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THE EFFECT OF WATER HAMMER ON PRESSURE INCREASES IN PIPELINES PROTECTED BY AN AIR VESSEL

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Original scientific paper

In the pipelines of water supply systems, the water hammer phenomenon often arises during rapid unsteady developments. Pipelines are mostly protected using an air vessel, which is designed by means of equations for oscillations of water mass. In this study, an analysis is made of the impact of pressure increases caused by water hammer on pressure variations in pipelines protected by an air vessel. The analysed unsteady (transient) developments occurred in a pressure system between the Ravnik pumping station and the Veliko Brdo reservoir, and thereby the measured pressure values were compared with values calculated with a numerical model. It was observed that although the air vessel converts kinetic energy into oscillations of water mass, part of the energy is transformed into elastic deformations of pipelines and into water compression. This study assesses the relationship of the conversion of kinetic energy into significant changes in pressure (phenomenon called water hammer), depending on the extent of the velocity change in time.

Keywords: *energy method, pipeline, water hammer*

Utjecaj vodnog udara na prirast tlaka u tlačnim sustavima štićenim zračnim kotlom

Izvorni znanstveni članak

U tlačnim cjevovodima može, pri nestacionarnom režimu rada, doći do pojave vodnog udara. Uobičajeno je da se takovi cjevovodi štite zračnim kotlom pri čemu se kod uključivanja i isključivanja crpki formiraju oscilacije vodnih masa. U ovom radu opisan je doprinos elastičnih sila na prirast tlaka u cjevovodima štićenim zračnim kotlom. Kao primjer je prikazan tlačni cjevovod od crpilišta Ravnik do vodospreme Veliko Brdo na kojem su provedena mjerenja oscilacija tlaka prilikom ispada crpki iz pogona uspoređena s izračunatim vrijednostima. Primijećeno je da, iako zračni kotao formira oscilacije vodnih masa, postoje i varijacije tlaka koje su posljedica vodnog udara. Istraživanje ističe vezu između pretvaranja kinetičke energije u značajnu i naglu promjenu tlaka (pojava nazvana vodni udar), ovisno o promjeni brzine u vremenu.

Ključne riječi: *energetski pristup, tlačni cjevovod, vodni udar*

1 Introduction

In hydrotechnical engineering, an unsteady flow is often encountered in pipelines, whereby the variations of flow (and consequently of water speed) cause the conversion of kinetic energy of water into other forms of energy. However, because water and other liquids are only slightly compressible, a small flow imbalance can produce large pressure changes and thereby allows a considerable quantity of energy to be stored.

Rapid changes in water speed can cause the water hammer phenomenon, which can damage pipelines and other hydrotechnical equipment. The most frequent causes of water hammer are the sudden closing (or opening) of a valve, and the sudden switching off (or switching on) of a pump. The modelling of unsteady occurrences in pressure systems is the basis for achieving the safe operation of a water supply system, and it is the most challenging part of the rational design of such a system.

To avoid the occurrence of water hammer, pipelines are mostly protected by introducing an air vessel. The main function of the air vessel is to slow down the change of speed, so as to avoid rapid changes in water flow speed. Yet one of the most difficult questions to answer in general is, How rapid is rapid? That is, how can the analyst know whether compressibility effects are important and what errors might be introduced by using a rigid water column model?

Towards the end of the 19th century, the development began of models which described the variations of speed and of pressure caused by water hammer [1], and many programs were made to enable the oscillation of water mass and/or of water hammer to be simulated. In this study, based on a comparison of measurement results of unsteady flow in a pipeline between the PPV Ravnik pump station and the VS Veliko Brdo reservoir, on the one hand, and respective numeric calculations, on the other hand, it is claimed that in real water supply systems simultaneous water hammer and oscillation of water mass occur. In this way, we show that in numerical analysis full equations of unsteady water flow in pipes should be used, and that it is very advantageous to take an energy approach in describing pressure systems.

