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An Analysis of the Impact of Valve Closure Time on the Course of Water Hammer

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Abstract

The knowledge of transient flow in pressure pipelines is very important for the designing and describing of pressure networks. The water hammer is the most common example of transient flow in pressure pipelines. During this phenomenon, the transformation of kinetic energy into pressure energy causes significant changes in pressure, which can lead to serious problems in the management of pressure networks. The phenomenon is very complex, and a large number of different factors influence its course. In the case of a water hammer caused by valve closing, the characteristic of gate closure is one of the most important factors. However, this factor is rarely investigated. In this paper, the results of physical experiments with water hammer in steel and PE pipelines are described and analyzed. For each water hammer, characteristics of pressure change and valve closing were recorded. The measurements were compared with the results of calculations perfomed by common methods used by engineers – Michaud's equation and Wood and Jones's method.

The comparison revealed very significant differences between the results of calculations and the results of experiments. In addition, it was shown that, the characteristic of butterfly valve closure has a significant influence on water hammer, which should be taken into account in analyzing this phenomenon. Comparison of the results of experiments with the results of calculations? may lead to new, improved calculation methods and to new methods to describe transient flow.

Key words: time of valve closure, butterfly valve, pressure characteristic, transient flow, water hammer

1. Introduction

There are two kinds of flow which can describe motion of liquids in pressure pipelines. These are steady flow and transient flow. Steady flow is very commonly used by engineers in calculating parameters of pressure networks. A model of steady flow consists of simple equations and can be used under most conditions. The other type of flow, transient flow, is rather rare, but, due to rapid changes in its velocity, can lead to significant problems in the maintenance of pressure systems.

The water hammer is one of the forms of transient flow. This term is used to describe a pressure wave which was generated by a rapid change of flow velocity in a pipeline (Ramos and de Almeida 2002). That change in pressure is caused by the transformation of kinetic energy into pressure energy. A pressure wave spreads in the pipeline with high celerity, which results in interactions between the liquid's precise bulk modulus, friction forces and inertia forces, as well as parameters of the pipe wall, such as the material's bulk modulus, thickness, diameter and length (Mitosek 2007, Streeter et al 1998).

The investigation of the water hammer phenomenon is important for science and for practical purposes. The practice of pressure system maintenance shows that the number of breakdowns due to transient flow in water supply systems is significant (Illin 1987). Moreover, the breakdowns resulting from water hammer are usually expensive. This is the most important reason for the large number of different models and equations used to calculate the main parameters of the phenomenon, such as the extreme value of pressure, wave frequency, time of duration etc. One of the major problems for most methods is the lack of experimental measurement data. For over a century, theoretical solutions have predominated in investigations of the water hammer phenomenon.

Generally, this phenomenon can occur in two situations: as a rapid water hammer, when the time of closing the gate is shorter then the return time of the reflected wave, or as a complex water hammer, when the closure time is longer than the return time of the reflected wave (Streeter et al 1998, Thorley 2004). Theoretically, the relationship between the closure time and the return time of the reflected wave makes it possible to distinguish precisely between two kinds of the phenomenon. Furthermore, the extension of the closure time is one of the most commonly used methods for reducing the maximum pressure increase (or minimum pressure decrease) (Marcinkiewicz et al 2008, Pires et al 2004). However, this seemingly simple solution depends on the parameters of different kinds of gates and valves. To date, the influence of the kind of closure has seldom been analyzed. The main aim of this paper is to compare an experimental analysis of the water hammer phenomenon and theoretical methods of determining the maximum pressure increase. It should be mentioned that the influence of the ball valve characteristic on water hammer was analyzed in a previous article (Kodura 2011). This paper is the result of the next stage of investigations.

List of symbols used in the paper

a – wave propagation celerity [m/s],
h_0 – the head drop across the valve under the initial steady flow conditions, which can be measured just before the water hammer phenomenon occurs [m],
L – pipeline length [m],
ρ – liquid density [kg/m^3],

T_C – gate clossure time [s],
t_C – dimensionless valve closure time [–],
T_R – return time of the reflected wave [s],
α – parameter of initial value of pressure losses during steady flow the beginning of the water hammer phenomenon,
$\Delta\upsilon$ – water velocity change [m/s],
υ_0 – velocity of steady flow before the beginning of the water hammer phenomenon [m/s].

