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Research paper

Water hammer mitigation by internal rubber hose

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Abstract: The aim of this research was to experimentally analyse the possibility of using a rubber hose placed inside a pipeline to mitigate the water hammer phenomenon. The experiments were conducted using a steel pipeline with an inner diameter of 53 mm and an EPDM rubber hose with a diameter of 6 mm. Hydraulic transients were induced by a rapid closure of the valve located at the downstream end of the pipeline system. In order to analyse the influence of steady-state flow conditions on the maximum pressure increase, measurements were carried out for different values of initial pressure and discharge. The experimental results indicate that placing a rubber hose inside a pipeline can substantially attenuate valve-induced pressure oscillations. It was observed that the initial pressure has a significant influence on the capacity of the rubber hose to dampen the water hammer phenomenon. Comparative numerical calculations were performed using the Brunone–Vitkovský instant acceleration-based model of unsteady friction. It was demonstrated that this approach does not allow satisfactory reproduction of the observed pressure oscillations due to the viscoelastic properties of the EPDM hose used in the tests.

Keywords: hydraulic transients, internal hose, pressure wave, unsteady friction, water hammer

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1. Introduction

Water hammer or hydraulic transients are undesirable pressure surges that occur in pressurised conduits caused by a sudden change in flow velocity. In typical fluid distribution systems, this phenomenon is usually triggered by events such as valve shutdowns and openings or by turning pumps on or off [1]. It is well known that severe pressure changes can cause significant harm to the pipes or connected equipment, leading to high repair costs and even safety hazards. Thus, the topic of water hammer control is relevant to many technical fields such as water supply systems [2] and the circuits of nuclear power plants [3] or hydropower units [4]. In recent years, various water hammer control methods have been developed to minimise the risk of damage and improve the safety of pressurised pipeline systems. Essentially, water hammer can be mitigated by using three major techniques: optimising the operational procedures, installing surge control devices or altering the pipeline properties. The latter may involve reducing the effective pressure wave velocity of the pipeline system by adding an in-line polymeric section [5], branched penstock [6] or additional highly-deformable pipe [7]. The response frequencies of complete systems may also be altered by adding an inner flexible hose length-wise inside the pipeline to absorb pressure waves.

Despite the fact that flexible hoses and tubes are a known method for the mitigation of hydraulic transients [8], there is little literature available on this topic. The first systematic investigation was conducted by Remenieras [9], who derived analytical formulas to predict the pressure wave velocity in a pipeline equipped with an internal tube and performed water hammer experiments to test the ability of the rubber air-inflated tube to dampen pressure waves. He suggested that using a highly-deformable element inserted along the entire length of the pipe to reduce the maximum pressure changes could be used in many technical applications. Tijsseling et al. [10] used PVC and aluminium rectangular tubes filled with air at atmospheric pressure placed length-wise in a steel pipe to reduce transient pressure fluctuations during valve-induced water hammer. They concluded that the reduction of a system frequency can be obtained by using internal rectangular tubes, but their application is limited by their strength. Some PVC sections used in their experiments collapsed and some of the aluminium tubes were deformed. In a more recent study, Kubrak and Kodura [11] used an inner air-inflated silicone rubber tube to attenuate pressure waves in a steel pipeline. Although the internal tube provided a significant damping of water hammer, it was reported that the strength of the internal tubes used in experiments restricts their practical application, as they tend to collapse and lose their ability to reduce transient pressure waves.

Previous studies on this subject have only focused on air-filled tubes. Although this approach is interesting, if the internal tube is unsealed, it no longer serves its purpose. To overcome this shortcoming, this research present the results of water hammer experiments with internal, full cross-section, highly deformable ethylene propylene diene monomer (EPDM) rubber hose. The results of valve-induced observed piezometric head-time histories are presented and compared to the head oscillations obtained in the pipeline system without the internal hose. The paper is constructed as follows: the second section gives a brief theoretical description of unsteady flow in elastic pipes, while the third section describes the experiments conducted on valve-induced water hammer in a steel pipeline system with and without an internal rubber hose. In the fourth section, the results of the experiments are analysed. The fifth section refers to comparative numerical calculations simulating a selection of the experiments conducted. The sixth and final section provides a summary and general conclusions.

