



# Identifying Head Accumulation due to Transient Wave Superposition in Pipelines

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**Abstract:** Fluctuations in pressures are part of the normal behavior of water distribution systems. The common perception is that transient events dissipate quickly in a network without significant consequences; however, under certain circumstances, the superposition of waves from a transient event can magnify the pressure response, effectively accumulating head in a pipeline. This paper studies this accumulation phenomenon in a single pipeline from a theoretical point of view, with supporting numerical simulation and laboratory validation. Transient wave propagation analysis shows that after the generation of a transient event, multiple wave reflections induce an increase in the head. A cycle of accumulation is defined and the potential maximum number of cycles is studied for a pipeline connected to a long, large impedance pipe section. The analysis is then extended to a system connected to a shorter large impedance pipe section where the maximum head accumulation is not reached. Expressions to calculate the potential maximum head accumulation in pipeline systems are proposed and numerically validated. A general classification for the head accumulation is presented to specify how severe a head accumulation event may be. Experimental validation of the phenomenon has been conducted, showing that under a proposed configuration, the head in the pipeline increases significantly after the first small head rise due to a valve closure. A comparison between the maximum measured head in the laboratory and the theoretical expected maximum head has been undertaken. More realistic configurations that could result in the same phenomenon are briefly discussed. DOI: 10.1061/(ASCE)HY.1943-7900.0001631. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <http://creativecommons.org/licenses/by/4.0/>.

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## Introduction

Water is a vital resource to society and its continuous distribution for all types of usage is becoming a challenge. In addition, water distribution systems are highly dynamic due to constant changes in demand induced by operational maneuvers, fire tests, bursts, or regular maintenance. In general, any perturbation in a network induces changes in head (and flow), which are known as transient events.

Pressure transients have been considered as part of the design of a pipe network system through a series of standards that provide protection with the adequate selection of pipe classes and with the installation of appropriate surge protection devices. However, limited attention has been given to the effect of repetitive small transients induced by normal operation in the system (Rezaei et al. 2015). One of the common premises regarding these small transients is that in complex systems, these perturbations are dissipated quickly and do not represent a risk for the functioning of the network. However, this premise is incorrect if specific system

configurations are analyzed. Changes in the cross-sectional area or material type, the replacement of short segments of pipe, or modifications of the water mains can induce a significantly large head accumulation in a pipeline after the generation of a transient event.

Understanding how this head accumulation develops is important because it could result in long-term damage and the potential failure of pipelines. Repetitive and significant transient events may affect the failure of water mains (Rezaei et al. 2015), even when the initial events are not severe. In addition, since these events are generated by any daily operation of the system, it is possible that they are rarely registered on the existing pressure transducers, thus preventing their direct analysis.

Recent research has shown that a water distribution system is exposed to repetitive transient events. The characterization of its impact and frequency can help in reducing its occurrence in a specific system (Stephens et al. 2017). Nonetheless, scant previous research has focused on the circumstances that can trigger a head accumulation in a pipeline following a transient event.

The current paper presents a comprehensive analysis of the potential head accumulation after a transient event. First, a transient wave propagation analysis is developed based on the MOC for a single pipeline example followed by the estimation of the potential maximum head accumulation in the pipe for two different situations. A general classification of how severe an accumulation occurrence can be in terms of the physical characteristics of a pipeline is also presented. An experimental verification is also shown when there is evidence of the existence of the accumulation and a comparison between the expected maximum head accumulation and the experimental value is included. Finally, a brief discussion on the occurrence of this phenomenon in real systems is presented, including three different examples.

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## Background

Pressure variations are always present in water distribution systems, either based on gradual changes or sudden changes recorded as transient events. Depending on the magnitude of these variations, pipelines can be at risk of failure (pipe bursts) or equipment in the system may be damaged. In water mains, the effect of a significant transient event can be traced easily; however, in systems that are more complex, the evolution of a transient event is less clear. Usually, the sense from previous experience is that network configurations (including loops and dead ends) can dissipate the pressure excesses produced by a transient event. Energy dissipation is assumed to occur due to repetitive reflections of the transient waves in the different elements of the system (junctions, valves, etc.) (Karney and Filion 2003). As an example, Meniconi et al. (2015) presented a series of field tests comparing the effect of the existence of branches in a pipeline on the transient pressure trace after a pump trip. The results showed that when more branches were active (open), the transient signal dissipated more quickly, making the determination of the location of anomalies more difficult. Nonetheless, several authors have also questioned this assumption with simple examples.

Wylie (1983) described how, due to the presence of a pipe junction, the magnitude of an incident wave can be amplified if the junction goes from a large cross-sectional area pipe to a smaller area. In addition, Wylie (1983) concluded that if several step changes in cross-sectional area are present in the pipeline, transient waves can be focused, achieving a magnitude greater than double the original incident wave. Karney and McInnis (1990) illustrated the effect that topology can have on the induced transient pressure trace. The responses of two similar systems to a valve closure, one considering the system as a series of single pipelines and the second including an offtake near the end of the system, were analyzed. Considering the offtake showed that the pressures in the system were larger due to multiple reflections of the transient waves. Meniconi et al. (2011a) conducted laboratory experiments to analyze the pressure behavior in a pipe with the presence of a butterfly valve, finding that for a total valve closure, the pressure increases with time, reaching almost five times its initial induced value.

Ellis (2008) analyzed the effect of different topologies on the propagation of transient waves after a transient event. Starting with single pipelines with branches or junctions (with reductions in diameter), situations in which pressures will increase from the induced transient were described, demonstrating that the assumption of the ability of a network to damp the effect of transient flow is not necessarily true. Furthermore, when the analysis was carried out in a real system, it was illustrated that if a transient is initiated within a larger diameter pipe and it propagates into smaller pipes, the potential for the amplitude of pressure fluctuations increases substantially (Ellis 2008).

More recently, Starczewska et al. (2014) mentioned that the reflection and transmission of transient waves lead to accumulation when the sum of the outgoing admittances is smaller than those of the incoming pipes. In addition, the reflections from junctions or dead ends provide the potential for the superposition of two or more transient waves, which can have either a destructive or a constructive effect on the magnitude of pressure in the system. Duan and Lee (2016) studied the effect of the presence of a branch in a system. They found that the magnitudes of the transient responses in certain locations of the system were larger when the branch was considered. In addition, a side branch induced more transient wave oscillations, which could also affect the dynamics of surge protection devices. This behavior is present in the transient pressure

measurements irrespective of the status of the branch (i.e., active if the branch pipeline is open and has flow or is inactive when it does not have flow) as presented by Meniconi et al. (2011b). Even when the transient pressure response in the branch is significantly different, the transient pressure in the main pipeline is similar, facilitating the location of illegal branches, even though these branches are inactive.

Furthermore, it is not only topological elements that cause head accumulation in a pipe. Ghilardi and Paoletti (1986) reported that the interaction between the small impedance of a plastic section (associated with a small wave speed) and a larger impedance of a metallic section could produce larger-pressure responses in a system. This potential head accumulation is not fully understood in terms of determining how severe it may become.

## Transient Wave Propagation Analysis

When a transient event is generated, a pressure wave travels through the pipes interacting with any discontinuity. This interaction can dissipate the energy of the transient or to the contrary, can accumulate more energy as pressure accumulates in the system. The system configuration in which a head accumulation can be analyzed is now presented, followed by the interpretation of the head response to the closure of a side discharge valve.

