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Water hammer in irrigation systems

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Professional paper

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Self-propelled sectorial rain guns (typhones) and self-propelled automated devices for linear or circular irrigation are often used in irrigation systems. However, unwanted overpressure can occur due to sudden closure of valves at the entrance segment of these devices. The system is protected against such overpressure by gradual closure of valves. The protection of the system against excessive and insufficient pressures, and the impact of simultaneous closure of valves at peripheral parts of the network, are defined in the paper based on an example of hydraulic calculation of unsteady flows at the Blata - Cerna Irrigation System.

Key words:
water hammer, underpressure, overpressure, air vessel, irrigation systems, Blata – Cerna

Stručni rad

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Vodni udar u sustavima navodnjavanja

U sustavima navodnjavanja se često koriste samohodni sektorski raspršivači (tifoni) i samohodni automatizirani uređaji za linijsko ili kružno navodnjavanje na kojima uslijed naglog zatvaranja zasuna na ulazu u uređaj može doći do pojave neželjenog predtlaka. Sustav se štiti od neželjenog predtlaka postupnim zatvaranjem zasuna. U radu je na primjeru hidrauličkog proračuna nestacionarnih stanja na sustavu navodnjavanja Blata – Cerna definirana zaštita sustava od prevelikih i premalih tlakova te utjecaj istodobnog zatvaranja zasuna na rubnim dijelovima mreže.

Ključne riječi:
vodni udar, podtlak, predtlak, zračni kotao, sustavi navodnjavanja, Blata – Cerna

Fachbericht

Martina Tadić Ananić, Goran Gjetvaj

Wasserschlag in Bewässerungssystemen

In den Bewässerungssystemen kommen häufig selbstfahrende Flächenberegnung-sanlagen (Typhone) und selbstfahrende automatisierte Anlagen für die Linear- oder Kreisberegnung zum Einsatz, bei welchen es infolge eines schlagartigen Schließens der Absperrarmatur am Geräteeingang zu einem unerwünschten Überdruck kommen kann. Das System schützt sich vor einem unerwünschten Überdruck durch ein langsames Schließen der Absperrarmatur. In der Arbeit wurden am Beispiel einer hydraulischen Kalkulation von nicht stationären Zuständen am Bewässerungssystem Blata – Cerna der Schutz des Systems vor zu hohen und zu niedrigen Drücken festgelegt und die Auswirkung des Schließens der Absperrarmatur auf die Randbereiche des Netzes dargestellt.

Schlüsselwörter:
Wasserschlag, Unterdruck, Überdruck, Wasserkessel, Bewässerungssysteme, Blata – Cerna

1. Introduction

Irrigation systems are planned and built to create and maintain necessary water regimen in soil, depending on requirements for optimum development of plant crops and achievement of their full biological potential or, in other words, the greatest possible yield. The design of irrigation systems involves finding an optimum solution in the functional and economic contexts, so as to fulfil requirements for maximum development of plant crops. The Blata – Cerna irrigation system, consisting of medium-pressure pumps, water distribution network, and typhoons (rain guns), is considered in the paper.
Sudden changes in the velocity of flow due to abrupt closure of valves and/or pump malfunction, resulting in water hammer, may occur in irrigation systems in which the flow is operated under pressure. Hydraulic calculation of unsteady flow must be made in the scope of design work so as to determine maximum and minimum pressures and, if necessary, to provide for protection against unfavourable pressure load.
The air entrapped in the pipeline can also cause problems in the system. As air is highly compressible, its compression and propagation along the pipeline may result in changes in flow velocity, and hence in considerable variations of pressure in the system [1]. All situations that may cause such changes are considered and analysed through hydraulic calculations, and appropriate system protections are planned so as to avoid unwanted consequences of water hammer.
Negative pressures are known to occur in flat-land areas. In case of pump failure the pressure drops immediately next to the pumping station and along the route. The protection against negative pressures is ensured by positioning an air vessel next to the pumping station, and by installing valves as appropriate along the pipelines.
The problems that may occur in irrigation systems as a result of pump failure or sudden valve closure by the user are presented in the paper. The following cases are simulated for the Blata – Cerna irrigation system: pump failure for system without protection, pump failure for system protected by air vessel, and sudden valve closure by the user. The scenarios involving simultaneous sudden valve closing by the user and gradual closing are also simulated and analysed, the purpose being to determine minimum time needed to close the valve so as to avoid unwanted pressure buildup. In addition, the influence of pressure change in typical nodes due to simultaneous valve closure is considered.

