# Water hammer in a pipe network due to a fast valve closure
## Golpe de ariete en una red de tuberías debido al cierre rápido de una válvula

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**Abstract**

*Water hammer in pipe networks is a subject little discussed in the technical literature. This may be due to the belief that the network shape helps to reduce its impact, since the pressure waves would tend to subdivide as they propagate through the system pipes. In this article the water hammer is analysed in a pipe network due to the closure of a valve modelled how if it were of type butterfly, gate circular, gate square, ball, needle and globe. It is concluded that the extreme pressure values depend on the type of valve which it is being closed, and that the network shape is not a relevant factor that it helps to attenuate the transient pressures.*

*Keywords: Method of Characteristics, valve, water distribution system, water hammer*

**Resumen**

El golpe de ariete en las redes de tuberías es un tema poco discutido en la literatura técnica. Esto puede deberse a la creencia de que la forma de la red ayuda a reducir su impacto, ya que las ondas de presión tienden a subdividirse a medida que se propagan a través de las tuberías del sistema. En este artículo, se analiza el golpe de ariete en una red de tuberías debido al cierre de una válvula modelada como si fuera de tipo mariposa, compuerta circular, compuerta cuadrada, bola, aguja y globo. Se concluye que los valores extremos de la presión dependen del tipo de válvula que se está cerrando, y que la forma de la red no es un factor relevante que ayude a atenuar las presiones transitorias.

Palabras clave: Método de las Características, válvula, sistema de distribución de agua, golpe de ariete

## 1. Introduction

Water hammer is a hydraulic phenomenon manifested through excessive changes in pressure when the fluid velocity is altered due to handling or failure of hydraulic devices (valves, pumps, etc.), changes in water demand, human errors, etc. (Bergant et al., 2010; Malekpour et al., 2015). The change in pressure mainly depends on the cause of the transient; point location of the disturbance and the shape and configuration of the system, pipe size and constituent material, etc. It also exerts influence the transient friction, air content in the water, fluid-structure interaction, water demand at the nodes, frictional losses due to small lateral pipes, and the interaction of pipes and connections with the surrounding soil. Jung et al. (2007) recognize that the transients are inevitable in large water distribution systems (WDS) and that they normally occur due to activation of valves and pumps, and that adequate protective measures are required, especially in cases where it should prevent the cavitation and subsequent water column separation effect. Several authors have reported the occurrence of excessive changes in pressure in pipe networks due to the water

hammer effect. For example, Karney and McInnis (1990), analyzing a very simple system, show that pipe networks can exacerbate rather than reduce pressure surges. Lindley (2001) and Nadeem (2001) analyze the activation of fire hydrants and the WDS susceptibility to negative pressures and intrusion of contaminants. LeChevallier et al. (2003) recognizes the water hammer existence in WDS's and its responsibility in the contaminant intrusion due to negative pressures. Fleming et al. (2005) detects negative pressures in 5 large pipe networks due to pump shutdown, valves activation, pipe breaks, etc. Svindland (2005) studies the detection and duration of events associated with negative pressures in a WDS. Boulos et al. (2005) and Wood et al. (2005) analyzed the pressure fluctuation in complex networks, recognizing that water hammer can cause contaminant intrusion affecting the quality of treated water. Ebacher et al. (2011) recognizes that a growing interest in the occurrence of negative pressures in drinking water distribution systems and their potentially adverse impact on tap water quality appears in the literature, and that to more accurately estimate the WDS' propensity for intrusion, confirmatory research requires the comparison of transient model output and field data. Daviau and Alkozai (2013) analyze the water hammer generated by the pump off in a WDS, verifying the existence of mild transient caused by several factors. Starczewska et al. (2014), when analyzing water hammer in pipe networks, concludes that pressure