### System Configuration

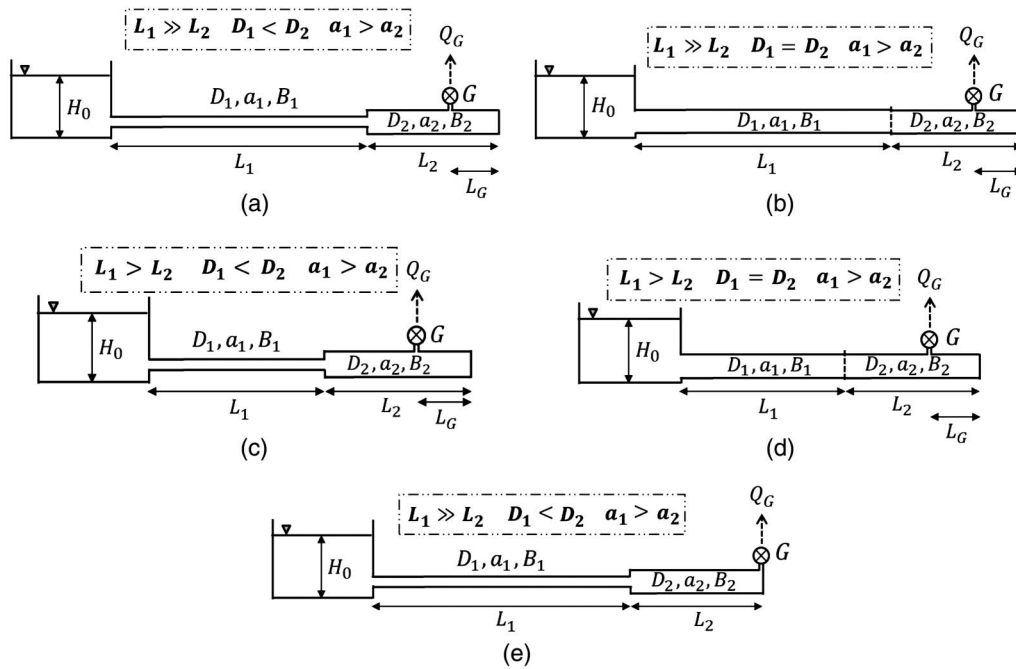
First, let us define the hydraulic pipeline impedance (in  $s/m^2$ ), which is  $B = a/(gA)$  (Wylie and Streeter 1993), where  $a$  is the wave speed in m/s,  $A$  is the cross-sectional area in  $m^2$ , and  $g$  is gravity in  $m/s^2$ . The system that is considered to understand the head accumulation in a pipe is shown in Fig. 1(a). It consists of two pipes in a series connected to a reservoir at the upstream end and with a dead end at the downstream end. The upstream pipe has a diameter  $D_1$ , length  $L_1$ , wave speed  $a_1$ , and hydraulic impedance  $B_1$ , while the downstream pipe characteristics are  $D_2$ ,  $L_2$ ,  $a_2$ , and  $B_2$ . The transient event is generated by the closure of a side discharge valve at an interior point of Pipe 2 marked as  $G$  in Fig. 1(a). This point is located at a distance  $L_G$  from the dead end.  $H_0$  and  $Q_G$  represent the initial head and flow in the pipeline (which is also the flow through the side discharge valve).

As shown in Fig. 1(a), the length of Pipe 1 is greater than the length of Pipe 2 and its diameter is smaller. This cross-sectional area configuration ( $D_1 < D_2$ ) is chosen to guarantee that the hydraulic impedance of Pipe 1 is larger than the hydraulic impedance of Pipe 2 ( $B_1 > B_2$ ). However, this same condition can be present with the same cross-sectional area in both pipes and a larger wave speed in Pipe 1 ( $a_1 > a_2$ ), as shown in Fig. 1(b).

This relation between the hydraulic impedances ( $B_1 > B_2$ ) is necessary for the development of the head accumulation as explained in the subsequent sections. Fig. 1 summarizes the different systems that will be used in this paper to explain the head accumulation phenomenon.

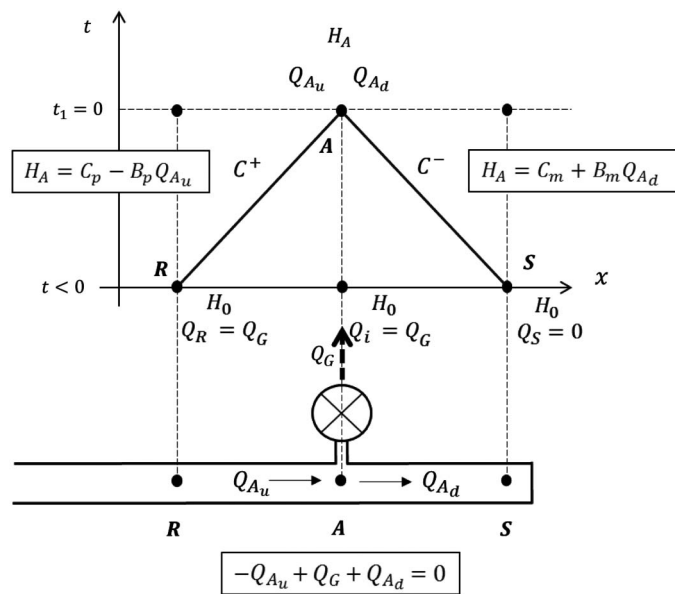
### Transient Wave Reflection and Transmission

Wave reflection and transmission are now studied in Pipe 2. A transient event is generated by closing the side discharge valve at  $G$ , assuming zero friction in the system. The analysis is carried out using the method of characteristics (MOC). This process is illustrated in Fig. 3 and divided into six different stages when the transient generation point (Point  $G$  in Fig. 3) is located close to the dead end.



**Fig. 1.** Layout of the considered systems: (a) Example A; (b) Example B; (c) Example C; (d) Example D; and (e) Example E.

After the valve is fully closed in a single step at  $t_1 = 0$ , referring to Fig. 3 (Stage 1), a transient wave is generated with head  $H_A$ . The head and flow conditions in the pipeline after the closure of the side discharge valve can be determined using the MOC according to Fig. 2, where there are three unknowns at  $t_1$ :  $H_A$ ,  $Q_{Au}$ , and  $Q_{Ad}$ . Using the two compatibility equations available and the continuity equation at the junction [Fig. (2)], the magnitude of the head is shown in Eq. (1) and the magnitude of the flow is shown in Eq. (2). From Eq. (1), the incident head rise in the pipe at the side discharge valve  $\Delta H_i$  can be calculated using Eq. (3). According to Eq. (2), the flow in the pipeline after the side discharge valve closure is not zero; it is half of the flow that was initially going through



**Fig. 2.** MOC analysis to determine head and flow after the closure of a side discharge valve.

the side discharge valve and it is propagated in both directions of the pipeline. However, when the transient wave reaches the dead end and reflects, the discharge becomes zero

$$H_A = H_0 + B_2 \frac{Q_G}{2} \quad (1)$$

$$Q_{Au} = \frac{Q_G}{2}; \quad Q_{Ad} = \frac{Q_G}{2} \quad (2)$$

$$\Delta H_i = H_A - H_0 = B_2 \frac{Q_G}{2} \quad (3)$$

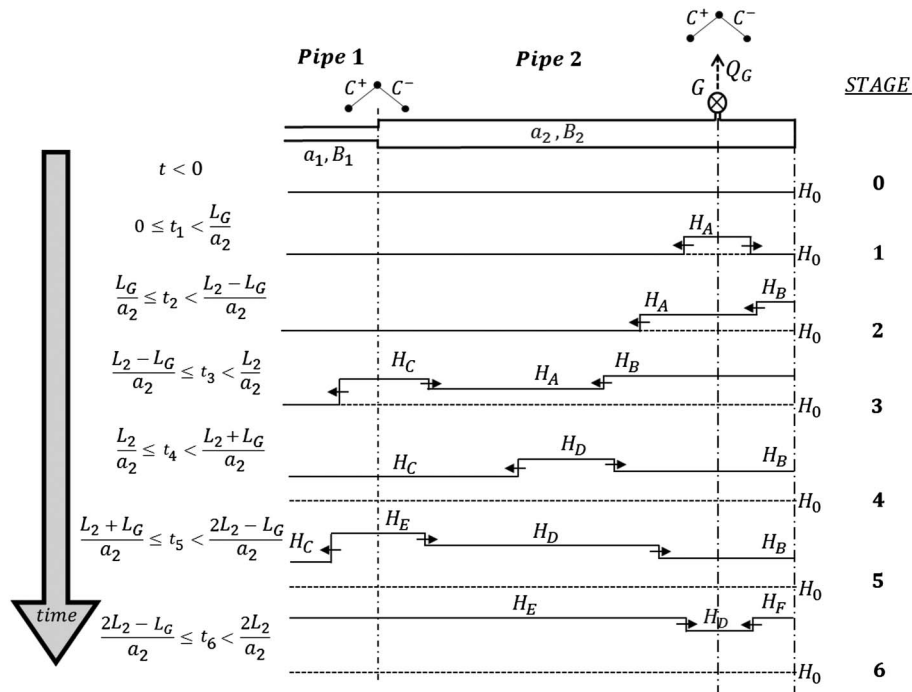
The incident transient wave  $H_A$  propagates in both directions along the pipeline, reaching first the dead end at the downstream end of the pipeline if the transient generation point ( $G$ ) is closer to this boundary condition. The reflection at the dead end occurs at  $t_2 = L_G/a_2$ , inducing a head shown in Fig. 3 (Stage 2) as  $H_B$ , where the magnitude may be determined from the MOC [following the same approach presented in Fig. (2)] and is shown in Table 1 in terms of the incident head rise at the side discharge valve  $\Delta H_i$ .