2. Unsteady pipe flow

Unsteady flow in pressurised elastic pipes is described by a system of two partial differential equations of hyperbolic type, resulting from mass and momentum conservation laws. By neglecting the convective acceleration terms, they can be written in the following form [12]:

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + f\frac{Q\,|Q|}{2DA} = 0 \tag{2.1}$$

$$\frac{\partial H}{\partial t} + \frac{c^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{2.2}$$

where: x – space coordinate (m), t – time (s), H – piezometric head (m), Q – flow rate (m^3/s), A – cross-sectional area (m^2), D – pipe diameter (m^2), f – Darcy–Weisbach friction factor (–), c – pressure wave velocity (m/s).

Equation 2.2, called the continuity equation, is derived by applying the mass conservation principle for an elastic pipe filled with a slightly compressible fluid. It includes a component c, which describes the speed of propagation of waves. The pressure wave velocity is governed by the physical properties of the fluid and the pipe-wall material. It is given by a Korteweg formula [13]:

$$c = \sqrt{\frac{\dfrac{K}{\rho}}{1 + \dfrac{KD}{E_p e}}} \tag{2.3}$$

where: K – bulk modulus of elasticity of the liquid (Pa), E_p – modulus of elasticity of pipe-wall material (Pa), e – pipe-wall thickness (m).

However, by inserting a hose inside a pipeline along its length, the physical properties of the entire pipeline system are altered and thus the pressure wave velocity is affected. The modified Korteweg formula that takes into account the internal hose has the following form [14]:

$$c = \sqrt{\frac{\dfrac{K}{\rho}}{1 + \dfrac{K}{A}\left(\dfrac{A_p}{E}\dfrac{D}{e} + \dfrac{A_h}{E_h}\right)}} \tag{2.4}$$

where: E_h– modulus of elasticity of hose material (Pa), A_p – cross-sectional area of the pipeline (m^2), A_p – cross-sectional area of the hose (m^2), A – cross-sectional area of the pipeline with internal hose, i.e. $A = A_p - A_h$ (m^2).

It should be noted that Eq. 2.4 is valid in elastic pipes with internal hoses made of elastic material. Eq. 2.4 shows that the lower the elastic modulus of the hose and the larger its diameter in relation to the inner diameter of the pipeline, the greater is its ability to reduce the pressure wave velocity [11]. According to the well-known Joukowsky equation, the maximum pressure increase is proportional to the pressure wave velocity. Thus, reduction of the pressure wave velocity has a damping effect on the maximum pressure increase caused by a rapid valve closure. On the other hand, adding an inner hose reduces the cross-sectional area, which causes an increase in the mean flow velocity. Therefore, in order to effectively suppress the water hammer event, the diameter of the hose placed inside a pipeline should be large enough to effectively absorb pressure waves, while small enough not to significantly increase the mean flow velocity during steady-state flow.

3. Experimental study

In order to investigate the effect of placing a rubber hose in a steel pipeline on the water hammer phenomenon, an installation presented in Fig. 1 has been built.

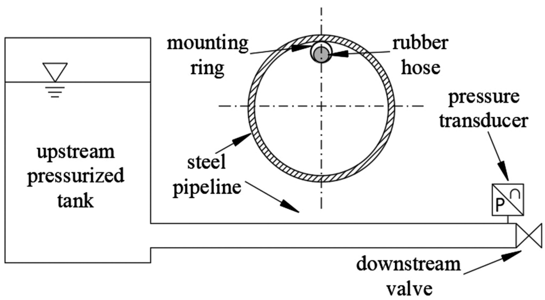

Fig. 1. Scheme of experimental setup

The main component of the experimental installation was a steel pipeline with a length of 48.5 m and an inner diameter of 53 mm. The pipeline was fixed with steel channels to the ground to prevent its displacement. Inside the pipeline, mounting rings with an inner diameter of 8 mm were welded to the top pipe-wall every 1 m. Inside the mounting ring, an EPDM rubber hose with a diameter of 6 mm was inserted along the entire length of the pipeline. The rubber hose was gently axially stretched to prevent it from coiling, and fixed at both ends of the pipe. At the upstream end, the pipeline was connected to a pressurised tank fed from the water supply network. A water hammer phenomenon was induced by rapid and full closing of a downstream ball valve installed at a distance of approx. 5 m from the outlet and equipped with a valve-closing timer. For each run, the valve closing time was shorter than the time of wave reflection. Pressure oscillations were measured by a pressure transducer installed near the valve, which initiated unsteady flow. Pressure changes were recorded at 500 Hz frequency using a computer and a DAQ device. Additional components of the setup were an inductive flow meter and a water temperature gauge and flow control valve, which were located downstream of the valve that induced the water hammer. The oscillations recorded with the pressure transducer were used to create head-time graphs from which the basic parameters of each water hammer run were then obtained. Based on the observed data, the maximum ($\Delta H_{\max}$) and minimum pressure changes ($\Delta H_{\min}$) were calculated (Fig. 2).