2. Mathematical model and relevant equations

2.1. Equation model and basic parameters

Mathematical model was prepared by means of the Bentley-Hammer computer program that describes unsteady flow using the method of characteristics. Equations relevant for the calculation of unsteady flow are the mass preservation principle (1) and the movement preservation principle (2) [2]:

$$\frac{\partial H}{\partial t}+v\frac{\partial H}{\partial x}+\frac{a^2}{g}\frac{\partial v}{\partial x}=0 \qquad (1)$$

where:
a - water wave velocity (L/T)
v - average pipe flow velocity, parallel to *x*-axis (L/T)
H - pressure head (L)

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+g\frac{\partial H}{\partial x}+\frac{fv|v|}{2D}=0 \qquad (2)$$

where:
f - Darcy-Weisbach friction factor (1)
D - internal pipe diameter (L)
v - liquid flow velocity

Properties of modelled liquid (water):
- water temperature, 4 °C
- kinematic viscosity, $1.566 \cdot 10^{-6}$ m²/s
- elastic modulus, $0.2188 \cdot 10^{10}$ N/m²
- water vapour pressure, -1.0 bar.

Time parameters:
- time increment, 0.01 s
- simulation time, 300 s.

2.2. Description of analysed system

The Blata – Cerna irrigation system occupies an area of approximately 500 ha [3, 4] that accommodates a branched pipeline network 13,955 m in length (Figure 1). The system consists of a water intake, pumping station, and pipeline network that will be built using ductile cast iron pipes and HDPE (PE100 PN10 SDR17) pipes. The system is situated on a flat terrain where the lowest lying point is at 77.2 m asl, and the highest one is at 83.3 m asl. The water is carried from the water intake by gravity toward the pumping station. The pumping station accommodates three operating pumps 325.8 l/s in total capacity, and one spare (standby) pump with the pressure head of H = 80 m. A non-return valve, located behind each pump (at the pressurized side), is used to protect the pump when it is not in use.
Rain guns each with the capacity of Q = 22 l/s will be used at 13 locations, and a linear unit (Q = 37 l/s) will be used at one location. The drop by drop (drip) irrigation system (localised irrigation) should also be considered. Considering the planned irrigation type, a pressure of at least 6 bars must be ensured at all parts of the system.

3. Simulations and mathematical model results

3.1. System without pressure protection

The three-pump failure simulation at maximum total flow of Q = 325.8 l/s during 10 seconds was conducted for the described irrigation system. The system was not protected against excessive pressure. A schematic diagram of the system is shown in Figure 1.