The propagation of the transient wave in the upstream direction reaches the junction between Pipe 2 and Pipe 1 at time  $t_3$ , while the transient wave with magnitude  $H_B$  is transmitted in the upstream direction from the dead end (Stage 3). Time  $t_3$  also depends on the wave speed  $a_2$  and the distance between the generation point and the junction ( $L_2 - L_G$ ). To determine the magnitude of the head  $H_C$ , three equations can be used, including Eq. (1), and the two compatibility equations from the MOC [shown in Fig. (3)] that apply at the series pipe junction are

$$H_C = C_p - B_p Q_C = (H_0 + B_1 Q_G) - B_1 Q_C \quad (4)$$

$$H_C = C_m + B_m Q_C = \left( H_A - B_2 \frac{Q_G}{2} \right) + B_2 Q_C \quad (5)$$

where  $H_C$  and  $Q_C$  = head and flow reflected once the transient wave has reached the series junction and  $C_p$ ,  $B_p$ ,  $C_m$ , and  $B_m$  = definitions



**Fig. 3.** Wave propagating through Pipe 2 after a step closure in point G.

taken from Wylie and Streeter (1993). By solving Eqs. (1), (4), and (5) for  $H_C$  and  $Q_C$ , Eqs. (6) and (7) are obtained. Expressions for  $H_C$  and  $Q_C$  can be obtained from Eqs. (4) and (5), but to express the head and the flow at the series pipe junction just in terms of the incident head rise  $H_A$ , Eq. (1) is required. An equivalent form of Eqs. (6) and (7) was presented by Wylie (1983) in a study where three compatibility equations were solved to find the reflection and transmission of an incident wave after reaching a pipe junction. However, for the case analyzed in this paper, the incident wave corresponds to  $H_A$  as a result of the closure of a side discharge valve in contrast to Wylie (1983), where an inline valve is closed

$$H_C = H_0 + \frac{B_1 B_2}{B_1 + B_2} Q_G = H_0 + \frac{B_1}{B_1 + B_2} (2\Delta H_i) \quad (6)$$

$$Q_C = \frac{B_1}{B_1 + B_2} Q_G \quad (7)$$

where  $\Delta H_i = B_2(Q_G/2)$ . Analysis of Eq. (6) shows that the magnitude of the head at the junction depends on the relation between the pipes' hydraulic impedances  $B_1$  and  $B_2$ . If the impedance of Pipe 1 is smaller than the impedance of Pipe 2,  $H_C$  will be smaller than the incident transient wave. However, if the impedance  $B_1$  is larger (either because the wave speed is larger and/or the area is smaller as in the case being analyzed in this section), the head in the junction will also be larger than the incident transient head, as reported by Wylie (1983).

If the generation point ( $G$ ) is located closer to the pipe junction than to the dead end, the transient wave reflection at the interface ( $H_C$ ) would occur before the reflection at the dead end ( $H_B$ ), but the rest of the head accumulation process would develop in the same way. The expressions presented in this section are valid as long as the transient event is generated at any interior point of Pipe 2.

Subsequently, at instant  $t_4$ , the reflection from the dead end ( $H_B$ ) traveling upstream and the reflection from the junction ( $H_C$ ) propagating downstream meet at an interior point of Pipe 2

(Stage 4). The superposition of these two waves induces a head increase when compared with the initial transient head rise at the side discharge valve. The magnitude of the head ( $H_D$ ) and the flow in the pipe at that time is shown in Table 1 and was developed again from the compatibility equations using the MOC. This transient wave is again propagated in both directions toward the pipe junction and toward the dead end.

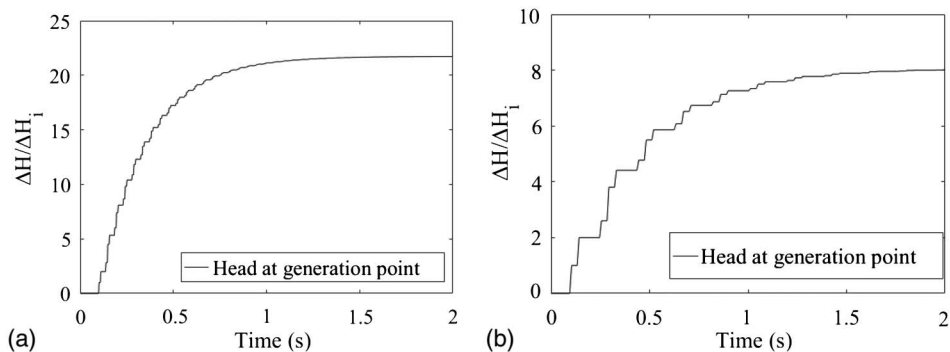
Depending on the position of the generation point along the pipeline, the transient wave with head  $H_D$  may reach either the junction first (as shown in Fig. 3, Stage 5) or the dead end first, but both of those reflections will induce a new head accumulation with magnitudes  $H_E$  and  $H_F$ , respectively, at times  $t_5$  and  $t_6$ . As can be seen in Table 1, the magnitudes  $H_E$  and  $H_F$  are the same, leaving the pipe at the end of the reflection cycle with head

$$H_E = H_F = H_0 + \frac{B_1}{B_1 + B_2} (4\Delta H_i) \quad (8)$$

**Table 1.** Head and flow in the first accumulation cycle

Time	Head (H)	Flow (Q)
$0 \leq t_1 < \frac{L_G}{a_2}$	$H_A = H_0 + \Delta H_i$	$Q_A = \frac{Q_G}{2}$
$\frac{L_G}{a_2} \leq t_2 < \frac{L_2 - L_G}{a_2}$	$H_B = H_0 + 2\Delta H_i$	$Q_B = 0$
$\frac{L_2 - L_G}{a_2} \leq t_3 < \frac{L_2}{a_2}$	$H_C = H_0 + \frac{B_1}{B_1 + B_2} (2\Delta H_i)$	$Q_C = \frac{B_1}{B_1 + B_2} Q_G$
$\frac{L_2}{a_2} \leq t_4 < \frac{L_2 + L_G}{a_2}$	$H_D = H_0 + \frac{3B_1 + B_2}{B_1 + B_2} \Delta H_i$	$Q_D = \frac{B_1 - B_2}{B_1 + B_2} \frac{Q_G}{2}$
$\frac{L_2 + L_G}{a_2} \leq t_5 < \frac{2L_2 - L_G}{a_2}$	$H_E = H_0 + \frac{B_1}{B_1 + B_2} (4\Delta H_i)$	$Q_E = \frac{B_1 - B_2}{B_1 + B_2} Q_G$
$\frac{2L_2 - L_G}{a_2} \leq t_6 < \frac{2L_2}{a_2}$	$H_F = H_0 + \frac{B_1}{B_1 + B_2} (4\Delta H_i)$	$Q_F = 0$





**Fig. 4.** Normalized head rise (with respect to the incident head rise  $\Delta H_i$ ) at transient generation point for (a) Example A; and (b) Example B.

Finally, as shown in Fig. 3, the transient waves  $H_E$  and  $H_F$  approach each other to meet at the generation point at the end of the head accumulation cycle (Stage 6). The total time ( $t_T$ ) of one head accumulation cycle is defined as

$$t_T = 2L_2/a_2 \quad (9)$$

Once these transient waves meet, a new cycle of head accumulation will start with an initial head defined by Eq. (8). The evolution of several head accumulation cycles will be analyzed in the next section.

If the transient generation point was at the end of the pipe instead of at any interior point of the pipe, a head accumulation phenomenon would also have occurred, but in a simpler way. When comparing this process with Fig. 3, only a reflection at the junction and at the dead end would occur. However, when the transient wave propagation analysis is developed for this situation, the final head accumulation can also be computed with Eq. (8) and the time from Eq. (9).

By analyzing a single pipeline, with the transient source  $G$  at the end, an understanding of the transient wave propagation is simpler to achieve than the one shown in Fig. 3 and could have been used to define the repetitive head accumulation; however, in a real system, it is more common either to find transient events induced along the pipe as a result of user demands, fire tests, or valve operation, rather than at the end of the pipeline.