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waves spread through the WDS, and in some cases the system configuration can help increase pressure surges depending the place and how the transient is generated. Skulovich et al. (2014) and Wang et al. (2014) indicate that quantitative analysis and management of transient flow started only recently for WDS, and that the advance of data processing allows many water hammer models to be accessible to engineers and modellers, and that the computer model system can not only improve work efficiency, but also provide the technical support for the operation and maintenance of the entire water supply network economically. Jung and Karney (2016) affirm that since all flows will eventually be altered, either suddenly or gradually, over a system's life, all pipeline systems inevitably experience transient effects generated by changes associated with routine operational adjustments, human error, equipment breakdowns, earthquakes, or other disturbances. Wang et al. (2016) indicate that sudden control actions in pressurized pipeline systems, whether caused by pumps or valves, can sometimes induce dramatic flow and pressure fluctuations, and that the combination between effects of liquid column separation (LCS) and water hammer may generate maximum pressures greater than the Joukowski pressure. It is estimated that as much as 70-80% of damage-causing events are associated with LCS related effects. Recently, the professor emeritus Benjamin Wylie expressed to in relation to a water hammer event which it affected to a city of 300,000 inhabitants in Oakland County (Detroit Free Press, 2017): "if you have water flowing at a high velocity in a pipe, and all of a sudden there's stoppage then there's a high-pressure build-up, maybe 100 times the velocity of the water. The high pressure propagates in the pipeline, reflecting off the end opposite the valve closure and coming back, oscillating back and forth, over and over, moving at the speed of sound. This effect can cause a pipe to burst at a weak point causing a weak pipe to collapse. The best, easiest way to protect pipelines is to have slow valve closures, but if it's a remotely operated valve closure, a malfunction can lead to a rapid closure." Depending on the pipe network importance, the water hammer damage can increase the economic, social and health costs due to: (i) high pressures which can destroy the pipe wall; (ii) pressure impulses which can affects various structural elements, with pipe displacements, flange damages or water leaks; and (iii) pressure oscillations (Sumskoi et al., 2016), all of which can cause cuts in the water supply and risk of contaminant intrusion into the system. Equations governing the transient flow along with wave speed and Method of Characteristics (MOC) formulation are extensively discussed in the classic books by Wylie and Streeter (1978) and Chaudhry (1979). These topics can also be studied in recent articles by Twyman (2016a, 2016b, 2017a). Finally, it is possible to study how to pose and solve boundary conditions within the MOC's context in Karney and McInnis (1992), so no further details will be given here.

## 2. Material and methods

### 2.1 Pipe, section and boundary condition

According to Karney and McInnis (1992), once a time step ($\Delta t$), has been selected, the MOC divides most conduits in the network into one or more reaches of length $\Delta x$. The term pipe is henceforth restricted to conduits that contain at least one characteristic reach. The end of each reach, where head and flow values must be determined, is called a section. At each end of the pipe an auxiliary relation between head and discharge must be specified. Such a head-discharge relation is called a boundary condition.

### 2.2 Equation for the simple node

The term node (or junction) indicates a location where boundary sections meet. For a frictionless multi-pipe junction, the following Equation 1 applies (Karney and McInnis, 1992):

$$H_P^{t+\Delta t} = C_c - B_c \cdot Q_{ext} \tag{1}$$

Where $t$ = current simulation time, $H_P^{t+\Delta t}$ = junction head, $C_c$ and $B_c$ are known contants, and $Q_{ext}$ = external flow (positive when is assumed to be from the junction). Equation (1) allows calculate $H_P^{t+\Delta t}$ at the junction for any number of pipes meeting at the node.

### 2.3 Equation for the reservoir

If hydraulic losses between the reservoir and the pipe junction are negligible, the nodal head equals the surface elevation of the reservoir, being valid the following expression (Karney and McInnis, 1992):

$$Q_{ext} = (C_c - H_0 - B_0 \cdot Q_e) \cdot (B_c + B_0)^{-1} \tag{2}$$

Where $H_0$ = reservoir head at the beginning of the time step, $B_0 = \Delta t/2A_r$, with $A_r$ = cross-sectional area of the reservoir, and $Q_e$ = initial external discharge. Note that if the constant $B_o$ is zero, the reservoir head is independent of the external discharge. The term $H_0$ may be either constant or a known function of time (e.g., waves on a reservoir). Equation (2) can be used to represent constant head reservoirs, storage tanks, and simple surge tanks.