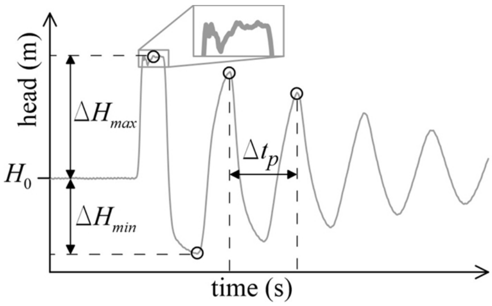

Fig. 2. Observed transient data and the water hammer parameters

The observed $H(t)$ function exhibits harmonic properties, and its period corresponds to the pipeline period of the reflection time. Therefore, in principle, it is possible to determine the pressure wave velocity based on the observed frequency of the pressure wave, i.e. the time difference between the occurrence of consecutive head peaks. Due to the observed head disturbances in the first head peak in the experiments with an internal rubber hose (zoom in Fig. 2), in order to estimate the pressure wave velocity, the time difference (Δt_p) between the third and second head peaks was taken into account. The pressure wave velocity c was calculated using the formula for the theoretical period value of pressure-head oscillations:

$$c = \frac{4L}{\Delta t_p} \tag{3.1}$$

where: Δt_p – time difference between head peaks (s), L – total length of the pipeline (m).

It should be noted that the value calculated in this way reflects the phase speed rather than the pressure wave velocity directly [15]. Although this approach has its limitations, to some extent, it can be used to estimate the pressure wave velocity for each experimental run.

Water hammer tests were conducted for three different initial flow rates (Q_0): approx. 0.68 L/s, 0.84 L/s and 1.00 L/s. When hydraulic transients are considered in a pipeline made of a material with elastic properties (such as steel), the initial pressure does not affect the transient pressure wave. However, due to the high deformability of the EPDM rubber from which the internal hose used in the experiments was made, the initial pressure was expected to have a significant influence on the pressure oscillations during valve-induced water hammer. For this reason, transient tests were carried out for three different values of the initial head (H_0): approx. 30 m, 40 m, and 45 m; that is, 9 experiments using rubber hose were conducted. To assess the effect of a rubber hose on the observed transient data, for the initial flow rates considered earlier, an additional 3 experiments were carried out using a pipeline without an EPDM hose inserted. Thus, a total of 12 water hammer runs were conducted. A list of all the experiments along with the corresponding water hammer parameters is presented in Table 1.

Table 1. List of water hammer runs

Run no.	Type of experiment	H_0 (m)	Q_0 (L/s)	ΔH_{max} (m)	ΔH_{min} (m)	c (m/s)
#1	with internal hose	30.74	0.68	16.84	–11.93	505
#2	with internal hose	30.30	0.84	21.25	–14.17	505
#3	with internal hose	29.80	1.00	26.18	–15.92	502
#4	with internal hose	39.83	0.67	18.97	–13.76	536
#5	with internal hose	38.06	0.84	23.79	–15.98	539
#6	with internal hose	39.66	1.01	30.86	–19.03	588
#7	with internal hose	45.83	0.68	21.13	–15.96	680
#8	with internal hose	44.48	0.84	26.63	–18.56	648
#9	with internal hose	45.38	1.00	32.20	–21.42	644
#10	no internal hose	51.43	0.67	36.40	–35.32	1230
#11	no internal hose	51.65	0.83	46.28	–43.38	1246
#12	no internal hose	51.21	1.00	56.87	–52.51	1263

4. Analysis of water hammer experiments

The aim of the experiments was to register pressure oscillations at the downstream end of the pipeline system during valve-induced water hammer. The observed head traces obtained for all the runs with the use of an internal hose (runs #1-9) are presented in Fig. 3.