2 Governing equations and a numerical model

Classical mass and momentum equations for one-dimensional water-hammer flow were fully established in the 1960s [1, 2] in the form:

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

$$\frac{\partial v}{\partial t}+g\frac{\partial H}{\partial x}+\frac{4}{\rho D}\tau_{\mathrm{w}}=0, \qquad (2)$$

where c is the celerity of water-hammer pressure wave, g is gravitational acceleration, v is the mean flow velocity, x is the spatial coordinate along the pipeline, H is the piezometric head, τ_{w} is shear stress at the pipe wall calculated according quasi-steady wall shear assumption, D is pipe diameter and t is the temporal coordinate. Eqs. (1) and (2) constitute the fundamental equation for 1D water-hammer problems and contain all the physics necessary to model wave propagation in a complex pipe system. With these two equations and the two unknowns of piezometric head and flow velocity, the system has a closed numerical solution. In this connection, the energy (power) equation is redundant [4].

In order to model the transient situation in a system, one has to solve these equations for a wide variety of boundary conditions of that system and its topologies. The full elastic water hammer equations cannot be solved analytically, except by some approximate methods.

Many authors have pointed out that energy concepts are at the heart of our understanding of the physical world [3] [4]. The energy concept plays an essential role in the interpretation and understanding of the physical world; its practical significance is well known and hardly needs illustration. Several authors have introduced the energy concept into the analysis of transient pipe flows. The studies made by Jelev [5] and Karney [3] are representative of these efforts.

Mathematical expressions describing transient energy transformations take in account the kinetic energy of the fluid, the internal energy associated with fluid compressibility and pipeline elasticity effects, the energy dissipated by friction, and the work done at the ends of the conduit. A case study identifies the conversion between internal and kinetic energy, and quantifies the behaviour and magnitudes of the related energy components of the system.

For convenience, the energy equation can be written in a more compact form as follows [3]:

$$\frac{\mathrm{d}U}{\mathrm{d}t}+\frac{\mathrm{d}T}{\mathrm{d}t}+D'+W'=0, \tag{3}$$

in which $U-$ the internal energy, $T-$ total kinetic energy, $D'-$ rate of viscous dissipation, and $W'-$ rate at which work is being done to force fluid into and out of the line. This simple equation allows for the following natural classification of flow regimes:

1) If the flow is steady, then the rate of change of internal and kinetic energy is zero; there is equilibrium between flow work (W') and the rate of mechanical energy dissipation (D');
2) Flows can be assumed "quasi-steady" when the work and dissipation terms dominate the two transient terms. In this case, flow conditions do not depart significantly from the steady state, and a time-stepping steady solution can be used to adjust flow and head values incrementally;
3) More rapid-flow disturbances disrupt the usual balance between dissipation and work, causing either or both of the first two terms in Eq. (3) to be nonzero. If the kinetic energy term dominates the internal energy term, the flow is unsteady and essentially incompressible (rigid water column), as the wave speed a increases without bound, and the internal energy becomes zero, thus reproducing the classical representation of a transient incompressible model in which disturbances travel instantaneously from one location to another.
4) If both the internal and kinetic energy terms in Eq. (3) are significant, the flow is unsteady and compressible, and must be solved with a full transient (water hammer) analysis.

In this study, the flow analysis comprises both regime 3 and regime 4. The question of quantifying the boundaries between these various zones is considered in more detail later.

Internal energy U can be calculated as

$$U=\frac{\rho A}{2}\left(\frac{g}{c}\right)^{2}\int(H-H_0)^2\mathrm{d}x, \tag{4}$$

in which H_0 (ma.s.l.) is usually taken as the initial steady state head. The ratio of the total change in internal energy to the total change in kinetic energy provides a natural index of the importance of compressibility effects. Thus, if Φ is the compressibility index, then

$$\Phi=\frac{|\Delta U|_{\max}}{|\Delta T|_{\max}}. \tag{5}$$

In the limit as ΔU approaches zero, the compressibility index Φ approaches zero. As has been shown, the original definition of U (Eq. (4)) guarantees that this limit is achieved as the wave speed a approaches infinity. In effect, flow disturbances propagate instantaneously relative to the rate of change in the work and dissipation terms.

Clearly, the change in state in a pipeline with a longer-duration valve closure is almost totally accounted for by the work at the ends of the conduit. Very little energy is stored. By contrast, when the time of valve closure is short, most of the change in kinetic energy is temporarily stored as an increase in internal energy, as is indicated by the large value of the compressibility index.