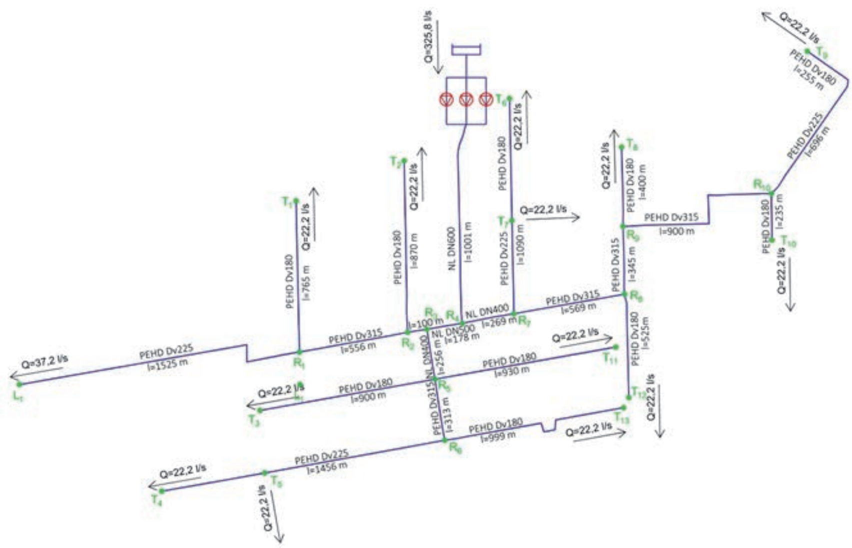

Figure 1. Schematic diagram of the irrigation system without pressure protection

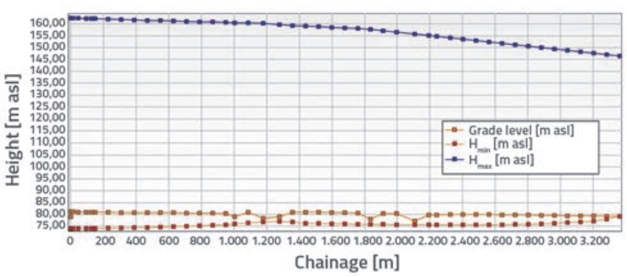

Figure 2. Envelopes of minimum and maximum pressure heads at the section from pumping station to linear unit – unprotected system (m asl = metres above sea level)

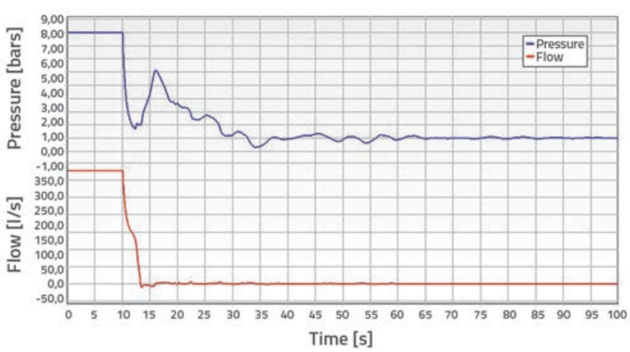

Figure 3. Flow and pressure at the pressurized side of pumps – unprotected system

Upon pump failure the flow of water gradually reduces until it is fully stopped, and then the water starts to flow in the opposite direction. Water backflow toward the pump is prevented by means of a non-return valve. At the moment of pump failure the negative pressure wave starts to propagate along the network. When the pressure head is primarily influenced by friction, as is the case in long pipelines, the water vapour pressure may be generated at pump failure, and hence the water column will be interrupted. The interruption most often occurs when pump fails at the highest points of the pipeline [5]. The decrease in pressure may provoke foaming and release of air bubbles that concentrate at the highest point of the pipeline. These air bubbles may travel along the pipeline and cause water hammer, especially when the water mass oscillates and pressurizes the air cushion from both sides (6). The envelope of minimum and maximum pressure heads at the section from the pumping station to the linear unit (from node CS to node L1) is shown in Figure 2. The unsteady flow is initiated in the system at pump failure (in the tenth second of the simulation). The smallest pressure values occur directly in front of the pump. Pressure variations are presented in Figure 3. The non-return valve closes immediately after pump failure, which results in a sudden fall in pressure immediately in front of the pumping station, and in propagation of negative wave along the network. The lowest pressure at the pipeline under study amounts to -0.7 bars, while the highest pressure is 8.2 bars.

3.2. System protected with air vessel

The installation of air vessels is the most efficient method for preventing negative pressures and reducing excessive pressures [5]. An air vessel is considered to be an effective protection because, after pump failure, when the flow at the pressurized side of the pump reduces and the pressure falls, the pressurized air in the vessel forces the water out of the vessel and into the network. In addition, at the moment the backflow is initiated, the water enters the vessel only by the amount permitted by the pressurized air in the vessel. This slows down the change in water velocity in the pipeline, and hence the accompanying pressure oscillations are reduced.

The propagation of negative pressure wave takes place along the entire pipeline network, which may cause negative pressure at some locations. The installation of air valves is an efficient protection against this undesirable phenomenon. These valves regulate the quantity of air in the pipeline so as to reduce or prevent potentially destructive consequences of the moving and entrapped air [7]. In the system under study, air valves are positioned along the route and their purpose is to deaerate the system during everyday operation, introduce the air in cases when the pressure in the pipeline is lower that the atmospheric pressure, and release the air from the pipeline when the system is refilled with water.