2. Theoretical Description of Complex Water Hammer

2.1. Basic Equations

As already mentioned, the history of water hammer phenomenon investigations is quite long. In the first equation, Joukowsky (in 1898) tried to find a value of the maximum pressure change due to rapid water hammer (Wylie et al 1993):

$$\Delta p = \Delta\upsilon \cdot \rho \cdot a, \tag{1}$$

where: $\Delta\upsilon$ = water velocity change, ρ = liquid density, a = wave propagation celerity.

Joukowsky's formula can be used to describe the maximum pressure increase (in that case, the phenomenon is called a positive water hammer) as well as the minimum pressure decrease (a negative water hammer). In the first case, a sudden gate closing leads to an enormous pressure increase. In the second, water hammer in the form of negative pressure is a result of a sudden acceleration of water (due to, for example, a pump starting or an opening of the gate). It should be noted that Joukowsky's equation can be used by engineers for maximum pressure change estimation.

The wave celerity can be calculated from the following equation (Wylie et al 1993):

$$a = \frac{2 \cdot L}{T_R}, \tag{2}$$

where: L = pipeline length, T_R = return time of the reflected wave.

Theoretically, the time of gate closure T_C should be shorter than the return time of the reflected wave for the rapid water hammer. The extension of the closure time reduces the extreme pressure change. For a linear change in liquid velocity and if the total pressure increase is less than 220% of pressure under steady conditions before water hammer, the pressure increase is estimated from Michaud's formula (Mitosek 2008):

$$\Delta p = \frac{2 \cdot \rho \cdot \upsilon_0 \cdot L}{T_C} \tag{3}$$

where: υ_0 = velocity of steady flow before the beginning of the water hammer phenomenon, T_C = gate closure time.

Eq. 3 is very similar to Joukowsky's formula Eq. 1 – one difference is the replacement of wave celerity by the quotient $2L/T_C$. The result of that form is the assumption of linear velocity change, which is very difficult achieve. This formula does not consider the influence of gate characteristics, which is another very important deficiency of Michaud's equation.

2.2. Wood and Jones's Method

Wood and Jones were the next researchers who tried to describe the influence of the gate on the transient flow. Their idea was to introduce two parameters: dimensionless valve closure and dimensionless maximum transient pressure change (Wood and Jones 1973, Thorley 2004). The boundary assumption is that Joukowsky's formula can be adopted as the best equation to calculate the maximum pressure change during a rapid water hammer. The restricted boundary between rapid and complex water hammer is still the same. Only the value of the transient pressure change can be calculated from the knowledge of the initial conditions of a head drop across the gate under the initial steady flow. Wood and Jones developed charts based on theoretical analysis of the most common types of valves (circular gate, globe, needle, square gate, butterfly and ball valve). Those charts, representing individual valve types, express the relationship between the dimensionless valve closure time and dimensionless maximum transient pressure change for very precisely described initial conditions. The α parameter is used to describe the influence of the initial conditions according to the equation (Wood and Jones 1973):

$$\alpha = \frac{g \cdot h_0}{\Delta \upsilon \cdot a}, \tag{4}$$

where: h_0 = the head drop across the valve under the initial steady flow conditions, which can be measured just before the water hammer phenomenon occurs, a = wave propagation celerity, $\Delta \upsilon$ – water velocity change.

The α parameter determines the value of the maximum pressure change. The unknown value has to be read from the chart by using the α parameter and the dimensionless valve closure time, which is described by the formula (Wood and Jones 1973):

$$t_C = \frac{T_C}{\frac{2 \cdot L}{a}}, \tag{5}$$

where: t_C = dimensionless valve closure time.

The value of the dimensionless maximum transient pressure change, which can be read from the chart, is related to the unknown maximum transient pressure change (Wood and Jones 1973):

$$\Delta p_m = \frac{\Delta p_{\max}}{\Delta \upsilon \cdot \rho \cdot a}, \tag{6}$$

where: Δp_m = dimensionless maximum transient pressure change, $\Delta p_{\max}$ = maximum transient pressure head.

That method, developed by Wood and Jones, is a significant improvement in the theory of complex water hammer. However, there are also two problems, which have to be solved. First of all, the gate is described by a constant resistance coefficient, which is calculated as for the steady flow. During the complex water hammer, the velocity across the valve is changeable, which can affect the results. The second problem ignores friction resistance in transient flow.