### Estimate of Maximum Head Accumulation

In the previous section, the head accumulation after the first transient wave reflections was described. Depending on the characteristics of the system, particularly the length and impedance of the pipes, the head accumulation can reach potentially damaging levels when compared with the initially induced transient wave. The interruption to the head accumulation cycle occurs when the first transient wave returns from the upstream reservoir and interacts with the previously described transient waves, causing a reduction of head in the pipe. However, for short lengths of Pipe 2, Pipe 1 does not need to be very long to result in a significant head accumulation.

The computation of the maximum head accumulation has been developed for two different systems: a first example in which Pipe 1 is considerably longer in comparison with Pipe 2, as shown in Figs. 1(a and b) (Example A and B), and a second example in which both pipes have similar lengths, as presented in Figs. 1(c) and 2(d) (Example C and D).

### Long Connecting Pipe

For this first approach, Pipe 1 in Fig. 1(a) is considerably longer than Pipe 2, meaning that there would not be an interaction of the transient wave that returns from the upstream reservoir with the multiple reflections between the dead end and junction in Pipe 2. In this sense, the maximum head accumulation computed for this system is only a potential maximum. The real head accumulation is analyzed in the next section. A more general equation for calculating the head in Pipe 2 at the end of any head accumulation cycle is presented in Eq. (10) as

$$H_n - H_{n-1} = \frac{4B_1}{B_1 + B_2} \left( \frac{B_1 - B_2}{B_2 + B_1} \right)^{n-1} \Delta H_i \quad (10)$$

where  $n$  represents a cycle that starts with a value of one and can take any positive integer value. This equation expresses the head in Pipe 2 at the end of each cycle. There are intermediate head values (e.g., visible in Fig. 4) that are not explicit in this definition. These values are presented in Table 1 for the first cycle and can be computed for subsequent cycles by multiplying the following term by  $\Delta H_i$ :

$$\left( \frac{B_1 - B_2}{B_2 + B_1} \right)^{n-1} \quad (11)$$

A better way to express the head accumulation is by computing it relative to the initial steady head in terms of the incident transient wave head increase ( $\Delta H_i$ ) and the characteristics of the system. This relative increase after the  $n$ -th head accumulation cycle is

$$\Delta H_N = \frac{4B_1}{B_1 + B_2} \Delta H_i \sum_{n=1}^N \left( \frac{B_1 - B_2}{B_2 + B_1} \right)^{n-1} \quad (12)$$

where  $\Delta H_N = H_N - H_0$  and  $H_N =$  head at the end of  $N$  accumulation cycles. In contrast to the situation analyzed by Wylie (1983), where wave focusing was studied for several consecutive changes in the cross-sectional area, in the present paper  $n$  corresponds to each head accumulation cycle due to multiple reflections from one junction. Eq. (12) is only valid when  $B_1 \neq B_2$  given that if the two impedances are equal, no extra reflections would occur. If there is no head reduction mechanism for this accumulation process, as analyzed in this first case,  $N$  will take a large value (it could become infinite) and Eq. (12) can be simplified to

$$\Delta H_\infty = \frac{2B_1}{B_2} \Delta H_i \quad (13)$$

This equation determines the maximum potential head accumulation in Pipe 2. The criteria that can be used to detect if a head

**Table 2.** Parameters used in the MOC model for Example A and B

Characteristic	Example A	Example B
Length of Pipe 1, $L_1$ (m)	2,000	2,000
Length of Pipe 2, $L_2$ (m)	25	25
Steady-state upstream reservoir head, $H_0$ (m)	30	30
Steady-state side valve discharge, $Q_G$ ( $\text{m}^3/\text{s}$ )	0.0389	0.0389
Wave speed Pipe 1, $a_1$ (m/s)	1,285	1,064
Wave speed Pipe 2, $a_2$ (m/s)	1,064	264 <sup>a</sup>
Internal diameter Pipe 1, $D_1$ (mm)	200	600
Hydraulic impedance Pipe 1, $B_1$ ( $\text{s}/\text{m}^2$ )	4,169	383.6
Hydraulic impedance Pipe 2, $B_2$ ( $\text{s}/\text{m}^2$ )	383.6	95.17
Internal diameter Pipe 2, $D_2$ (mm)	600	600
Initial head rise, $\Delta H_i = B_2(Q_G/2)$ (m)	7.46	1.85

<sup>a</sup>Plastic pipe.

accumulation will take place are: (1) if the hydraulic impedance of Pipe 1 ( $B_1$ ) is larger than the impedance of Pipe 2 ( $B_2$ ). This occurs if the cross-sectional area of Pipe 1 is smaller ( $A_1 < A_2$ ) or if the wave speed in this pipe is larger ( $a_1 > a_2$ ); and (2) if Pipe 1 is long enough to allow the development of a complete accumulation (which is the case analyzed in this section). On the other hand, Eqs. (13) and (3) can be combined to obtain

$$\Delta H_\infty = \frac{2B_1}{B_2} \left( B_2 \frac{Q_G}{2} \right) = 2 \left( B_1 \frac{Q_G}{2} \right) \quad (14)$$

This equation shows that the potential maximum head accumulation in Pipe 2 can also be computed as twice the incident head rise if a transient event had been generated along Pipe 1 (rather than in Pipe 2). Therefore, the larger the impedance of Pipe 1, the larger the maximum potential head accumulation in Pipe 2.

To illustrate this finding, Figs. 4(a and b) show the normalized head rise at the side discharge valve [calculated by normalizing the head rise at the transient generation point at any time with the initial head rise  $\Delta H_i$  from Eq. (3)] from a numerical simulation using the MOC for two different systems. Example A is the system described in Fig. 1(a) and Example B is a system in which the diameter of both pipes is the same, but the pipe material is different and is shown in Fig. 1(b). Pipe 1 is assumed to be a metallic pipe and Pipe 2 is a plastic pipeline. The main parameters of both examples are summarized in Table 2.

As can be seen in Table 2, the steady-state conditions for both examples are assumed to be the same (head and flow); however, the characteristics of Pipe 2 (in which the transient event is generated) are different. Therefore, the initial head rises are also different. Fig. 4 presents the normalized head rise at the side discharge valve for both cases, showing that head accumulates to almost 22 times the initial transient head rise in Example A, while in Example B, head builds up to 8 times the incident head rise.

Using the information in Table 2 and Eq. (13), it is possible to obtain the exact values for the maximum head accumulation in the systems. In Example A, the impedance of Pipe 1 is 4,169  $\text{s}/\text{m}^2$ , the impedance of Pipe 2 is 383.6  $\text{s}/\text{m}^2$ , and the initial head rise is 7.46 m; therefore, using Eq. (13), the maximum normalized head rise is 21.73 [the same value as in Fig. 4(a)]. In Example B, the impedance of Pipe 1 is 383.6  $\text{s}/\text{m}^2$ , the impedance of Pipe 2 is 95.17  $\text{s}/\text{m}^2$ , and the initial head rise is 1.85 m, resulting in a maximum normalized head accumulation of 8.07 [this value is also evident in Fig. 4(b)]. The same results can be obtained using Eq. (14), showing that the maximum potential head accumulation in Pipe 2 is

a function of the hydraulic impedance of Pipe 1 and not of the characteristics of the pipe in which the transient event is generated.

Fig. 4 shows some of the intermediate head accumulations described in Table 1. For instance, in Example A, the head at the beginning of the second cycle of accumulation [obtained by using Eq. (8) and modified equations of Table 1] is 63.54 m, which corresponds to a relative head rise of 4.49 times. This value is visible in Fig. 4(a); however, two extra reflections are visible in the figure before the relative head rise reaches 4.49. Those reflections correspond to  $H_B$  and  $H_D$  in Table 1. Not all the reflections described in Table 1 are visible in Fig. 4 because, as shown in Fig. 3, some of these reflections never reach the transient generation point.

According to Eq. (13), the maximum head accumulation only depends on the impedance of Pipe 1 (the one causing the repetitive transient wave reflections) and not on the characteristics of the pipe in which the transient event is induced. However, this is only true when the pipe causing the head accumulation is significantly long. In a system that receives reflections from an upstream reservoir or another source in a relatively short time, the maximum head accumulation can be considerably smaller than the one described by Eq. (13). In the next section, a more realistic system, in which the length of Pipe 1 is not excessively long, is presented to determine the real maximum head accumulation.

### Short Connecting Pipe

A potential maximum head accumulation in a system with a long Pipe 1 was described in the preceding section. To obtain Eq. (13), the limit in Eq. (12) when  $N$  tends to infinity was computed. However, this limit is only valid when no reflections from the upstream reservoir (on any other element in a different system) interact with the pipe in which the transient event is generated. In this section, Pipe 1 is assumed to have a finite and shorter length [Fig. 1(c)] and an estimate of the number of head accumulation cycles that will occur ( $n$ ) is required to determine the maximum head accumulation.