Since all major changes of state are accounted for in the energy analysis, these conclusions are general. That is, whenever the value of Φ is large (say greater than 0,1), compressibility effects are important; as the value of Φ decreases (say to values less than 0,01), compressibility effects become less important and the rigid water column model becomes a better approximation of the transient response of the pipeline. Values of Φ between about 0,01 and 0,1 indicate that compressibility is moderately important and can be neglected only with some loss of accuracy. Note that since the rigid water column model is by its nature an approximation, no absolute limits of Φ values can be given. It is really a question of trading numerical accuracy for computational speed. Karney finds that the limit of $\Phi = 0{,}01$ represents a good working compromise for a wide range of systems and applications [3].

The Φ index is ideally suited for the aforementioned kind of adaptive algorithm. That is, the index evaluates the influence of compressibility during a particular time step; if compressibility is important, the current time step can be decreased to improve accuracy. On the other hand, if the compressibility effects are not important, the time step is increased (say by wave speed adjustments) to obtain an equivalent degree of accuracy at less expense.

3 Case study

The focus of this example is to describe the difference between the long-term transformation of kinetic energy to potential energy and the short-term transformation of velocity into head and back again under transient conditions.

3.1 Pressure variations in the mains

The network of pipelines within the Moslavačka Posavina system is comparatively well developed (Fig. 1), and one of its segments is the PPV Ravnik - VS Veliko Brdo pipeline. Forming part of the Ravnik - Veliko Brdo mains is what is known as KrižnaŠahta, from which branches run towards consumers. One branch runs east towards Kutina, another runs west to the Vidrenjak settlement (Fig. 1), while the mains continues north, i.e. to the Veliko Brdo reservoir.

The Ravnik pump station has a capacity of 100 l/s, and it is planned to upgrade it in the future to 200 l/s. Conditioned water from the Ravnik pump station is pumped towards consumers in Kutina, Popovača, Vidrenjak and other settlements connected to the water supply system, while the surplus flows into the Veliko Brdo reservoir which serves to equalize the imbalances. The node in which the pipelines branch towards Kutina and Vidrenjak is 2810 m from the pump station, and the total length of the pipeline between the pump station and the Veliko Brdo reservoir is 3355 m. The maximum consumption in the Kutina branch is $Q_{\max1}$ = 150 l/s, which is the same as in the Vidrenjak branch: $Q_{\max2}$ = 150 l/s. The Ravnik - Veliko Brdo pipeline is made of ductile iron with a diameter of DN 500 mm; the branch towards Kutina is a PVC pipeline with a diameter of DN 400 mm; and the branch towards Vidrenjak again is made of ductile iron with a diameter of DN 500 mm. On the pump pressure side, there is a non-return valve, which automatically closes if the pump is shut down. The system is protected by an air vessel which is installed on the water conditioning device, immediately next to the pump. The diameter of the air vessel is 2000 mm, the height is 2500 mm (with a total volume of cca 9,5 m^3), while the reference water level is 1350 mm. Branching within the system causes reflections of elastic waves. Propagation velocity of a pressure wave is c = 1000 m/s. For the purpose of analysing the possible increase in flow through the existing system from Q_1= 100 l/s to Q_2=200 l/s, measurements of pressure and flow variations were performed, thereby calibrating the numerical model of unsteady flow in the pressure system.