Figure 3 illustrates the comparison between the transient data obtained for water hammer runs with similar values of the initial head. It should be noted that in Figs. 3a and 3c the consecutive head amplitudes overlap, while Fig. 3b shows a discrepancy between the response frequency of the pipeline systems. This is related to the fact that the initial head that occurred during run #5 (H_0 = 38.06 m) was considerably lower than the initial head in experiments #4 (H_0 = 39.83 m) and #6 (H_0 = 39.66 m). Differences in steady-state conditions are also apparent in the zoom window in Fig. 3b. This provides evidence that the pressure wave velocity depends on the initial head. In order to investigate this effect, the values of pressure wave velocity c calculated using the measured head frequencies are presented in Fig. 4 as a function of H_0.

As illustrated in Fig. 4, the pressure wave velocity increases with increasing initial pressure. This is related to the fact that increasing initial pressure reduces the volume of the hose and thus its ability to absorb pressure waves. It should be noted that the diameter of the EPDM hose used in the experiments (6 mm) was measured at atmospheric pressure. The experimental setup used in this research did not allow the actual diameter of the hose to be measured under pressurised water flow conditions. One can notice that, for initial pressure values of approx. 40 m and 45 m, some of the values of the calculated pressure wave velocities differ considerably. This may be due to the fact that the determination of the pressure wave velocity from measured head frequencies is subject to large uncertainties. Another possible explanation of this phenomenon