3. Experimental Analysis

3.1. Model

The Wood and Jones's method was developed by theoretical analysis of transient flow in pressure pipelines. Over the years, the development of knowledge of course of water hammer and the impact of the closure time of the valve on the pressure increase has not been sufficiently explained. In order to analyze the phenomenon, a physical model, shown in Fig. 1, was built. The model consisted of a pressure pipeline (1) and a pressure tank (2) supplied from the water network (3). At the downstream end of the pipe, a butterfly valve (4) with a unique system for registering the angle of closing in time was installed. Two pressure transducers (5), located close to the valve, were connected to a personal computer (6) via an analog/digital card (7) to store experimental data. An additional ball valve (8) was located downstream to ensure a constant value of discharge during steady flow. The discharge was measured by an electro-magnetic water meter (9).

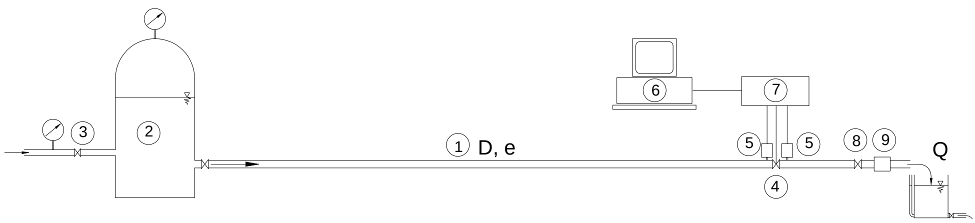

Fig. 1. A sketch of the experimental model

Two series of experiments were made. The first series were carried out in a 177 m long steel pipeline with an internal diameter of 32 mm, and the second in a 240 m long HDPE pipe with an internal diameter of 35 mm. In both cases, the same butterfly valve was used. For each series, at least 35 measurements of water hammer were performed. The time of valve closing was measured each time. The idea was to measure water hammer episode for different closing times but with a linear function of valve closing. This assumption is similar to the Wood and Jones's model.

3.2. Experimental Results

The experimental data were recorded in the form of pressure characteristics. Fig. 2 and Fig. 3 show samples of data for the steel and HDPE pipelines, respectively. Each characteristic was analysed, and the characteristic parameters of transient flow were calculated: valve closing time, return time of the reflected wave, wave frequency, and maximum pressure increase.

As already mentioned, the experiments were made in two series – each for a different material of the pipeline. The idea was to determine the influence of the butterfly valve closure characteristic on the pressure increase. A comparison between the two series makes it possible to eliminate the influence of the pipe material on the phenomenon.