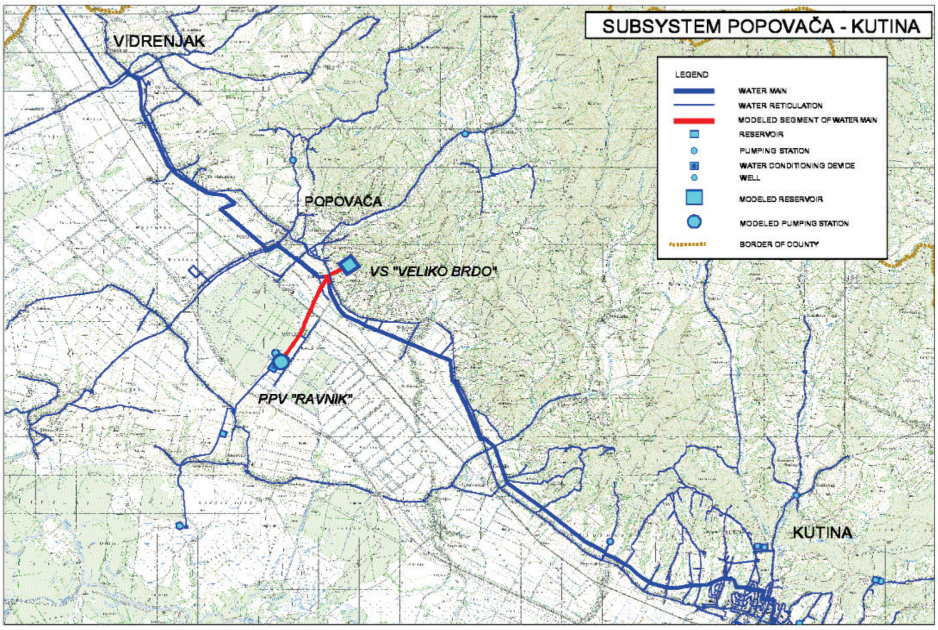

Figure 1 Water supply system network of Moslavačka Posavina

Measurements were performed while the pumps were temporarily fully shut down, and records were made of the flow and pressure at PPV Ravnik and at Križna Šahta towards the Kutina and Vidrenjak settlements. For measurements, the SCADA data acquisition system was used. This system is also usually applied in the everyday use of the system.

The results of the pressure measurements and of the calculations (Fig. 3) show that in the existing system oscillations of water mass arise as a result of the effect of the air vessel, but smaller pressure variations are caused by water hammer. It may also be noted that the measured and calculated values are in agreement, which confirms that the numerical model adequately describes the transient states within the pipeline.

The differences between the results obtained by the numerical model and by measurements on the installed pressure systems may derive from [5, 6]:

- the inability to precisely determine the propagation of elastic disturbances in dug-in pipelines, which are influenced by the bed and thickness of the surrounding soil;
- the inability to exactly model the elements installed within the system (such as valves, pumps and air vessels – protection elements) because their performance varies over time and with maintenance modifications;
- differences in the value of the friction index in steady and unsteady conditions. In unsteady conditions, the flow direction changes, while the velocity gradient also causes changes in the shear loads within the

pipelines. The friction index used in modelling should ideally account for both local and for transfer gradients (accelerations).