This number of cycles is related to the time that it will take the first transient wave to return from the upstream reservoir. This time can be computed using Eq. (15) and then compared to: (1) the time that it takes for each head accumulation cycle to develop, as described by Eq. (9); and (2) the time it takes to reach the maximum head accumulation computed with Eq. (16)

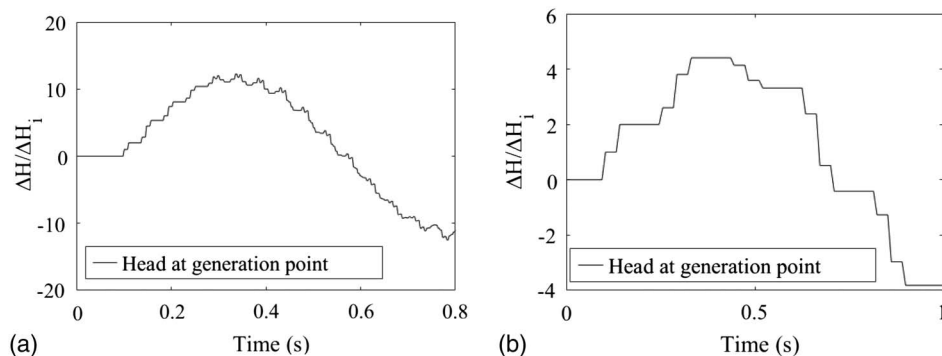
$$t_R = \frac{(L_2 - L_G)}{a_2} + \frac{2L_1}{a_1} \quad (15)$$

$$t_{NT} = N_t \frac{2L_2}{a_2} \quad (16)$$

where  $t_R$  corresponds to the time of arrival of the first transient wave from the upstream reservoir.  $L_1$ ,  $L_2$ ,  $L_G$ ,  $a_1$ , and  $a_2$  are defined in Fig. 1(c),  $t_{NT}$  is the time required to reach the maximum head accumulation, and  $N_t$  represents the number of cycles when the head accumulation is considered to be maximum. The maximum head accumulation would only be reached when  $N_t$  is infinite; however, in a real system, from a certain point the head accumulation could be considered the maximum given the fact that with each cycle, the extra head accumulation decreases (behavior that is visible in Fig. 4). Considering this behavior,  $N_t$  can be computed as

$$N_t = 1 + \frac{\ln(\varepsilon)}{\ln\left(\frac{B_1 - B_2}{B_2 + B_1}\right)} \quad (17)$$

where  $\ln$  = natural logarithm. The term  $\varepsilon$  corresponds to a threshold value that defines when the maximum head accumulation is considered to have been reached and is based on the relative difference



**Fig. 5.** Relative head rise at transient generation point in a system with a short connecting Pipe 1 (100 m) for (a) Example C; and (b) Example D.

between the potential maximum head accumulation [given by Eq. (13)] and the real head accumulation after  $N_i$  cycles. Upon applying Eq. (17), the term  $\varepsilon$  can be used in the same way as a tolerance: a smaller threshold will result in a larger number of cycles and a maximum head accumulation that is closer to the potential maximum head accumulation.

Using the previous equations, the head accumulation in a real pipeline can be computed. If  $t_R$  is greater than  $t_{NT}$ , the maximum potential head accumulation will be reached and the maximum head in the pipe can be approximately computed using Eq. (13) or (14). If  $t_{NT}$  is greater than  $t_R$ , the first transient wave coming back from the upstream reservoir will interact with Pipe 2 to reduce the head before reaching the potential maximum head accumulation. In this case, the number of head accumulation cycles can be determined using Eq. (18) and the head accumulation can be calculated using Eq. (12)

$$n = \frac{t_R a_2}{2L_2} \quad (18)$$

In order to illustrate how these equations represent a general case, a numerical model using the MOC was developed to obtain the head variation for two systems with the same characteristics as Example A and B (as previously described in Fig. 4) except for the length of Pipe 1, which was defined as 100 m. These new cases are now referred to as Example C and Example D and their characteristics are shown in Figs. 1(c and d). The results of these numerical simulations are shown in Figs. 5(a and b).

Fig. 5(a) shows that the maximum head accumulation is not reached [when compared to Fig. 4(a)]. Therefore, using Eqs. (15)–(17), it is found that the required time to obtain the maximum head accumulation (with an  $\varepsilon$  value assumed to be =1%) is  $t_{NT} = 1.22$  s and the reflection from the upstream reservoir returns to the junction at Pipe 2 at  $t_R = 0.18$  s. With this comparison, it is possible to determine that four complete head accumulation cycles will take place in Pipe 2 and the maximum expected accumulated head will be 114.7 m, which corresponds to a relative head rise of 11.35. When comparing this value with the results presented in Fig. 5(a), it is evident that the maximum relative head obtained with the MOC is larger (12.25 corresponding to a head of 121.4 m). This difference is due to the fact that in the equations presented in this section, a detailed analysis of the interaction between the reflections from the upstream reservoir and the transient wave that had been accumulating is ignored; depending on the stage of the cycle described in Fig. 3 during which the reflection arrives, an extra head accumulation can develop. However, this extra head accumulation is small when compared to the rest of the head accumulation phenomenon.

For Example D,  $t_{NT} = 1.89$  s and  $t_R = 0.28$  s, which results in only two cycles of head accumulation and an expected maximum relative head of 5.14 ( $\Delta H_i = 9.50$  m) or a maximum head of 39.50 m. Based on Fig. 5(b), the maximum relative head is 4.41 (or  $\Delta H_i = 8.15$  m or a maximum head of 38.16 m). In this case, the extra interaction between the accumulated transient wave and the reflected transient wave from the upstream reservoir causes a reduction in head (diminishment mode) instead of an increase in head (magnification mode), as shown in Example C. These two examples support the statement of Starczewska et al. (2014) about the possibility of having both destructive or constructive interactions between transient waves depending on the characteristics of a water pipeline system.

### Head Accumulation Classification

The previous sections have shown the mechanisms that explain a potential head accumulation in a pipeline under certain circumstances and the maximum possible head values. However, a more general description of the head accumulation can be useful to determine its severity. This section presents a method to classify these phenomena and to predict the expected maximum accumulated head in a pipeline with pipe sections that have different impedances.

The classification of this severity has been developed using a slightly different system than the one described in the preceding text to facilitate the derivation of the required equations. The system considered is shown in Fig. 1(e) and referred to as Example E. Here, the transient generation point is at the end of Pipe 2 ( $L_G = 0$ ). In addition, four non-dimensional quantities have been defined. Firstly, the ratio between the hydraulic impedances [shown in Eq. (19)] summarizes part of the physical properties of the pipeline. The rest of these properties are combined in the relative release time, representing the time when the head that has accumulated starts to dissipate, which is defined in Eq. (20)

$$\frac{B_1}{B_2} \quad (19)$$

$$\frac{L_1/a_1}{L_2/a_2} \quad (20)$$

If this relative release time is large, the system could develop the maximum head accumulation described in Eq. (13). The two non-dimensional variables in Eqs. (21) and (22) summarize the pressure conditions of the system. The non-dimensional head accumulation is described in Eq. (21). This quantity differs from the relative head rise described in the previous sections because it is normalized with

**Table 3.** Head accumulation classification

Category	Final head	Non-dimensional head accumulation
Mild	$H_0 < H \leq 1.5H_0$	$0 < \frac{\Delta H}{H_0} \leq 0.5$
Moderate	$1.5H_0 < H \leq 2H_0$	$0.5 < \frac{\Delta H}{H_0} \leq 1.0$
Severe	$2H_0 < H \leq 2.5H_0$	$1.0 < \frac{\Delta H}{H_0} \leq 1.5$
Extreme	$H > 2.5H_0$	$\frac{\Delta H}{H_0} > 1.5$

respect to the initial steady state head ( $H_0$ ), rather than with respect to the incident head rise at the side discharge valve ( $\Delta H_i$ )

$$\frac{\Delta H}{H_0} = \frac{H - H_0}{H_0} \quad (21)$$

This non-dimensional description of the head accumulation has been modified to account for the fact that if the initial transient event is severe enough, even with less than one complete cycle of head accumulation, the head in the pipe could be considered dangerous. Finally, to characterize the severity of the initial transient event, the non-dimensional initial head rise is defined using

$$\frac{\Delta H_i}{H_0} = \frac{H_A - H_0}{H_0} \quad (22)$$

Four categories have been established to classify the head accumulation in a pipeline: mild, moderate, severe, and extreme. The quantitative definition of these categories responds to how large, in comparison to the initial steady state head, the final head is in the pipeline. This definition is shown in Table 3 in terms of the final head ( $H$ ), the initial head ( $H_0$ ), and the non-dimensional head accumulation ( $\Delta H/H_0$ ).