Necessary air vessel parameters were defined through a number of simulations. A particular feature of the system is that the installed air vessel will have two functions. As it was also necessary to consider the possibility of using drip irrigation, and as the planned pumps can not operate at low flow rates, during regular operation the air vessel will ensure sufficient quantity of water at minimum flow rates, i.e. it will be used as a storage tank, while in exceptional cases – during pump failure – it will protect the system against

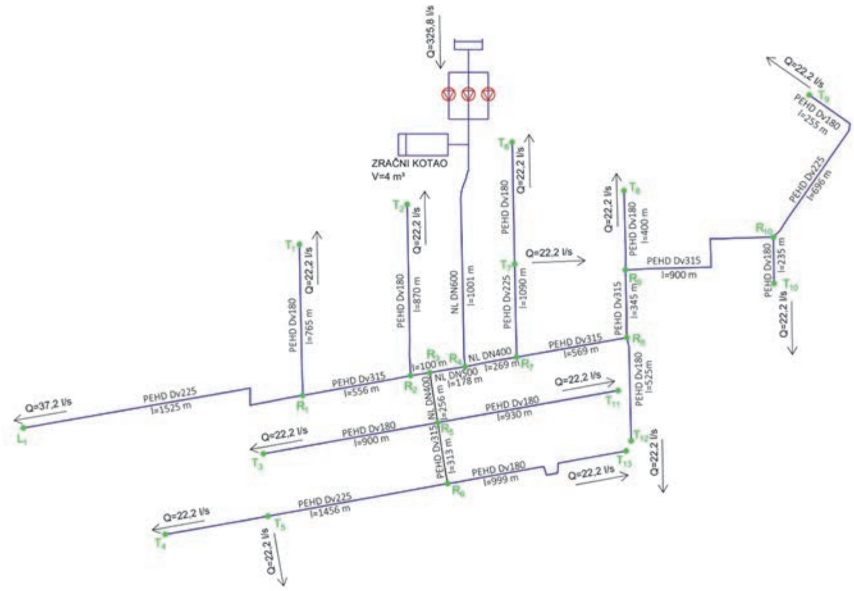

Figure 4. Schematic diagram of irrigation protected with air vessel

During valve closure, the pressure increases along the pipeline. The maximum pressure head can be achieved during valve closure or at the moment when the valve is closed. The pressure head value and the moment when it occurs greatly depend on the valve closure velocity. Instantaneous valve closure refers to valve closure during which the closing time tends toward zero, while the term sudden valve closure refers to the time of less than 2L/a (where: L-pipe length, a-water wave velocity). Generally, the shorter the valve closing time the greater the increase in pressure head [8]. The change in pressure and flow values in node L1 at various valve closing velocities (T = 1 s, T = 10 s, T = 50 s, T = 100 s, T = 200 s), at the initial flow rate of Q = 37.2 l/s, is shown in Figure 6. The sudden valve closure at node L1 results in water compression and, hence, in pressure increase. The diagram shows that the maximum pressure can attain 11 bars or more, which can result in rupture at that part of the network. That is why the unwanted maximum pressures in the system can be prevented by gradual closure of valves.

In the case of unsteady flow, pressure relief valves can be used to protect the system against pressures that greatly exceed the pressure capacity of individual elements of the system. Pressure relief valves have to be installed in such a way that they open when the pressure exceeds the operating pressure by 5 m of water column. Experience has shown that pressure relief valves should be installed approximately 500 m away from the valve at each branch, and that they must be spaced at 2 km intervals along the main pipeline [9].

pressure surge. This is why the volume of the selected vessel is greater than would actually be needed for the protection against pressure surge. The planned volume of the air vessel is 4 cubic meters. The air to water volume ratio is V_z/V_v = 0,25/0,75, i.e. the volume of water in the vessel is V = 3 cubic meters. A schematic diagram of the system with protection is shown in Figure 4.