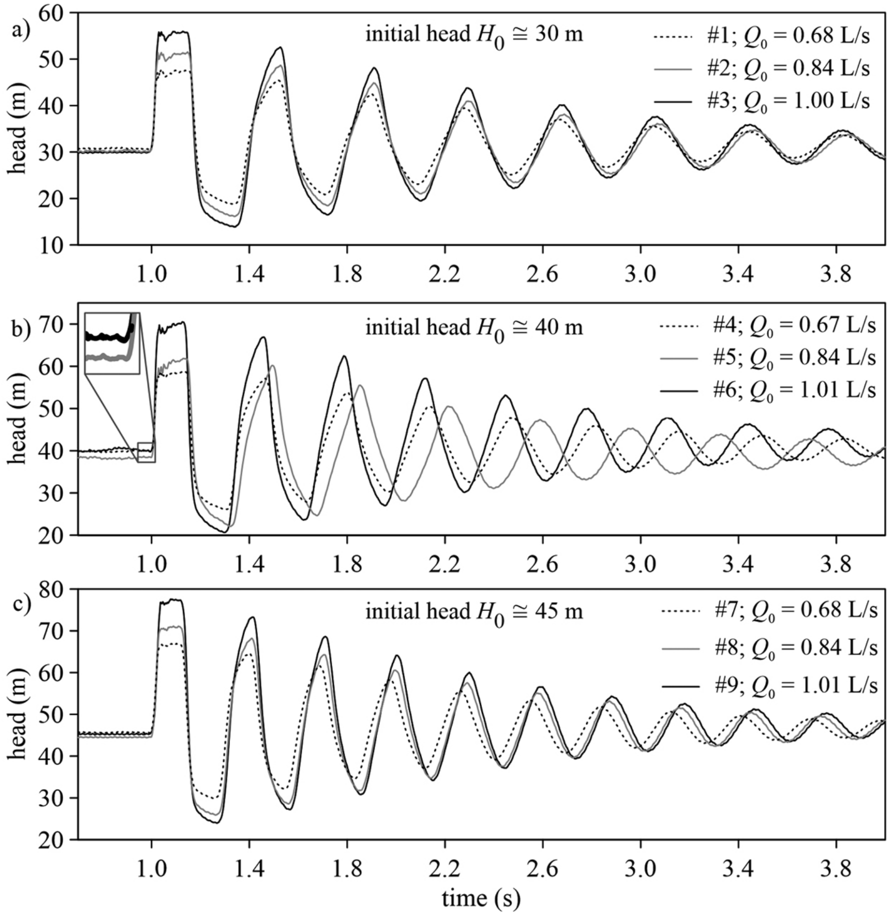

Fig. 3. Transient data obtained using a pipeline system with an internal hose

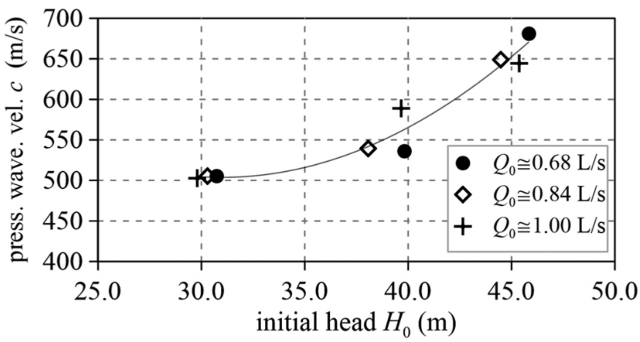

Fig. 4. Values of pressure wave velocity c as a function of initial head H_0

may be the effect of the water temperature on the properties of the EPDM hose. As is well known, the temperature can have a significant effect on the mechanical properties of elastomers. For example, a recent study was conducted by Sun et al. [16] on the effect of water temperature on hydraulic transient damping in viscoelastic pipes. While no substantial fluctuations in water temperature were noticed during the measurements (approx. 21°C), as mentioned earlier, the tank was fed from the mains water supply, which made it impossible to maintain a constant water temperature during the experiments.

To illustrate the effect of inserting the EPDM hose on the transient pressure waves, head changes observed during run #3 (pipeline with internal rubber hose; H_0 = 29.8 m) are presented along with the corresponding results obtained in the unmodified pipeline system for the same initial flow rate ($Q_0 \cong 1.00$ L/s).

As expected, Fig. 5 shows that placing a rubber hose inside a pipeline results in a significant damping of the first head peak. The EPDM hose reduced the head change from 56.87 m to 26.18 m during the up-surge phase and from –52.51 m to –15.92 m during the down-surge phase in comparison with the pipeline system without the hose. Moreover, this protection technique substantially increased the period of head wave oscillations and softened consecutive head peaks. In the case of the unprotected system, severe head surges (approx. 20 m) continue to occur about 3 seconds after the valve closes. For the same transient event, in a pipeline system with an EPDM hose, after the same time, the pressure oscillations are practically negligible. The values of both the maximum and minimum head changes obtained in all the experiments are reported in Fig. 6 as a function of the initial flow rate.

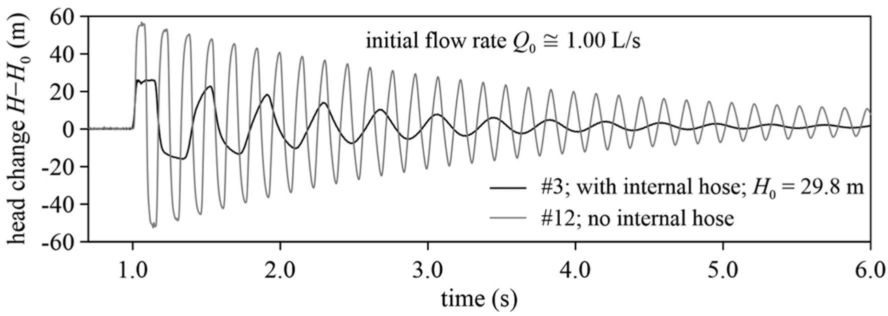

Fig. 5. Comparison between observed head oscillations for the pipeline system with and without EPDM hose

It is apparent from Fig. 6 that inserting an EPDM hose provided a significant pressure surge attenuation in each analysed scenario. The effect of the initial pressure on the performance of this water hammer control method is also noticeable – the most effective mitigation of fluctuation of the transient pressure waves was obtained for the lowest values of H_0. These figures also reveal that inserting an EPDM hose is more efficient in damping the minimum head changes (during the down-surge phase) than the maximum head changes (during the up-surge phase). To explore this effect further, the values of the $\Delta H_{max}/|\Delta H_{min}|$ ratios were calculated and are presented in Fig. 7.

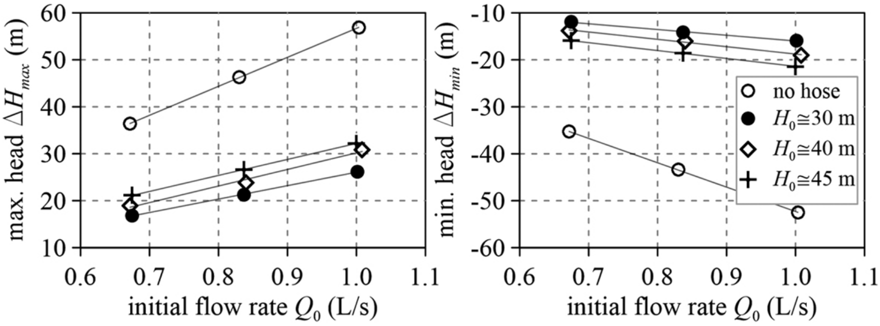

Fig. 6. Values of maximum and minimum head changes as a function of initial flow rate Q_0