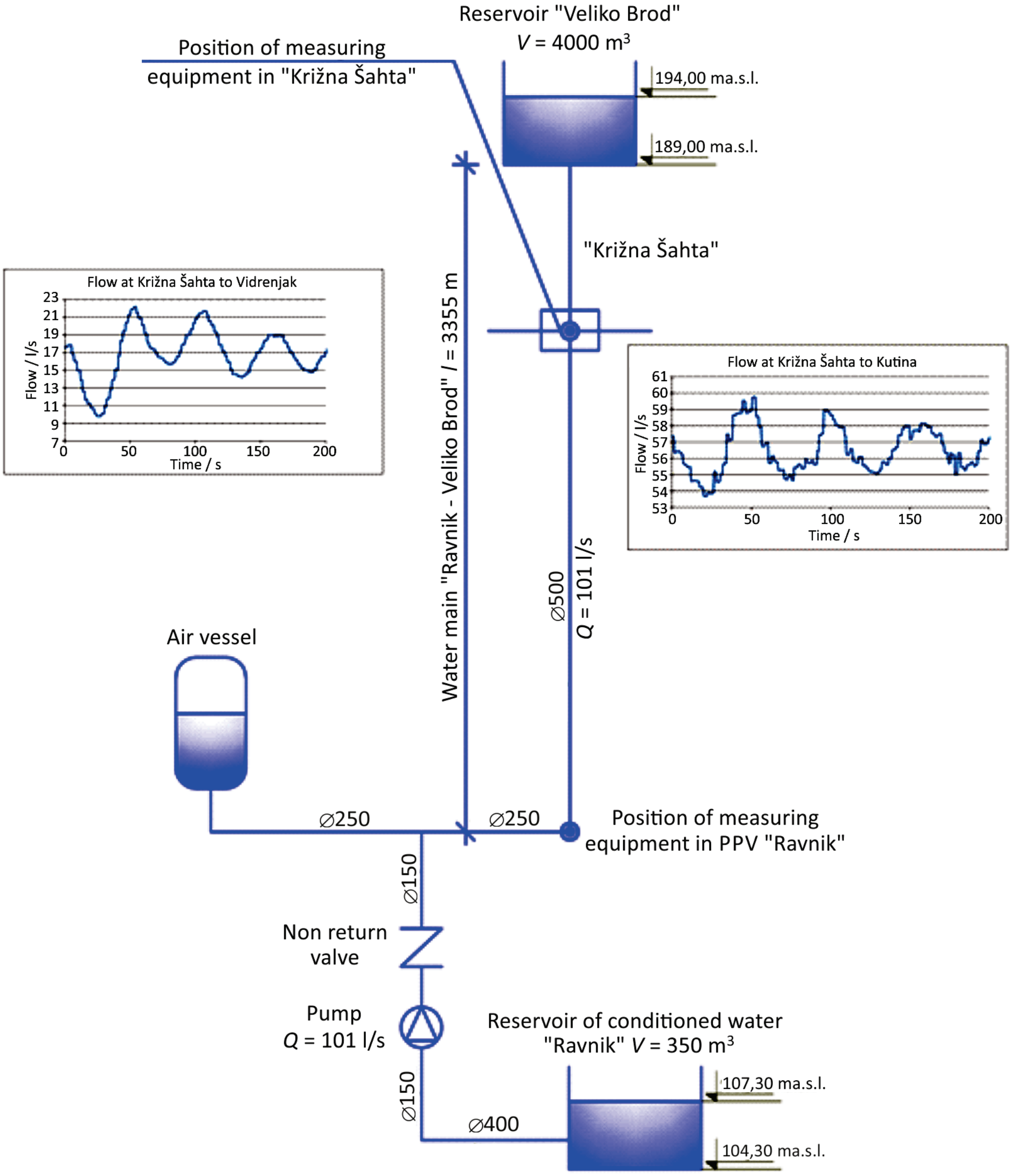

Figure 2 Diagram of the system

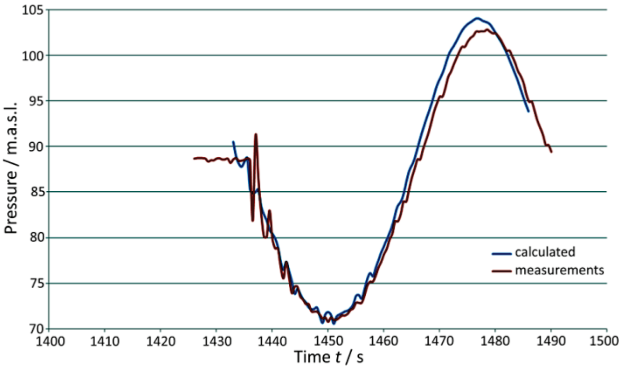

Figure 3 Comparison of measured and calculated pressure values at PPV Ravnik

To illustrate the magnitude of the energy transformations in the investigated pipeline, it can be considered that the pipeline length is L = 3355 m with a cross-sectional area A = 0,196 m^2 carrying water with an initial velocity v_0 = 0,51 m/s. Since water has a density (ρ) of approximately 1000 kg/m^3, this pipeline contains 658 m^3 of water having a mass of 658 000 kg, a momentum of 335 600 kg·m/s, and kinetic energy of E_K of 85 570 J. As the fluid velocity in the pipe was changed by turning off the pump, the kinetic energy of the pipeline would be decreased. Thus, the rate of the energy transformation in this conduit would be about 0,85 MW. This means that the compressibility index is Φ = 0,01. If the installed flow was increased to 200 l/s, the compressibility index would also increase, thus increasing the water hammer impact. In such conditions, care must be taken to ensure that the time step is sufficiently small to adequately cover all the unsteady developments in the pipeline.

