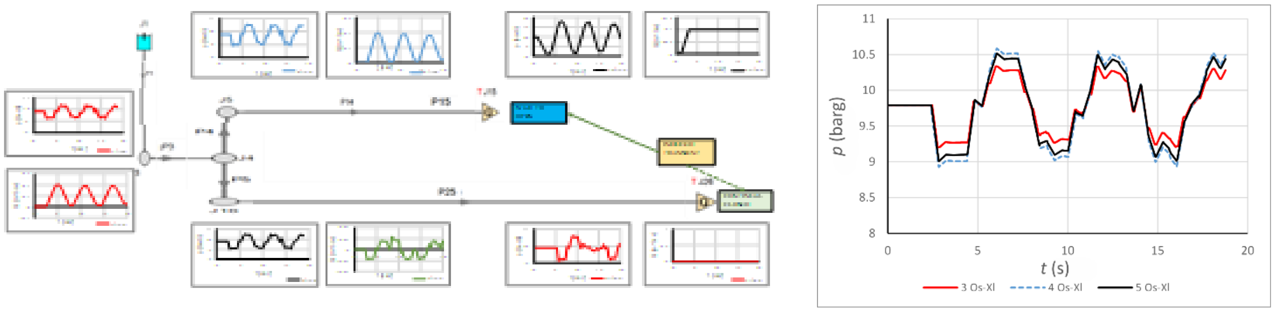
For the 1:1 model, a negative pressure wave from only one of the branches enters the T-junction, which is transmitted to the closed branch and the supply pipeline (section 3). The calculations showed that due to the hydraulic symmetry of the system, the same diagram is obtained for the transmission of the negative pressure wave during the transient states, regardless of which of the branches is opened. The pressure wave transmitted through the T-junction has the highest amplitude.

For the 1:2 model, a negative pressure (rarefaction) wave is applied to the T-junction from either the long or the short branch. In both cases, the negative pressure wave is transmitted to the closed branch and the supply pipeline (section 3).



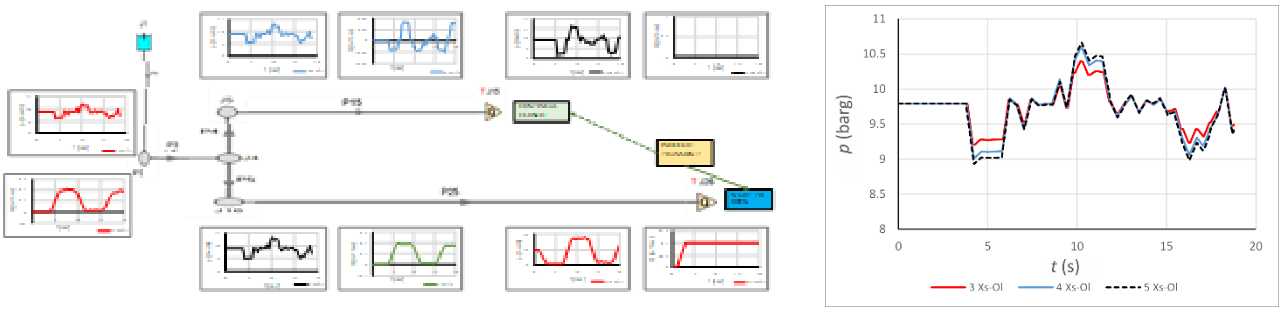
a) Pressure wave distribution at T-junction and initiation

Fig. 11. Pressure wave distribution at T-junction – 1:1 model: opening at one branch



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 12. Pressure wave distribution at T-junction – 1:2 model: opening one branch (shorter)



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 13. Pressure wave distribution at T-junction – 1:2 model: opening one branch (longer)

The results in Figure 14 show that the pressure wave transmitted through the T-junction has the highest intensity, which is the same regardless of which branch opens. The difference in these two cases is in the periodicity of the transition modes, that is, due to the unequal lengths of the branches, the pressure wave propagation time differs, leads to variations in the period and phase of pressure wave reflections and superpositions throughout the system.

The transient conditions in the pipeline in the case of simultaneous opening of both branches and opening of only one branch shows a difference in the pressure wave intensity. Figure 15 shows the wave amplitude is greater in the case of opening both branches due to the superposition of rarefaction waves from both sides at the T-junction.