The air vessel efficiency can be seen in the diagram shown in Figure 5. At pump failure, the minimum pressure in front of the pump amounts to -0.1 bar, while the maximum pressure is 8 bars. Therefore, the planned irrigation system protection with air vessel and air valves along the route meets the criteria set with regard to pump failure.

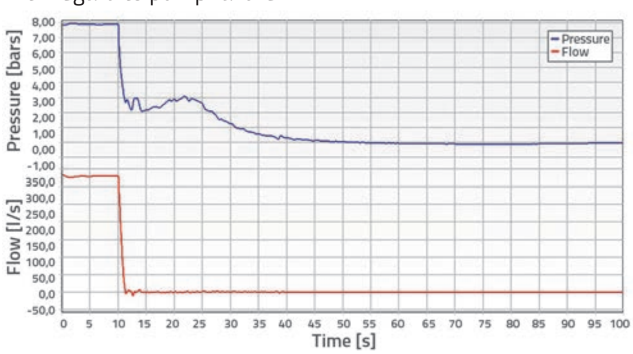

Figure 5. Flow and pressure at the pressurized side of the pump – protected system

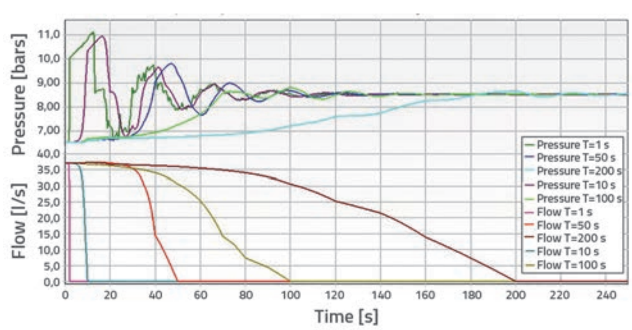

Figure 6. Pressures and flows at various valve closing velocities in node L1

3.3. Sudden valve closure at rain guns and linear unit

Rain guns, each with the flow rate of 22.2 l/s, and the linear unit with the flow rate of 37.2 l/s, positioned at the end points of the irrigation system, are water consumers. The adequacy of planned protection for the case of valve closure by the user was tested by mathematical model simulations.

Mathematical model simulations were made to test correlations of simultaneous sudden valve-closure events. Figures 7 to 9 show resulting pressures at typical nodes: node CS at pressurized side of pumps, node R3 at pipeline branching, and node T1 at boundary part of the system at the valve closure location.

Valve closure at node L1 causes maximum pressure of 9.5 bars at node T1, while simultaneous valve closure at nodes L1 and T1 causes pressure increase to 11.25 bars. Also, valve closure in nodes L1, T1 and T2 causes maximum pressures of as many as 12 bars in node T1. Sudden simultaneous valve closure cases change in pressure at all nodes along the system and, hence, also in the node immediately in front of the pumps and at the branching. The closure of one valve causes maximum pressures that are by as much as 1.5 bars lower compared to simultaneous closure of three valves. The maximum pressure depends on the location of a particular node as related to the location of the valve that is being closed. The influence of the distance of simultaneously closed valves on the change in pressure at the node in front of the pumping station (CS), and at the node where the valve is being closed (L1), is considered, see Table 1. At node L1 the change in pressure is mostly influenced by simultaneous closure of valves at nodes L1 and T1, where the change in pressure amounts to Δp = 4,35 bars. The valve in node T2 is situated at the same branching but its simultaneous closure causes much smaller change in pressure in node L1 (Δp = 2,52 bars). The change in pressure due to closure of other gates in the network is almost identical. Significant changes do not occur in node CS in case of simultaneous closure of two valves, regardless of their distance. The greatest change of pressure (Δp = 0,49 bars) occurs during simultaneous closure of valves at nodes L1 and T1.