By increasing the initial flow before turning off the pumps, the oscillations and the contribution of the elastic forces also increase (Fig. 4). In the existing pipeline between the Ravnik pumping station and the Veliko Brdo reservoir, sudden turn of the pumps will cause deceleration of water and according to its intensity, compressibility index will be different.

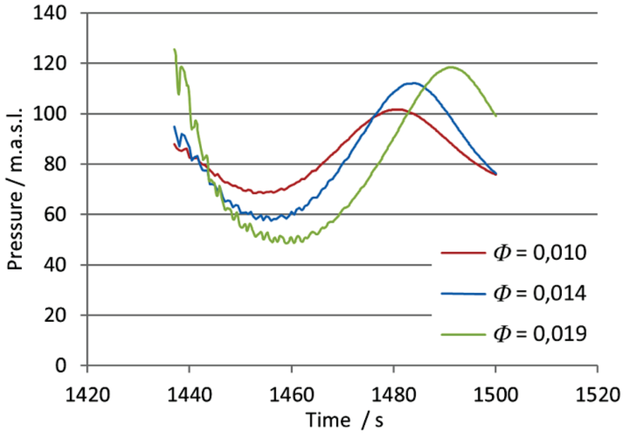

Figure 4 Variation in pressure when the pumps are turned off for various initial flows

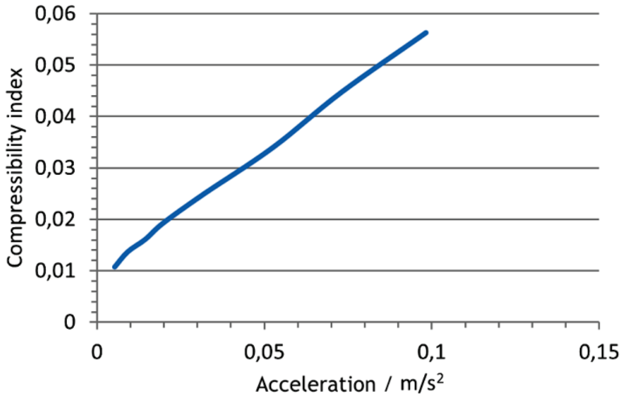

Figure 5 Compressibility index as a function of the acceleration

3.2 Impact of branching

It is well known that branching causes a reflection of water hammer, thereby diminishing the value of the maximum pressure increase during an unsteady process in pressure systems [7, 8]. The impact of branching in the examined pipeline is shown in Figs. 6 and 7.

The charts show system pressure variations obtained by:

a) measurements on the installed system as shown in Fig. 1;

b) the numerical model by taking into account branching in Križna Šahta (the impact of consumption in Kutina and Vidrenjak) and branching at Ravnik station (by assuming two pipeline branches within the station);

c) the numerical model without Križna Šahta and consumption in that node, but with one branch at Ravnik station and the modelled pipeline within the station (by assuming one branch);

d) the numerical model without Križna Šahta and without the modelled pipeline at Ravnik station (by assuming no branching).

From this chart it can be seen that the model was well calibrated and that variations of pressure are small between the measured values and the calculated ones obtained under different assumptions. The chart shows that pressure variations obtained by measurement (curve 1) have small oscillations, most probably deriving from shocks caused by branching. To prove this claim, the above described numerical models were used (curves 2, 3, 4 in Fig. 6). The plotted pressure variations show that the impact of branching at Križna Šahta was insignificant regarding the pressure oscillations at Ravnik, because of the small differences in the pressure oscillations in cases 2 and 3. The reason for this is the distance of 2880 m between the valve and the point of measurement.

A comparison of the measurement results and the calculations made by different models of branching at Križna Šahta (Fig. 7) show that the branches contribute significantly to the pressure variations. It can be concluded that the branches should be appropriate incorporated in numerical model especially if compressibility index is large.