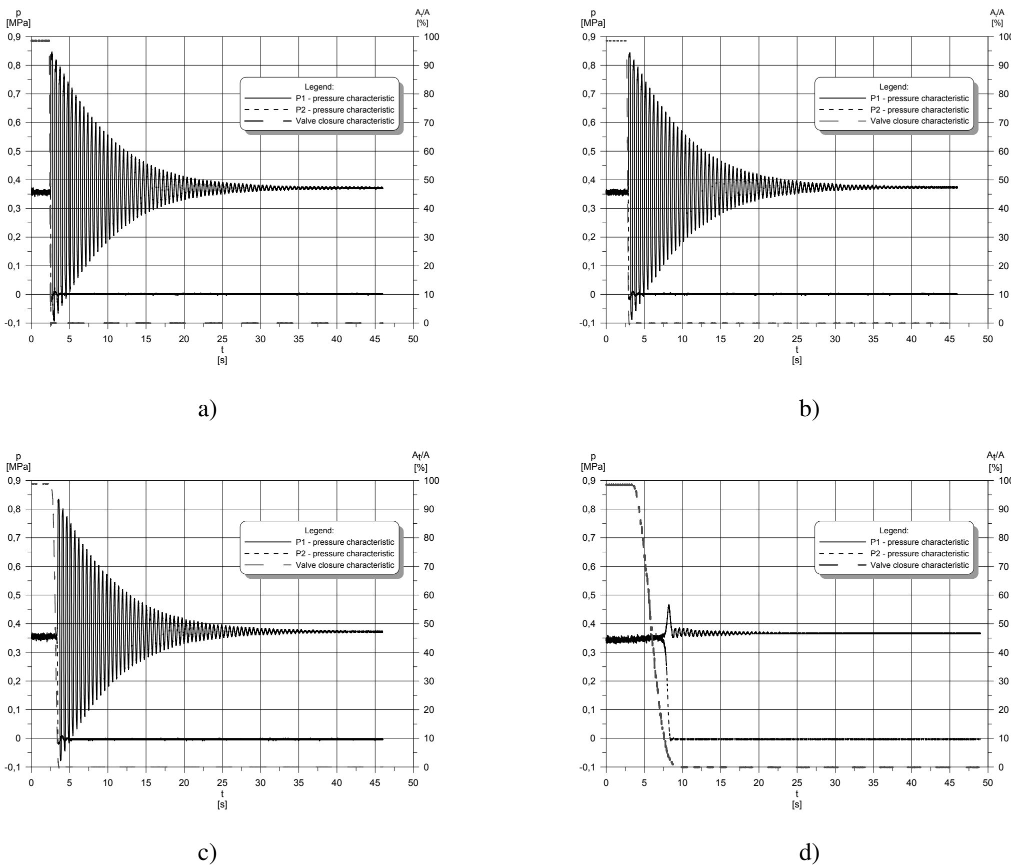

Fig. 2. Pressure characteristics for the steel pipeline and the return time of the reflected wave T_R = 0.26 s: a) butterfly valve closure time T_C = 0.21 s < T_R; b) T_C = 0.37 s > T_R; c) T_C = 1.1 s > T_R; d) T_C = 5.7 s > T_R

Both figures (Fig. 2 and Fig. 3) present the results in the same way. A smooth solid line was used to represent pressure just upstream of the butterfly valve. A fine dotted line was used to illustrate pressure just downstream of the valve. The third, dashed line represents the closure angle of the gate. That line expresses the temporary cross-section of the butterfly valve during closure.