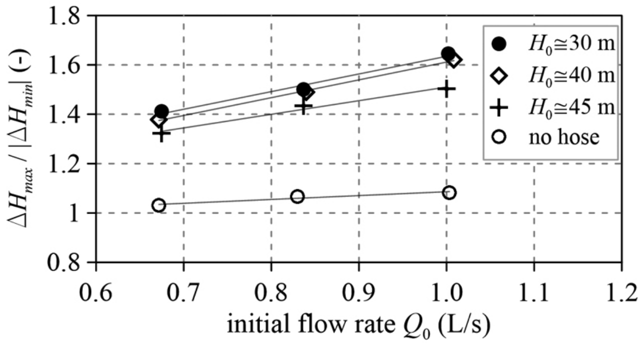

Fig. 7. Values of $\Delta H_{max}/|\Delta H_{min}|$ ratios as a function of initial flow rate Q_0

As can be seen in Fig. 7, in the case of the pipeline system without a rubber hose, the absolute values of the minimum head changes ΔH_{min} are only slightly smaller than the values of the maximum head changes ΔH_{max}. However, if the rubber hose is placed inside a pipeline, the minimum pressure changes are significantly lower than the positive head-peaks. Again, this is due to the high deformability of the EPDM hose. In the up-surge phase, the hose is compressed harder and its ability to absorb water hammer waves is lower than in the down-surge phase. This indicates that inserting a rubber hose would be more effective in damping hydraulic transients induced by rapid flow acceleration (i.e. transient events with an initial sudden pressure drop). Another possible explanation for this effect could be related to the properties of EPDM rubber, which is a viscoelastic material and exhibits time-dependent strain.

5. Numerical calculations

Hydraulic transient simulations play a crucial role in ensuring the secure functioning of pressurised pipeline systems. By simulating water hammer events, a potential hazard can be mitigated and operation procedures can be optimised. The mathematical model of hydraulic transients consists of the system of Eqs. 2.1 and 2.2, which can be solved numerically. Traditionally, the steady or quasi-steady friction factor f is used in the momentum equation 2.1 to take into account energy losses during water hammer events. Because this approach tends to overestimate pressure oscillations during fast transient events, many researchers have been concentrating on identifying the dynamic effects responsible for pressure wave damping. One of the methods to reduce discrepancies between the calculated and observed data is to use one of the unsteady-friction models available in the literature [17]. Interestingly, most commercial engineering programs for unsteady pipe flow analysis do not allow unsteady friction to be taken into account. The only model that is available in some programs is the IAB Brunone–Vitkovský model [18]. The purpose of the numerical calculations was to test the suitability of this model for simulating rapid water hammer events in a pipeline system with an internal EPDM hose. In this model, the friction factor f is expressed as [19, 20]:

$$f = f_q + \frac{k_V}{V\,|V|}\left(\frac{\partial V}{\partial t} + c\,\mathrm{sign}\,(\mathrm{V})\left|\frac{\partial \mathrm{V}}{\partial \mathrm{x}}\right|\right) \tag{5.1}$$

where: f_q – quasi-steady friction factor (–), k_V – unsteady friction factor (–), V – mean flow velocity (m/s).

The unsteady friction factor can be calibrated on the basis of experimental results or determined using the analytically deduced shear decay coefficient [21]:

$$k_V = \frac{\sqrt{C^*}}{2} \tag{5.2}$$

where: C^* – decay coefficient (–).

For turbulent flow, the decay coefficient is given by:

$$C^* = \frac{7.41}{\mathrm{Re}^{\log\left(14.3/\mathrm{Re}^{0.05}\right)}} \tag{5.3}$$

where: Re – Reynolds number (–).

In this paper, in order to solve the unsteady flow equations, the widely used fixed-grid method of characteristics was used. The momentum and continuity equations are transformed into a set of ordinary differential equations valid along the characteristic lines C^+ and C^-. To satisfy the characteristic relations, the $x - t$ grid is chosen to ensure $\Delta x = \pm c\Delta t$. A fragment of the computational grid is shown in Fig. 8.