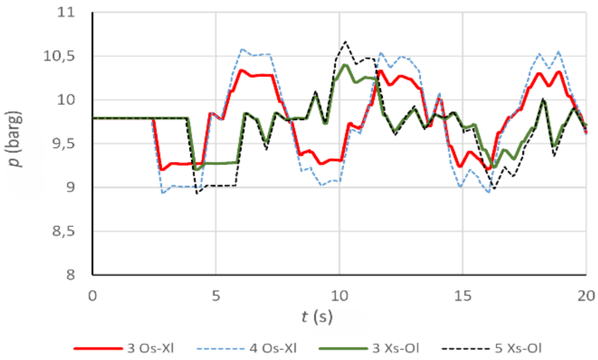


Fig. 14. Comparative diagram of pressure wave distribution at T-junction – 1:2 model: opening one branch, shorter vs. longer

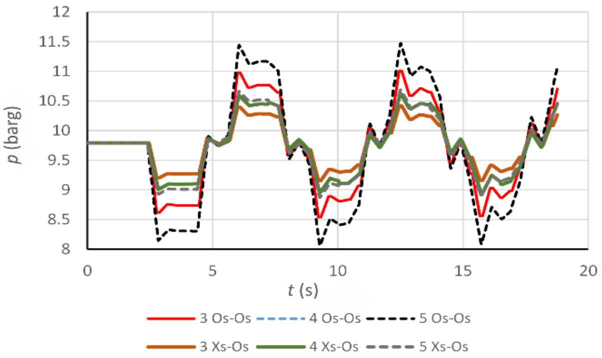


Fig. 15. Comparative diagram of pressure wave distribution at T-junction – 1:1 model: opening one branch vs. opening both branches

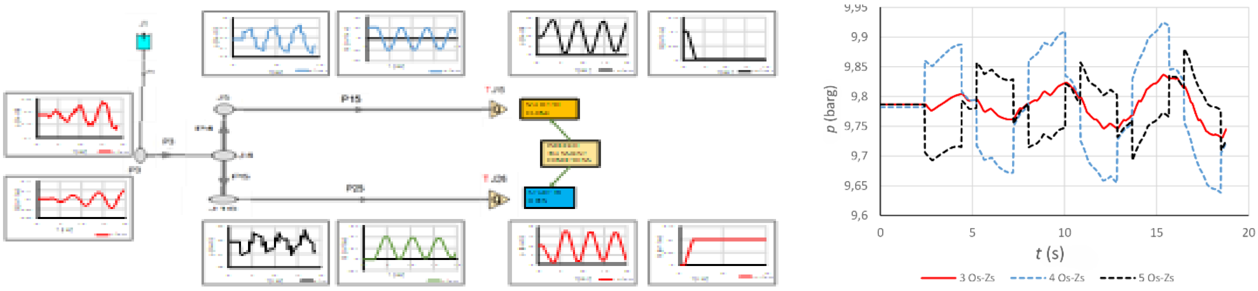
Effects of positive and negative pressure wave simultaneously

The transient states and the pressure wave distribution in the case of inducing a positive and negative pressure wave in the T-junction zone are given in Figure 16 for the 1:1 model and in Figure 17 and Figure 18 for the 1:2 model.

From the results obtained for the 1:1 model, where the positive and negative pressure waves arrive simultaneously in the T-junction, it is concluded that the pressure wave transmitted to the supply pipe is minimal due to the interference from the branches.

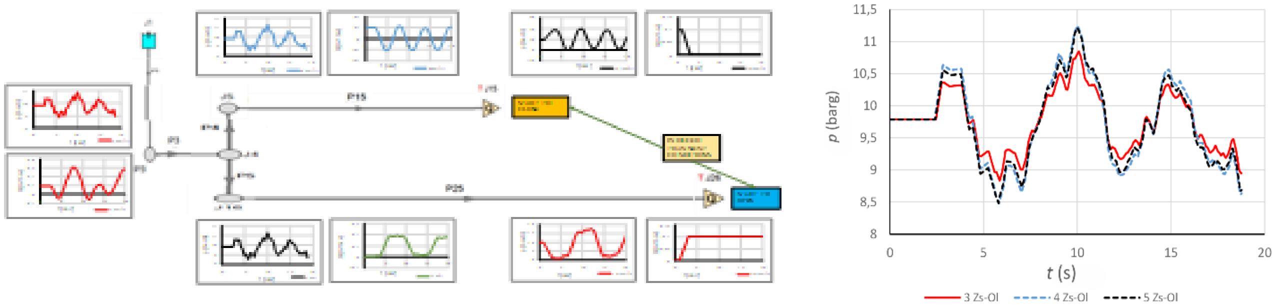
From the results obtained for the 1:2 model, where the positive and negative pressure waves do not arrive simultaneously in the T-junction, the transient states shape depends on which pressure wave (positive or negative) will arrive first at the T-junction.

As shown in Figure 17b, a positive pressure wave initially occurs in the T-junction transmission system, while in Figure 18b, a negative pressure wave is observed first. The transition modes that are reached under these conditions have the same magnitude and period, but they are of opposite signs, forming mirror-image responses in terms of the unsteady flow dynamics.