### 2.4 What is a Valve?

It is a device that regulates, directs or controls the fluid flow by opening, closing, or partially obstructing various passageways (Al-Juhani, 2012). Among its main functions highlighting: stopping and starting fluid flow, varying (throttling) the amount of fluid flow, controlling the direction of fluid flow, regulating downstream system or process pressure, relieving component or piping over pressure.

### 2.5 General valve classification

**Linear motion valve**

It is characterized by its stem which it moves in a straight line to allow, stop, or throttle the flow (e.g., gate and globe valves).

**Rotary motion valve**

It is characterized by its stem which it moves along an angular or circular path (e.g., butterfly and ball valves).

**Quarter turn valve**

Some rotary motion valves requires approximately a quarter turn, 0° through 90°, where the stem motion goes to

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fully open from a fully closed position or vice versa (e.g., butterfly and ball valves).

### Ball valve

Ball valve is valued for its longevity and its ability to work perfectly after years of disuse. Inside a ball valve, a metallic sphere has been drilled through from one end to the other. Attached to the top of the sphere is a lever whose range of movement is just a quarter-turn. One advantage to the quarter-turn valves is that they can be shut off quickly. The disadvantage is that this makes water hammer more likely. For that reason, it is best to turn the lever on a ball valve slowly.

### Gate valve

A gate valve is operated with a wheel that moves a gate up and down. When the gate is in the lowest position, it blocks the flow of water; when it is in the highest position, water can flow freely. Gate valves are susceptible to corrosion, which it can prevent them from opening or closing fully. A heavily corroded stem can even break, rendering the valve useless. Because of it opens and closes slowly, gate valve will not create water hammer. They should be used only in the fully open and fully closed positions. If the gate valve is left partially open, then it will vibrate and possibly it will become damaged.

### Globe valve (also known as linear motion or rising stem)

Unlike ball valves and gate valves, globe valves are designed for limiting the flow of water. They are operated with a wheel and a stem like gate valves, but the stem is attached to a stopper that seals shut a baffle, essentially two half-walls that force the water to flow in a Z-pattern. Because of the baffle makes it impossible for water to flow through the valve freely, even in the fully open position, a globe valve reduces water pressure. That reduction makes the stopper and seat less vulnerable to damage. For water to flow through a globe valve efficiently, the valve must be installed so that the water encounters the top half-wall first.

### Needle valve

In this valve the shape of the closure member consists on a threaded stem with a conical end. Stems with fine threaded have a slow linear movement when they turn, therefore a great number of turns are needed to have a full flow section. This makes the needle valve suitable for regulating flow, with a minimal waste and without cavitation at important differential pressures. The slow opening and regulated closure of the needle valve avoid cavitation and water hammer in the pipeline system.

### Butterfly valve

In a butterfly valve the flow is regulated through a disc-type element held in place in the centre of the valve by a rod. Similar to ball valves, valve operation time is short because of the disc-type element is simply rotated a quarter turn (90°) to open or close the passageway. It is characterized by its simple construction, lightness in weight, and compact design. Their face-to-face dimension is often extremely small, making the pressure drop across a butterfly valve much smaller than globe valves. Materials used for the disc-type element and sealing they can limit their applications at higher temperatures or with certain types of fluids. Butterfly valves are often used on applications for water and air, and in applications with large pipe diameters.