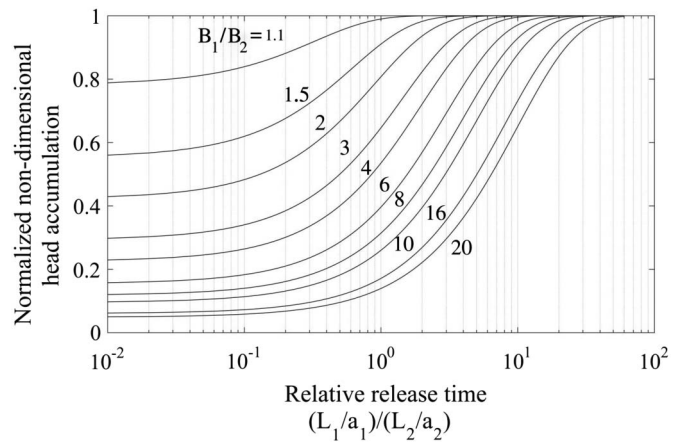
Table 3 shows that to define a head accumulation event as extreme, the final head in the pipeline must be 2.5 times larger than the initial head. In addition, the definition of the categories considers different initial transient head rises and how severe those could be, even without the development of a head accumulation phenomenon. Using the non-dimensional variables, four defined severity categories, and Eqs. (12) and (13), a new set of non-dimensional equations has been developed

$$\frac{\Delta H}{H_0} = -\frac{B_1}{B_2} \frac{\Delta H_i}{H_0} \left[ \left( \frac{B_1 - B_2}{B_1 + B_2} \right)^{\frac{L_1/a_1}{L_2/a_2} + \frac{1}{2}} - 1 \right] \quad (23)$$

$$\left( \frac{\Delta H}{H_0} \right)_{\max} = \frac{B_1}{B_2} \frac{\Delta H_i}{H_0} \quad (24)$$

Eq. (23) describes the non-dimensional head accumulation for a specific set of ratio of hydraulic impedances, a non-dimensional initial transient, and a relative release time. Using this equation, the expected head accumulation can be established and classified. On the other hand, Eq. (24) presents the maximum non-dimensional head accumulation in terms of the ratio of hydraulic impedances and the non-dimensional initial head rise. The influence of the ratio of impedances and the relative release time is shown in a non-dimensional plot in Fig. 6.

Fig. 6 shows the relationship between the relative release time (shown on a log scale to facilitate visualization) along the  $x$ -axis, the non-dimensional head accumulation normalized with respect

**Fig. 6.** Non-dimensional plot to determine head accumulation in pipelines.

to the maximum head accumulation described in Eq. (24) along the  $y$ -axis, and the different curves represent different hydraulic impedances ratios ( $B_1/B_2$ ). The non-dimensional plot is useful to understand the influence of the physical characteristics of the pipeline in the head accumulation phenomenon. In general, a larger relative release time develops a larger head accumulation and the maximum head is reached faster than for smaller hydraulic impedances ratios.

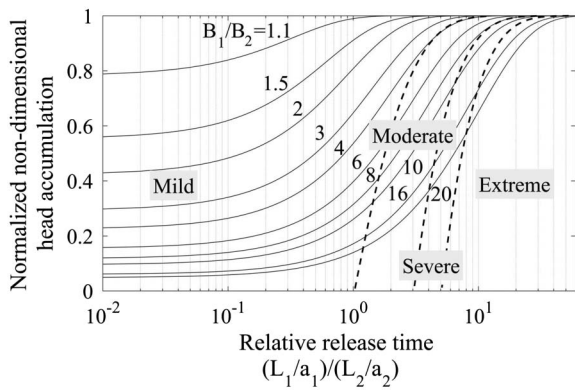
The plot presented in Fig. 6 can be used to determine the head accumulation using the following procedure. First, for the desired system, the hydraulic impedance ratios and the relative release time should be computed. With those two values, an estimate of the non-dimensional head normalized with respect to the maximum non-dimensional head is obtained from the plot (reading off the  $y$ -axis value in Fig. 6). Then, by multiplying that value by Eq. (24), the non-dimensional head ( $\Delta H/H_0$ ) is obtained. Finally, using Table 3, the category for the head accumulation event can be defined.

The non-dimensional plot can also be used directly to classify the head accumulation into one of the four categories if a non-dimensional initial transient event is set. The equations for the limits of the categories can be obtained from Eqs. (23) and (24) by setting a fixed value of the head accumulation and varying the ratio of hydraulic impedances ( $B_1/B_2$ ). An example of the non-dimensional plot, including the categorization of the head accumulation for Example B and D presented in the previous section, is shown in Fig. 7.

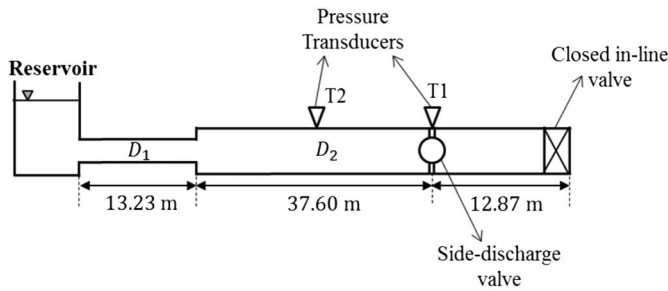
For a non-dimensional initial transient ( $\Delta H_i/H_0$ ) of 0.123, the four categories of head accumulation are shown in Fig. 7. This value can be obtained in two ways: if the measurements of the initial transient event are available, the initial head rise must be doubled to account for the fact that the plot has been defined for a transient generation at the end of Pipe 2 instead of at an interior point. If measurements are not available, the initial transient head rise can be computed by multiplying the hydraulic impedance of Pipe 2 ( $B_2$ ) and the initial flow in the pipe ( $Q_G$ ).

Considering the characteristics presented in Table 2 (using  $L_1 = 100$  m as in Example D), the relative release time would be 0.992 and the ratio between the hydraulic impedances is 4.03, showing that the transient head accumulation event of Example D would be classified as mild. In addition, the resulting non-dimensional head accumulation for this system according to the plot would be 0.266, which corresponds to 37.98 m, the value that is close to the one obtained in the numerical simulation of Example D and shown in Fig. 5(b).





**Fig. 7.** Non-dimensional plot to determine head accumulation in pipelines, including categories for Example B and D.



**Fig. 8.** Experimental pipeline system layout.

Eqs. (23) and (24) and the plot on Fig. 6 are general and powerful tools used to determine how severe the head accumulation process can be for any combination of pipes without doing the specific calculations of the number of head accumulation cycles shown in the previous sections.

## Experimental Verification

### System Configuration

Experiments in the laboratory of the University of Adelaide have been conducted to validate the existence of head accumulation in a pipeline after the generation of a transient event. The test pipeline

was a 50.83 m copper pipe with nominal diameters of 25.4 and 76.2 mm, internal diameters of  $D_1 = 22.14$  mm and  $D_2 = 72.94$  mm, and a wall thickness  $e_0 = 1.63$  mm. The length of the segment of the pipeline with an internal diameter of 22.14 mm was 13.23 m. The upstream end of the pipeline was connected to a larger water main that served as a reservoir to the system and the downstream end was a closed in-line valve (creating a dead end). The element that would induce the head accumulation is represented by a segment of the pipe with a smaller diameter.

A transient wave was generated in the downstream segment of the pipeline by sharply closing a side-discharge solenoid valve located 12.87 m upstream of the closed in-line valve. The valve closure time was estimated as 3 ms. Head variation responses were measured at the side-discharge valve with a sampling rate of 10 kHz. The pressure transducer was a Druck PDCR 810 with an absolute pressure range of 0–15 bars. The pipeline system is illustrated in Fig. 8.