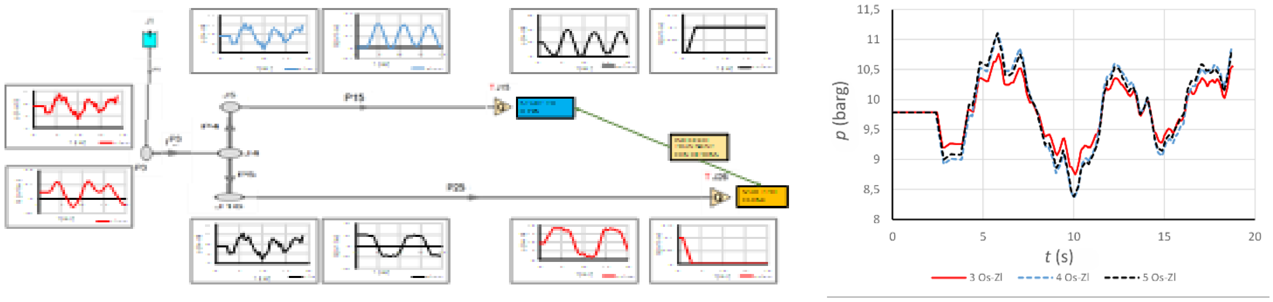
a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 16. Pressure wave distribution at T-junction – 1:1 model: opening/closing of branches at same time



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 17. Pressure wave distribution at T-junction – 1:2 model: opening (longer) and closing (shorter) of branches at same time



a) Pressure wave distribution at T-junction and initiation b) Comparative diagram

Fig. 18. Pressure wave distribution at T-junction – 1:2 model: opening (shorter) and closing (longer) of branches at same time

The simultaneous presence of a positive and negative pressure wave in the T-junction has the effect of reducing the pressure increase that is transmitted through the inlet pipe (Figure 19), while in case of non-simultaneous presence of a positive and negative pressure wave in the T-junction, the transfer of pressure to the inflow pipe (press 3) is the same as if when closing only one branch (the shorter one), Figure 20.

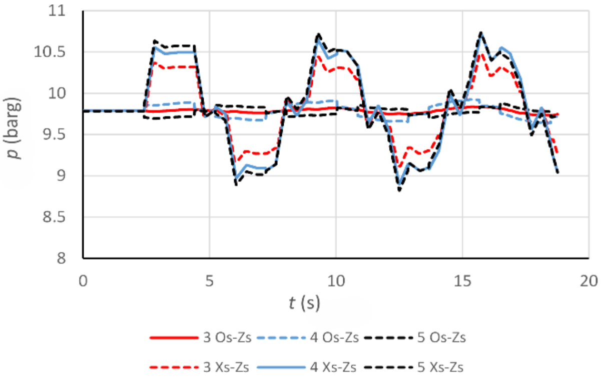


Fig. 19. Comparative diagram of pressure wave distribution at T-junction – 1:1 model: closing one branch vs. closing/opening regime

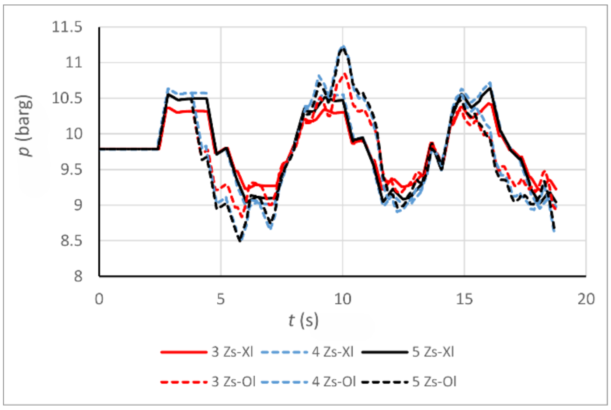


Fig. 20. Comparative diagram of pressure wave distribution at T-junction – 1:2 model: closing one branch (shorter) vs. closing/opening regime

CONCLUSION

The effects of superimposing pressure waves and their transmission through the T-junction are presented. A T-junction, i.e., a nodal point with three branches, is considered.

When pressure waves from both branches (positive or negative) arrive simultaneously at the T-junction, superposition occurs, leading to a more intense pressure response at the junction compared to cases where a wave enters from only one branch. In all scenarios, the transmitted wave into the supply pipeline (section 3) consistently exhibits the highest amplitude, whether it is a compression or rarefaction wave, due to the direct energy transfer from the initiating disturbance. When pressure waves originate from branches of unequal lengths, the arrival times and reflection phases differ, but the maximum transmitted wave intensity at the T-junction remains the same due to the hydraulic symmetry of the system. However, the timing and periodicity of the transient regime vary. Simultaneous closure or opening of both branches generates higher pressure amplitudes in the T-junction due to the interaction of waves from both sides. In contrast, closing or opening only one branch results in lower wave intensity because of absence of superposition. The system also shows that compression and rarefaction waves produce transient regimes of the same amplitude and frequency, but with opposite pressure signs.

The knowledge gained through the analyzed variant conditions is only an indicator of the need for a more detailed definition of the transitional regimes in a pipeline, and the same can be used in the design of pipelines and for the protection of pipelines from uncontrolled pressure increase/decrease occurrence.

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