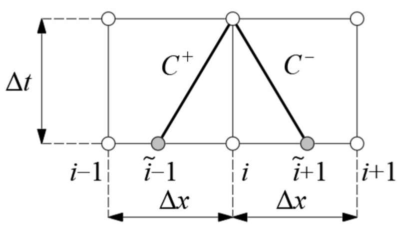

Fig. 8. Characteristic lines in the x-t plane

The values of flow rate Q and the piezometric head H at the i-th node at each time step were computed using the procedure presented in [22]. In the calculations, the cross-sectional area of the water stream was estimated by $A = A_p - A_h$. To take into account that the hose inserted inside the pipeline changes also the shape of the water stream, the hydraulic radius ($4R_h$) was used instead of the pipeline diameter:

$$R_h = \frac{\left(D^2 - D_h^2\right)}{D + D_h} = D - D_h \tag{5.4}$$

where: D_h – diameter of the rubber hose measured at atmospheric pressure (m).

It should be noted that due to the lack of information on the actual diameter of the rubber hose placed inside the pipeline with an initial head of H_0, in the calculation, value of D_h measured at atmospheric pressure was assumed. Moreover, for simplicity, it was assumed that the pipeline and the hose have the same absolute roughness of 0.5 mm. Numerical calculations were performed to simulate two experiments conducted for the highest initial flow rates, namely run #3 and #9. The steady-flow parameters listed in Table 1 were used as input. Different values of the unsteady friction factor were assumed. First, k_V is calculated with Eqs. 5.2 and 5.3 were used ($k_V = 0.0139$). Next, the calculations were performed for arbitrarily adopted values of the unsteady friction factor. In each simulation, the values of the pressure wave velocity were adjusted to match the observed pressure oscillations. Calculations were made for the space interval $\Delta x = 0.55$ m. The time step was selected to provide a Courant number equal to 1. Boundary conditions were applied according to [12]. In the first node, a constant head was assumed. In the last node, the downstream valve boundary was used with the relative valve closing function τ defined as:

$$\tau = \left(1 - \frac{t_c}{t}\right)^2 \tag{5.5}$$

where: t_c – valve-closing time (s).

A comparison between the calculated and experimentally obtained head oscillations at the downstream end of the pipeline system is presented in Fig. 9.

Comparison between the experimental and calculated head traces shows that the IAB model used in the calculations does not satisfactorily reproduce the head oscillations at the downstream end of the pipeline system with an inserted hose, regardless of the assumed k_V factor. While the calculated maximum head changes have similar values to those measured, the shape of the wave fronts and their damping rate differ significantly. It is also worth noting that the numerical model substantially overestimated the absolute value of the minimum pressure change. This is due to the fact that the EPDM hose used in the experimental tests is a material of high deformability and it does not show elastic rheological behaviour. Despite the small cross-sectional area of the hose relative to the area of the pipe ($A_h/A_p = 0.013$), its effect on transient pressure oscillations is large enough to cause pressure wave dissipation and the dispersion characteristic of water hammer events in pipelines made of viscoelastic materials. This demonstrates that the hydraulic transient solver incorporating unsteady friction model is unable to simulate a water hammer in a steel pipeline with an internal EPDM hose. As shown in the experimental runs, the volume of the hose has a direct effect on the speed of the pressure