Table 1. Effect of simultaneous valve closure on pressure increase at node L1 and CS

Node	Node distance [m]	Node L1		From pressurized side of CS	
		p_{max} [bara]	Δp_{max} [bara]	p_{max} [bara]	Δp_{max} [bara]
L1		11.1		8.74	
L1-T1	2290	13.09	4.35	9.23	0.49
L1-T2	2951	11.26	2.52	9.13	0.39
L1-T3	3337	11.1	2.36	9.06	0.32
L1-T4	4206	11.1	2.36	9.08	0.34
L1-T5	3680	11.1	2.36	9.07	0.33
L1-T6	3718	11.1	2.36	9.08	0.34
L1-T7	3083	11.22	2.48	9.07	0.33
L1-T8	3942	11.1	2.36	9.06	0.32
L1-T9	5393	11.1	2.36	9.09	0.35
L1-T10	4677	11.1	2.36	9.05	0.31
L1-T11	3367	11.1	2.36	9.06	0.32
L1-T12	3722	11.1	2.36	9.08	0.34
L1-T13	3749	11.1	2.36	9,11	0.37

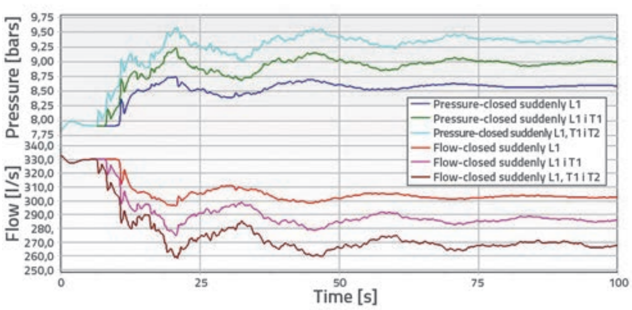

Figure 7. Flow and pressure at the pressurized side of pumps at sudden valve closure

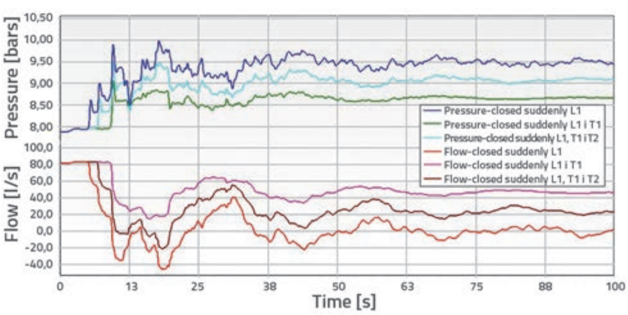

Figure 8. Flow and pressure at node R3 at sudden valve closure

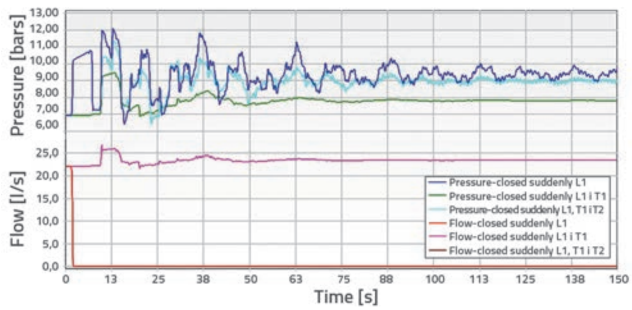

Figure 9. Flow and pressure at node T1 at sudden valve closure

3.4. Gradual valve closure at rain guns and linear unit in the period of 200 seconds

Sudden valve closure causes unwanted pressure changes in the system. The greatest consumption, i.e. the greatest flow of 37.2 l/s, was registered at node L1 (linear unit). Instantaneous valve closure at that node causes the greatest pressure changes in the system. Sudden valve closure at node L1 causes the greatest pressure changes in the vicinity of the node, and involves pressures of 11 bars and more. The effect of valve closure weakens along the route, and so maximum pressures amount to 8.8 bars at the node in front of the pumping station. Gradual valve closure scenarios for closure time of t = 200 s were simulated on a mathematical model, see Figure 10. Figures 11 to 13 show pressure diagrams for gradual closure of one valve (valve L1), simultaneous closure of two valves (valves L1 and T1), and simultaneous closure of three valves (valves L1, T1, and T2). Gradual closure of valves also causes pressure changes in the system, but they are no longer so sudden and are compliant with allowable values.