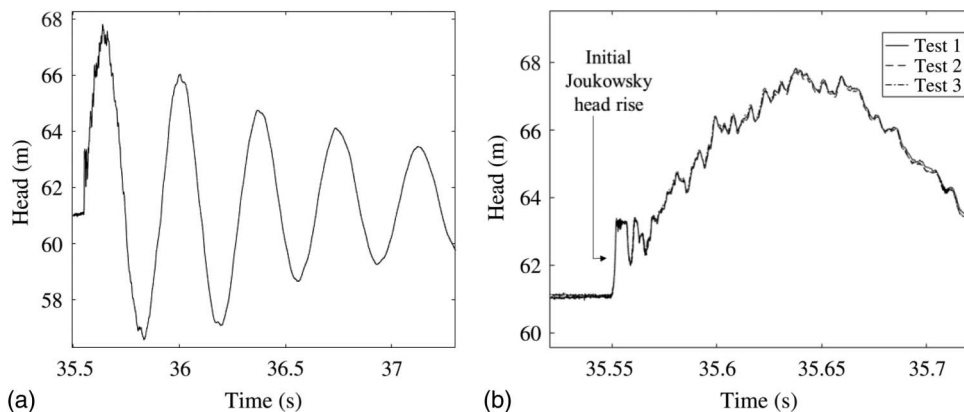
### Experimental Head Variation Traces

Several tests were conducted to verify the repeatability of the experiments using the same pipeline configuration. The head trace obtained for Test 1 is shown in Fig. 9(a). The transient response of the system shows signal attenuation due to the dissipation of the head in the pipeline. However, in the first  $4L_2/a$  s, the head rises in comparison with the value associated with the initial generated transient wave.

Fig. 9(b) presents an enlarged view of Fig. 9(a) for the first  $4L_2/a$  s for three different tests. In this figure, it is evident that the existence of head accumulation occurs in the pipeline, considering that the initial head rise was 2.16 m for Test 1. This figure shows that the results between different tests are similar with a reflection in the middle of the first plateau that will be discussed later in the paper.

### Determination of Wave Speed and Impedance

The preceding head variation traces were used to observe and analyze the head accumulation in the pipeline; however, a second pressure transducer (located 12.2 m upstream of the first pressure transducer) was installed to determine the wave speed of the downstream section of the pipe. An enlarged plot for the initial head rise for Test 1 (Fig. 10) shows that the transient wave front of the incident transient wave is not a vertical step, but is a curve with a total rise time of 3 ms. This transient wave front travels along the pipe, reaching the second pressure transducer with a certain delay. Using



**Fig. 9.** (a) Experimental head trace of Test 1; and (b) enlarged view of the wave for three different tests.

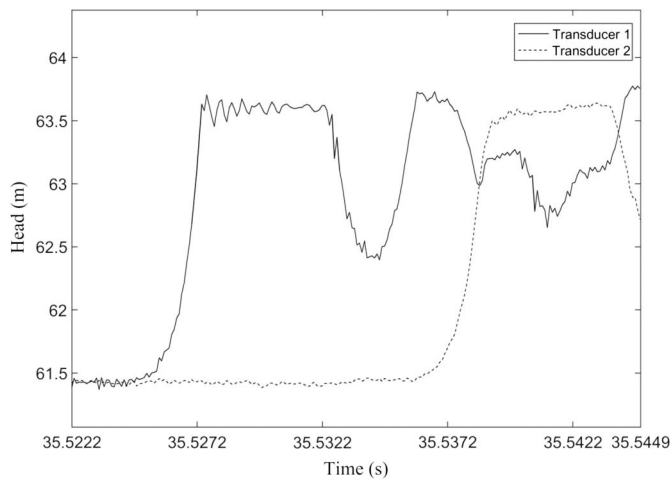


Fig. 10. Wave front in transducer 1 and transducer 2.

these two traces, the wave speed in the downstream segment of the pipe of diameter 72.94 mm was estimated to be 1,060 m/s, which corresponds to the results presented by Wang (2002).

On the other hand, to estimate the wave speed of the upstream segment of the test pipeline, the formula proposed by Wylie and Streeter (1993) was used, considering a parameter  $c_1$  of 1.0 and obtaining a wave speed of 1,198 m/s. The steady-state head was estimated to be  $H_o = 61.43$  m by calculating the average of the head values within a short time interval before the valve closure. In the same way, the incident transient wave can be estimated to be  $H_A = 63.59$  m by averaging the head between 35.527 and 35.533 s. As a result, the magnitude of the incident transient wave is determined to be  $\Delta H_i = 2.16$  m. Finally, the impedance of the upstream segment of the pipeline was calculated to be 317,200 s/m<sup>2</sup> and the impedance of the downstream segment was 25,860 s/m<sup>2</sup>.

### Determination of Head Accumulation

Using the information related to the initial conditions of the system and the initial generated transient, an analysis of the potential and real head accumulation was conducted. Table 4 summarizes the relevant characteristics of the pipeline to use the set of equations proposed in this paper. Considering the dimensions of the pipeline, a maximum head accumulation was not expected, mainly due to the length of the upstream segment. However, the verification was made using Eqs. (15) and (16). The time of arrival of the first transient wave from the upstream reservoir ( $t_R$ ), assuming a vertical step wave, is 0.057 s. On the other hand, with the information in Table 4 and a threshold of  $\varepsilon = 1\%$ , Eq. (17) states that to reach the maximum potential head accumulation in the pipeline, 29 accumulation cycles are required, which would take 2.78 s.

Table 4. Experimental setup characteristics

Characteristic	Experimental verification
Length of Pipe 1, $L_1$ (m)	13.23
Length of Pipe 2, $L_2$ (m)	50.47
Length to transient generator, $L_G$ (m)	12.87
Wave speed Pipe 1, $a_1$ (m/s)	1,198
Wave speed Pipe 2, $a_2$ (m/s)	1,060
Hydraulic impedance Pipe 1, $B_1$ (s/m <sup>2</sup> )	317,200
Hydraulic impedance Pipe 2, $B_2$ (s/m <sup>2</sup> )	25,860

Therefore, a maximum head accumulation will not occur under these conditions.

Fig. 8 shows that the upstream segment responsible for the head accumulation is shorter than the pipe in which the transient is generated. Thus, a dramatic accumulation was unlikely. Using Eq. (18), only one head accumulation cycle is likely to develop in the system, resulting in a head accumulation of 7.99 m as calculated with Eq. (12). This result implies that the head in the pipe by the end of the head accumulation phenomena would be 69.41 m.

For the conducted laboratory experiment, the set of equations proposed successfully predicted the maximum head with an error of 1.9% (considering that the maximum head obtained in the laboratory was 68.13 m). Differences in the results are associated with two features of the experimental setup: valve maneuverability and extra transient wave reflections. First, even with the use of a solenoid valve, the closure of this element is instantaneous, thus it generates a transient wave front that is not vertical (as shown in Fig. 10) compared with the instantaneous closure considered to obtain the proposed equations.

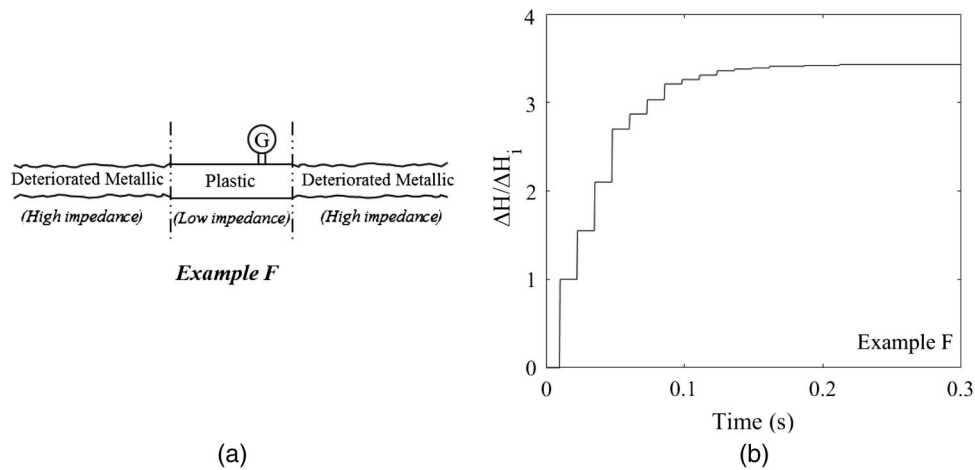
Second, the presence of additional features in the pipeline might have affected the reflections of the incident transient wave and therefore, disturbed the head accumulation process. In Fig. 10, a drop in head is visible after the arrival of the first transient wave. This head drop corresponds to the presence of a flow meter that has different characteristics (cross-sectional area and wave speed) from the pipeline and might have altered the head accumulation in the rest of the experiment. Regarding possible sources of error in the equations, neglecting the effect of the friction (including unsteady friction) in the system can influence the predicted maximum head accumulation. An analysis of the experimental setup can be conducted using the preceding non-dimensional equations, but is not shown in the paper for the sake of brevity.