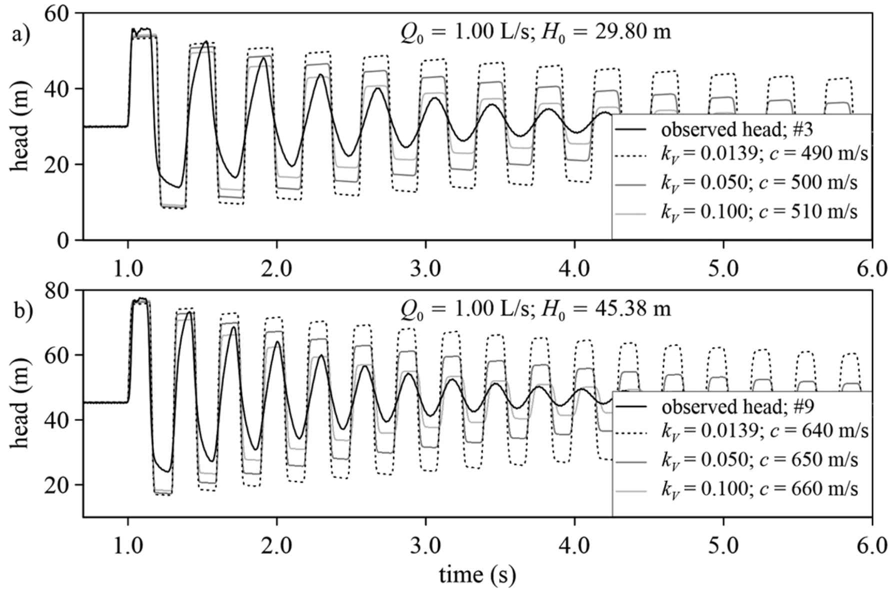

Fig. 9. Comparison of observed and calculated head oscillations

wave. This means that, in fact, the pressure wave velocity varies with time and along the length of the pipeline during the unsteady oscillations. Therefore, in order to mathematically describe this phenomenon, a coupled model that takes into account the fluid-structure interaction between the transient pressure wave and rubber hose is necessary.

6. Conclusions

In this paper, water hammer mitigation using internal rubber hose was investigated. Laboratory tests conducted on a simple hydraulic setup confirmed that inserting a highly-deformable EPDM hose into a steel pipeline can substantially attenuate both positive and negative valve-induced water hammer waves. In addition, the use of this technique significantly increases the period of head wave oscillations and softens consecutive head peaks. Despite the small diameter of the hose relative to the pipe diameter, the EPDM hose caused significant dissipation of the observed head trace. The results of the experiments have shown that the pressure wave velocity depends on the initial head. This is due to the fact that the pressure prevailing in the pipeline reduces the volume of the hose and thus its ability to absorb pressure waves. In the up-surge phase the hose is compressed harder than in the down-surge phase, which reduces its capacity to attenuate positive pressure waves. Hence, inserting a rubber hose would be more effective in damping hydraulic transients with an initial pressure drop.

Comparative numerical calculations have been conducted using the IAB Brunone–Vitkovský unsteady friction model. It was demonstrated that this approach is unable to reliably reproduce the head oscillations during water hammer events. This is due to the fact that the EPDM rubber from which the hose used in the experiments was made is a material that does not show elastic rheological behaviour. Future work should concentrate on establishing a fluid-structure interaction model that would be able to reproduce the effect of pressure wave velocity varied in time and space.

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Łagodzenie uderzeń hydraulicznych za pomocą umieszczonego wewnątrz rurociągu gumowego węża

Słowa kluczowe: lepkosprężystość, oscylacje ciśnienia, ruch nieustalony, uderzenie hydrauliczne, wąż EPDM

Streszczenie:

Celem przeprowadzonych badań była eksperymentalna analiza możliwości zastosowania węża gumowego umieszczonego wewnątrz rurociągu do łagodzenia zjawiska uderzenia hydraulicznego. Pomiary przeprowadzono wykorzystując stalowy rurociąg o średnicy wewnętrznej 53 mm i długości 48.5 m oraz wąż gumowy EPDM o średnicy 6 mm ułożony na całej długości rurociągu. Uderzenia hydrauliczne inicjowane były poprzez gwałtowne i całkowite zamknięcie zaworu znajdującego się na końcu układu. W celu przeanalizowania wpływu parametrów przepływów panujących w rurociągu w ruchu ustalonym na maksymalne przyrosty ciśnienia, pomiary przeprowadzono dla różnych wartości początkowego ciśnienia i natężenia przepływu. Wyniki eksperymentów wskazują, że umieszczenie węża gumowego w obszarze nieustalonego przepływu cieczy może skutecznie tłumić oscylacje ciśnienia podczas prostego, dodatniego uderzenia hydraulicznego. Zaobserwowano, że ciśnienie początkowe ma istotny wpływ na zdolność węża gumowego do tłumienia fal ciśnienia. Celem przeprowadzonych obliczeń numerycznych było sprawdzenie przydatności najczęściej wykorzystywanego w praktyce modelu tarcia nieustalonego (tzw. IAB Brunone–Vitkovský model) do symulowania analizowanego zjawiska. Wykazano, że podejście to nie pozwala na zadowalające odtworzenie obserwowanych oscylacji ciśnienia ze względu na lepkosprężyste właściwości użytego w badaniach węża EPDM.

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