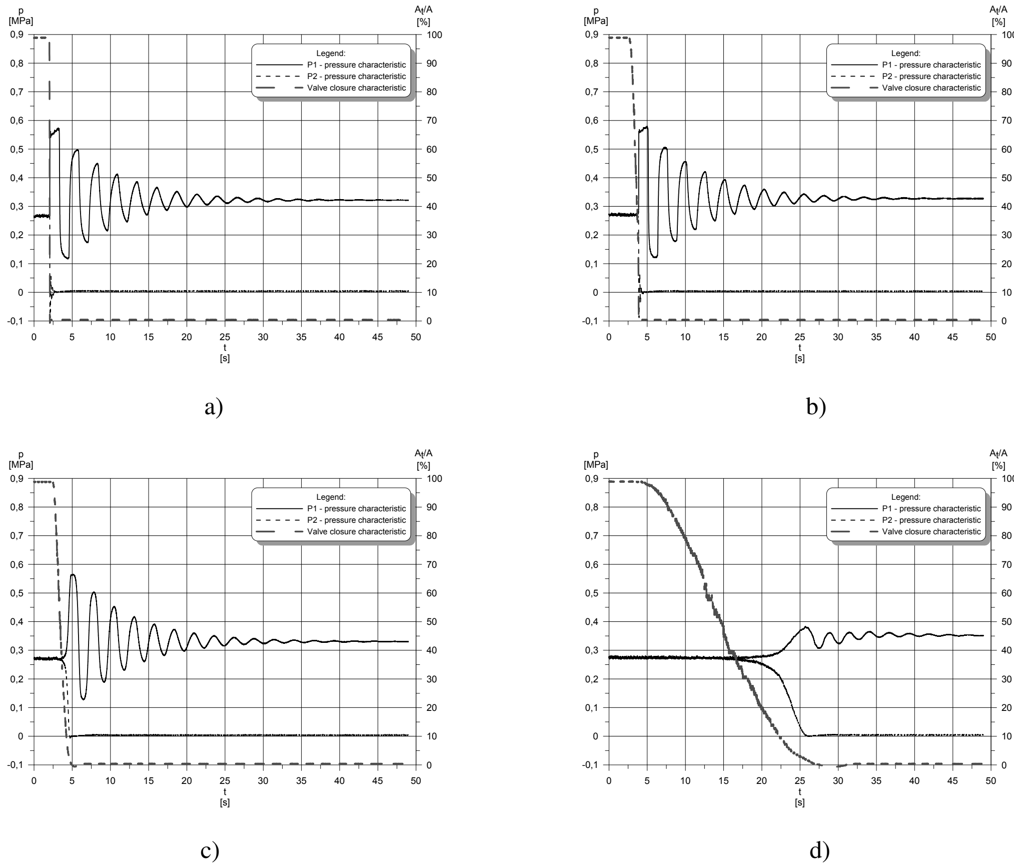

Fig. 3. Pressure characteristics for the HDPE pipeline and the return time of the reflected wave T_R = 1.30 s: a) butterfly valve closing time T_C = 0.095 s < T_R; b) T_C = 1.35 s > T_R; c) T_C = 2.67 s > T_R; d) T_C = 23.7 s > T_R

For the steel pipeline, the initial measurements of velocity during steady conditions was compared for each measured series and equalled 0.32 m/s. The return time of the reflected wave was 0.26 s.

In the case of the HDPE pipeline, the initial velocity was equal to 0.50 m/s, and the return time of the reflected wave was 1.30 s.

Fig. 2 and Fig. 3 show examples of different relationships between the closure time and the return time of the reflected wave. The first plot in both figures represents a rapid water hammer phenomenon. The other plots illustrate complex water hammers, in which the closure time is longer then the return time of the reflected wave.

3.3. Comparison with Common Theoretical Methods

The next step was to compare the experimental data with the results of theoretical methods. For each closing time, the maximum pressure increase was calculated by Michaud's equation. The other theoretical method used for comparison was Wood and Jones's method. For each collected characteristic, the measured head drop across the valve was used to calculate the α parameter. Next, the proper curve from Wood and Jones's chart was chosen. For the steel pipeline, the α parameter is 0.005, and for the HDPE pipeline the α parameter equals 0.001. The results are shown in Fig. 4 and Fig. 5.

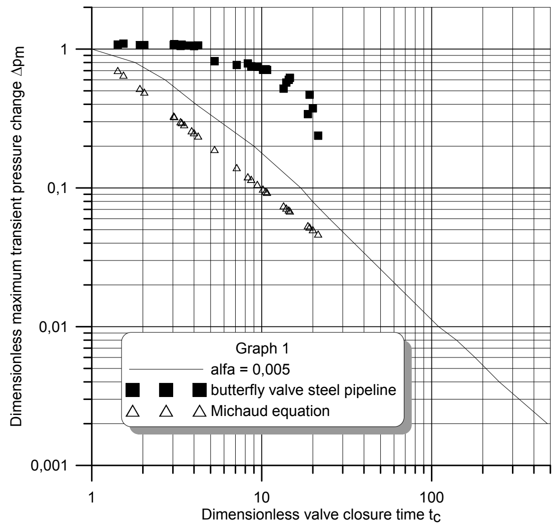

Fig. 4. Comparison of the experimental data with the results of calculations by Michaud's equation and Wood and Jones's method for the steel pipeline

The experimental data are represented by filled circles. The results from Michaud's equation are marked by empty circles. Wood and Jones's method is illustrated by α curves. The X axis represents the dimensionless valve closure time, and the Y axis expresses dimensionless maximum pressure change.

It is worth noting that the experimental data shown in both figures are located in totally different areas of the chart. For both pipelines the measured values of the

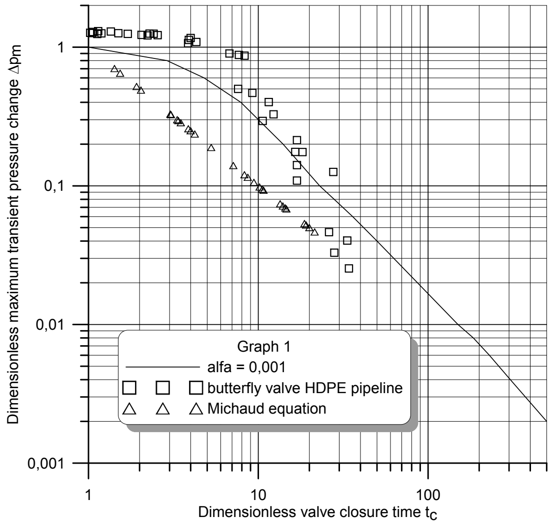

Fig. 5. Comparison of the experimental data with the results of calculations by Michaud's equation and Wood and Jones's method for the HDPE pipeline

maximum pressure change are significantly bigger than those calculated by Michaud's formula as well as by Wood and Jones's method. In fact, the latter theoretical method yields greater pressure increase values than Michaud's formula, but the difference between calculation results and measurements is significant in this case as well.