### Potential Head Accumulation in Real Systems

The development of head accumulation can be present in more complex systems, such as real water distribution networks. Even if the potential maximum head accumulation described in Eq. (13) and observed in numerical experiments is unlikely to develop given the presence of different sources of head dissipation in the system (e.g., junctions), a partial head accumulation (as observed in the experimental example) can still be present if a transient wave travels from a small impedance section to a larger impedance section. Several situations could trigger this head accumulation. This section presents two of them: (1) a plastic replacement pipe section of a short segment in a deteriorated metallic pipe (Example F); and (2) the supply of a larger water main through a smaller main due to maintenance (Example G).

Example F is presented in Fig. 11(a), where a segment of a deteriorated metallic pipe has been replaced with a plastic section. The lengths and other physical properties of this system are not presented for brevity, but the impedance of the plastic section is considerably smaller than the two segments of metallic pipe, mainly due to the smaller wave speed. The transient event is generated at any point along the plastic pipe, which in a real system could be represented by the sudden change in the consumption of water or a fire test at an existing connection.

The head accumulation would only occur if the transient event was triggered in the small impedance section. If, to the contrary, the event is generated in the metallic section, the plastic section helps to dissipate the head as established by Pezzinga and Scandura (1995) and Gong et al. (2018). The magnitude of the initial head rise depends on the change of flow in the pipe. If the change is larger, then



**Fig. 11.** Replacement by a plastic pipe section in a deteriorated metallic pipe: (a) system description; and (b) normalized head accumulation at generation (G) point.

the initial head rise would also be larger, resulting in a larger head accumulation at the end, as shown in Eq. (13).

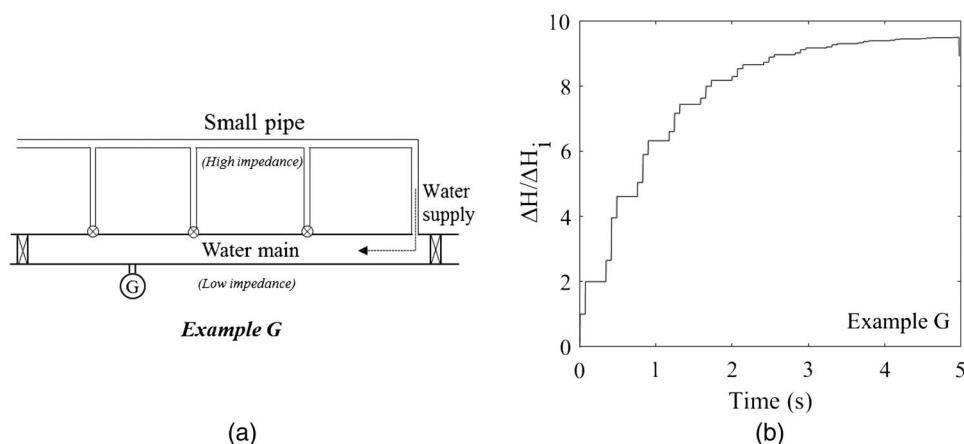
Fig. 11(b) shows the evolution of the head (normalized with respect to the initial transient head rise) in the plastic section at the generation point. The lengths of the surrounding deteriorated metallic have been assumed to be long enough to allow the full development of the head accumulation event. The final head rise is almost 3.5 times larger than the initial head rise and the non-dimensional head accumulation ( $\Delta H/H_0$ ) was 0.67, which, according to the classification presented in Table 3, is a *moderate* head accumulation event. The main value that controls how much the head accumulation event develops is the relative release time, and this value is related to the length of both pipes. Therefore, if the replaced segment is shorter, a full or at least more severe head accumulation event could develop, even if the surrounding pipes are not that long. This example was chosen because the replacement of short pipe segments is a common practice in real water distribution systems, especially after burst events or localized major leaks. When a segment of pipe is replaced, often little attention is allocated to the new segment, but the generation of transient events through a user or an industrial connection in these sections could actually be very harmful for the system.

The second example (Example G) that illustrates that the head accumulation events can develop in real systems is shown in

Fig. 12(a). In this situation, the flow on a large water main has been interrupted due to maintenance (or other) reasons. However, supply is still needed in part of that main due to the existence of important users in the area and is provided through a smaller pipe (shown in the upper part of the figure). The water main represents the pipe with a small impedance, mainly due to its larger cross-sectional area, for this analysis and both pipes are assumed to be metallic.

The transient event is generated at point G and may again represent a user or a fire test that is triggered in the larger water main. Fig. 12(b) shows the normalized head accumulation ( $\Delta H/H_i$ ) for this example, where again, for brevity, the physical characteristics are not presented. The head accumulates, reaching a value of 9.5 at the end of the trace. If the non-dimensional head accumulation ( $\Delta H/H_0$ ) is computed, its value is 2.66, meaning that under these conditions the head accumulation event would be *extreme*. This figure also shows that the head accumulation happens quickly, in less than 5 s, which in a real situation could represent a dangerous situation for the system.

The use of this configuration is common in real systems, especially when maintenance activities are scheduled. Supply for the water main needs to be guaranteed and the small pipes can help with this. For this case, the head accumulation event could be worse if the differences in the diameter between the two pipes are greater since this would increase the difference in the hydraulic



**Fig. 12.** Supply of a water main through a small pipe: (a) system description; and (b) normalized head accumulation at generation (G) point.

impedances. In addition, after the maintenance activities, it is possible that the valves are not fully opened to reestablish the normal supply and the system may end up working with the shown supply configuration, increasing the probability of the occurrence of the head accumulation events.

The previous situations are just two examples that could occur in real water distribution systems, causing head accumulation events. In addition, the partial replacement of long segments of deteriorated pipes or sudden valve openings can also induce these kinds of events. In general, different circumstances could generate this head accumulation and further research is required to understand the impact of this phenomenon in real systems and how it can be related to the sudden failure of pipelines.

## Conclusions

An analysis to understand and characterize the superposition of waves that causes the accumulation of head in a pipeline after a transient event has been presented. The succession of transient wave reflections when a side discharge or inline valve is fully closed in a pipeline has been described in terms of the different stages involved to characterize a full cycle of head accumulation. By analyzing the repetitive cycles of head accumulation, the potential maximum head can be computed using Eq. (13). This expression showed that the maximum head is directly related to the ratio between the hydraulic impedances of the two pipes; the larger the ratio of the impedances, the larger the head accumulation in the pipe where the transient event was generated.

The case for the head accumulation in a pipe with a shorter connecting pipe has also been analyzed. The maximum head accumulation in this situation depends on the relation between the pressure release time  $t_R$  and the head accumulation development time  $t_{NT}$ . Based on this comparison, the number of expected head accumulation cycles can be estimated and with this estimation, the expected maximum head can be estimated. Numerical simulations, using the MOC, have shown that the expressions can adequately predict the maximum head when the hydraulic impedance and the length of each pipe are known. Depending on the interrupted stage of the cycle, when a reflection from the upstream reservoir arrives back at the junction, the estimation can be slightly different since the additional reflections that influence this interaction have not been considered.

A classification for head accumulation events has been defined using a non-dimensional approach. By determining the ratio of hydraulic impedances and the non-dimensional release time (values that can be estimated with the physical characteristics of the pipeline), the head accumulation can be classified as mild, moderate, severe, or extreme and the final value for this head accumulation can be estimated if the initial transient head rise is available or can be computed. A non-dimensional plot has been presented to develop the analysis graphically and for one example, the plot including the categories has been shown.

The proposed analysis was also applied to experimental data obtained from a pipeline with two segments, one with a larger pipe diameter. The existence of the head accumulation was confirmed. The comparison between the maximum head measured and the estimated head using the proposed equations showed that in the experimental test setup, only one head accumulation cycle could occur, and the maximum head was determined with a slight discrepancy.

The numerical analysis and the laboratory validation have shown that it is possible to observe a head accumulation instead

of head dissipation in certain pipeline configurations. Two real situations in which this could happen have been discussed to demonstrate that the head accumulation develops under certain common circumstances in real distribution systems. Further analysis of this phenomenon should be conducted to identify additional configurations that cause this phenomenon and to attempt to understand how severe its consequences can be in more complex systems. The impact of pipe impedance changes may need to be considered throughout the operational life of the pipe system rather than just in the design phase.

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