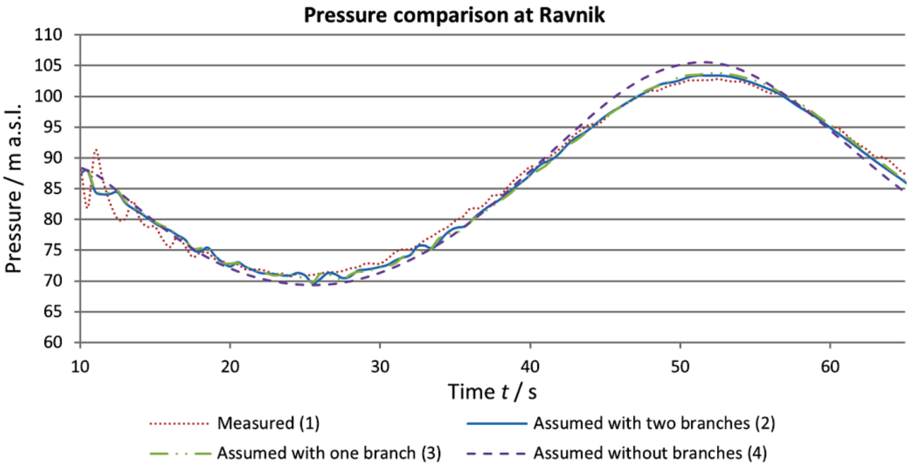

Figure 6 Pressure oscillations at Ravnik obtained by measurement and by various numerical models

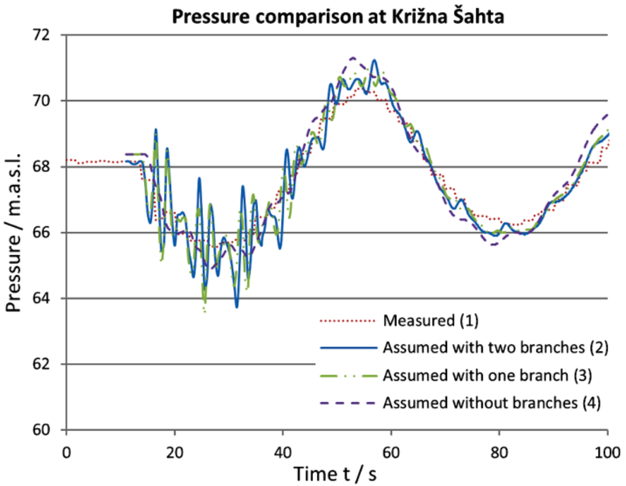

Figure 7 Pressure oscillations at Križna Šahta gained by measurement and by different numerical models

4 Conclusions

By designing the refurbishment and the upgrades and/or capacity increase of the installed pressure systems, it is useful to verify the numerical models by comparing the measured and calculated states within the pipelines, for the unsteady flow regime, at the current level of installations. It is recommended that for hydraulic analysis, besides the classical approach using dynamic equations and continuity equations, the energy method should also be used.

The energy method is applied to analyse unsteady flow in the water supply system of the Ravnik pumping station – Veliko Brdo reservoir. It has been shown that the energy expression provides a natural interpretation of the transient condition within a pipeline. In this case, there is no classical distinction between "rigid water column theory" in which the effects of water and pipeline elasticity are ignored, and the water hammer analysis in which elasticity is included.

The compressibility index Φ is ideally suited to the aforementioned kind of adaptive algorithm. That is, the index evaluates the influence of compressibility during a particular time step; if compressibility is important, the current time step can be decreased to improve accuracy. On the other hand, if the compressibility effects are not important, the time step is increased (say, by wave speed adjustments) to obtain an equivalent degree of accuracy at less expense.

The energy approach provides an integrated view of transient conditions in the pipeline and is thus a simple, efficient, and logically consistent way of comparing the transient response of different systems and solution techniques. In particular, the compressibility effects are shown to be negligible when the ratio of the change in internal energy to the change in kinetic energy is much less than one.

Analysis made in the present paper, where the reconstruction of Popovača water supply system is considered, show that during unsteady flow condition when the kinetic energy of the fluid transforms in internal energy associated with fluid compressibility and pipeline elasticity, the influence of fluid compressibility should be considered. To determine if it is necessary to take influence of fluid compressibility in the numerical model, compressibility index is a useful parameter.

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