Three remarks need to be made at this point. First of all, Michaud's equation gives unrealistically small values of pressure increase and should not be used for calculation or estimation of pressure increase during water hammer. Second, Wood and Jones's method leads to more realistic values of pressure increase, but the results of calculations are still significantly smaller than the measured values. The third remark concerns the theory of water hammer: the boundary between rapid and complex water hammer is not very sharp. Extending the closure time reduces the maximum pressure increase, but the relationship is different than described by Michaud's equation. From the practical point of view, the influence of closing time extension can be significant only when the closure time is approximately 10 times as long as the return time of the reflected wave.

The analysis of the above results leads to the question about the influence of the valve type on water hammer phenomenon. A comparison of experimental data collected during water hammer in a steel pipeline and a HDPE pipeline equipped with ball valves is shown in Fig. 6 and Fig. 7, respectively. For the steel pipeline, differences between water hammer caused by the ball valve and the butterfly valve are not

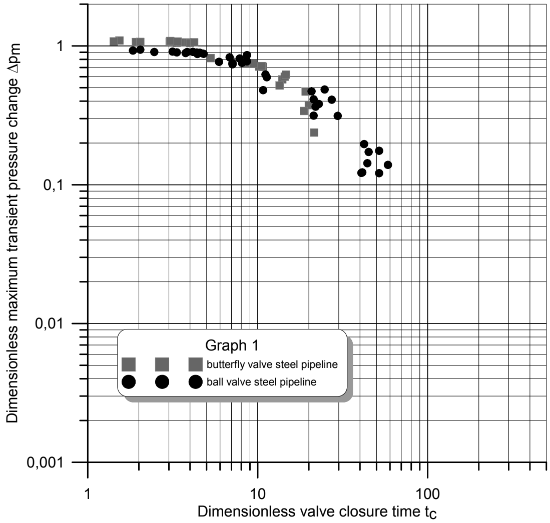

Fig. 6. Comparison of experimental data collected during water hammer in steel pipelines with a ball valve (Kodura 2011) and a butterfly valve

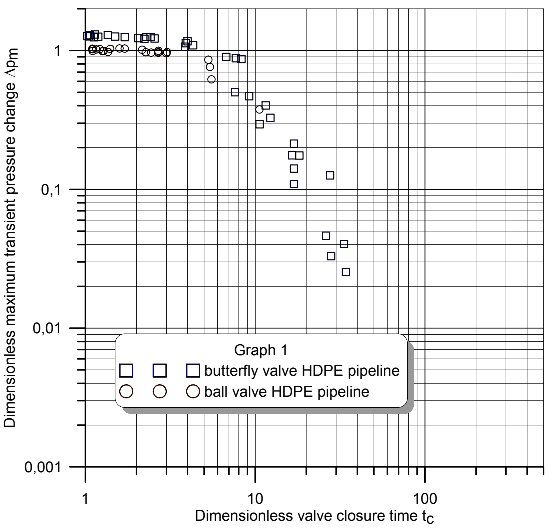

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Fig. 7. Comparison of experimental data collected during water hammer in HDPE pipelines with a ball valve (Kodura 2011) and a butterfly valve

very significant. When the closing time is shorter than 10% of the return time of the reflected wave, the butterfly valve produces a slightly higher pressure increase. For longer closure times, water hammer due to butterfly valve closing has slightly smaller values than that due to the ball valve. In the case of the HDPE pipeline, the relationship is similar, but the difference between water hammers caused by the ball valve and the butterfly valve is bigger.

4. Conclusion

The water hammer phenomenon still has not been precisely defined in theory and described by the existing equations. A significant lack of experimental data leads to inadequate theoretical models. The commonly used Michaud's equation significantly underestimates pressure increase and therefore should not be used.

Although the main idea of Wood and Jones's method of introducing the valve type is correct, this method still leads to estimates lower than the actually observed values. By taking into account only the valve type and initial steady head losses it is still impossible to describe the phenomenon properly. The problem should therefore be investigated experimentally.

From the practical point of view, the maximum pressure increase for a closure time shorter than 25% of the return time of the reflected wave can be calculated by Joukowsky's formula.

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