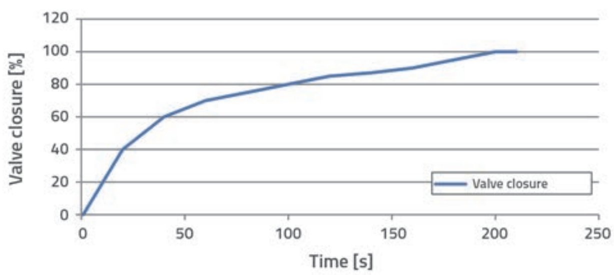

Figure 10. Gradual valve closue, T = 200 s

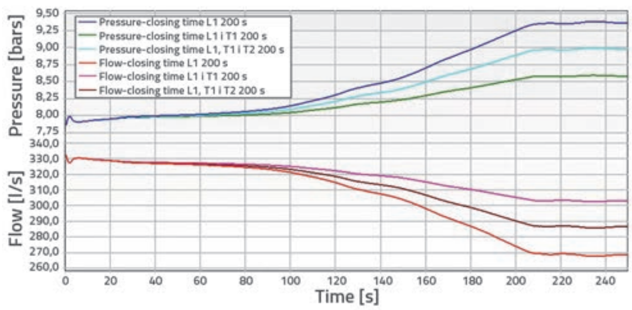

Figure 11. Flow and pressure at pressurized side of pumps, for valve closure in T = 200 s

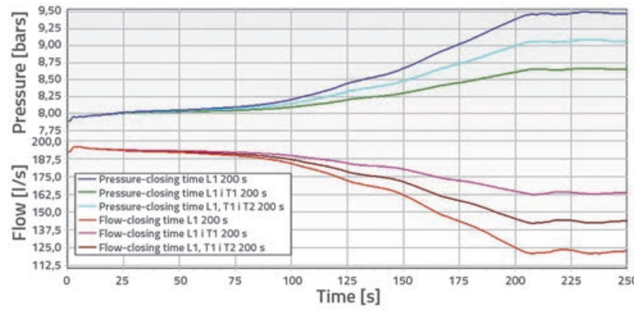

Figure 12. Flow and pressure at node R3 for valve closure in T = 200 s

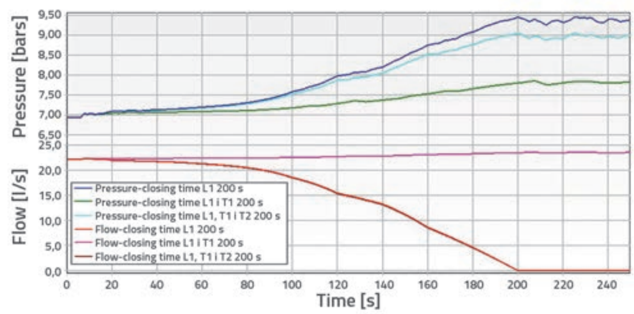

Figure 13. Flow and pressure at node T1 for valve closure in T = 200 s

4. Conclusion

Significance of hydraulic analysis of nonstationary phenomena in branched irrigation systems is presented through the example of the Blata – Cerna irrigation system. Pump failure causes significant fall in pressure at the pressurized side of the pump and along the route, which may lead to negative pressure. Pressurized systems can be protected against unwanted consequences of water hammer by means of air vessels and air valves. The protection involving an air vessel and air valves along the route is planned at the Blata – Cerna irrigation system. The efficiency of this protection is shown in the paper.

An emphasis is placed on the problem of pressure surge due to sudden valve closure at terminal nodes in the network. The planned protection with air vessel is not considered sufficient as protection against sudden valve closure. Consequently, the necessary valve closing time is planned so as to reduce oscillations and changes in pressure head.

The analysis of simultaneous closure of several valves has enabled determination of the influence exerted by the change of maximum pressure in the system. This analysis has also shown that the distance of the valves that are being closed affects the change of pressure up to a certain limit, after which this change tends to assume a constant value.

Due to insufficient knowledge about valve operation, moment of inertia of pumps to be installed, and other parameters that have been adopted in the analysis, it is planned to install measuring equipment that will be used to monitor operation of the system and, on that basis, analyses will be checked and operation rules will be made and, if necessary, additional air valves will be installed.

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