### Valve closure

Operation of key flow control facilities such as valves, especially for the emergence scenarios, it is of great importance to ensure safety of water transmission systems. For many installations the provision for rapid flow shutoff is of particular importance, especially in emergency conditions (Nerella and Rathnam, 2015). These cases require a short valve closure time and therefore the closure arrangement has great importance in reducing the maximum pressure head rise (Karney and Ruus, 1985). Although a fast valve closure enables engineers to reduce water loss under emergence conditions but likely results in pressure surge or water hammer that may cause disastrous pipe bursts (Yu et al., 2010). For that reason, its proper simulation has great relevance even more knowing that the magnitude of a pressure surge associated with a valve closure largely depends on the water velocity, valve closure time and closure arrangement (Karney and Ruus, 1985; Kodura, 2016). During the closure of the valve, the pressure head along the pipe rises and reaches a maximum. This maximum can occur during or at the end of the closure operation. The magnitude of the maximum pressure head and the instant when it occurs largely depend on the valve opening versus time relation. Valve closure arrangements are often classified on the basis of the duration of the closure movement. Instantaneous closure refers to a closure arrangement where the time of closure approaches zero, whereas the term sudden closure refers to a closure time of less than $2L/a$ s ($L$ = pipe length, $a$ = wave speed). In general, the shorter the closure time, the greater the pressure head rise. However, the very maximum pressure head rise occurs at the valve end for all closures occurring in $2L/a$ (s) or less (Karney and Ruus, 1985). If flow passes into a reservoir through a restriction, a general loss and storage expression may be derived, which it can be used to represent valves or orifices discharging to linear reservoirs or to atmosphere. The external flow is related to the head at the junction by the orifice expression (Karney and McInnis, 1992):

$$Q_{ext} = s \cdot \tau \cdot E_s \cdot (s \cdot [H_P - H_P^c])^{1/2} \qquad (3)$$

In which $s$ = sign of the external flow [i.e., $s$ = sign $(Q_{ext})$ = ±1] and $H_P^c$ = head at the node side of the connector. The terms $\tau$ and $E_s$ in (3) are valve or orifice parameters; by convention, $\tau$ = 1.0 implies a fully open valve, while a value of zero requires the valve to be closed. Opening and closing valves can be represented if $\tau$ is a function of time. The valve scaling constant $E_s$ represents two values: $E_+$ for flow from the network when $s$ = +1.0 and $E_-$ for negative flow. The values of these terms are determined by knowing $H_P$, $H_P^c$, $\tau$ and $Q_{ext}$ for one positive and one negative flow (further details in Karney and McInnis, 1992).

## 3. Results

Pipe network consists of 45 pipes and 29 nodes (Figure 1) is solved. Two boundary conditions (1 constant head reservoir and 1 valve) are depicted in the drawing as well as two nodes with a fixed demand (pressure-insensitive) of $q_0 = 50$ L/s (node 8) and $q_0 = 15$ L/s (node 21). Except for pipes 8, 15, 30, 36 and 43 which have 169.7 (m) in length, all the pipes have 120 (m) in length, and the pipe diameter ranging between 75 (mm) and 200 (mm). The nodes have different elevations (z) ranging between 22 m (node 1) and 8 m (node 29). Because of the pipes have different constituent material the wave speed is equal to 1,037-1,102 (m/s) in 13 steel pipes, 778-881 (m/s) in 4 copper pipes and 181-209 (m/s) in 28 PVC pipes. Pipe network was subdivided into a total of 508 reaches, with $\Delta t = 0.038$ (s), which it corresponds to the time step selected for the computer simulations. The Courant number is equal to 1.0 for all pipes after applying the discretization procedure described in Twyman (2016a, 2017b). The following assumptions are adopted in order to simplify the numerical analysis: friction factor (Darcy) is steady (with values ranging between $f = 0.017$ and $f = 0.037$), water has zero air content and no air pockets exist in the pipes. The supporting condition of different system components (pipes, valves, etc.) is such that it prevents the longitudinal movement, the fluid-structure interaction or an interaction between the pipe and the surrounding soil.

Other assumptions of the analysis are: the pipe diameters are constant; the valve is located at downstream end of the pipe 45 and its closure arrangement is from a fully open to a totally closed position, the network has not water leaks which could affect the flow or pressure. The system has not anti-surge devices (surge relief valves, air-vacuum valves, accumulation devices, etc.) or emergency controls to mitigate inadmissible transient pressures. Steady-state flow was solved using EPANET (Rossman, 1993), and the transient flow was solved applying the MOC traditional version. The state variables were calculated in a fixed and square space-time mesh (Twyman, 2017a). All simulations were carried out in a standard PC (32 bits) with 1.2 (GHz) of processing speed.
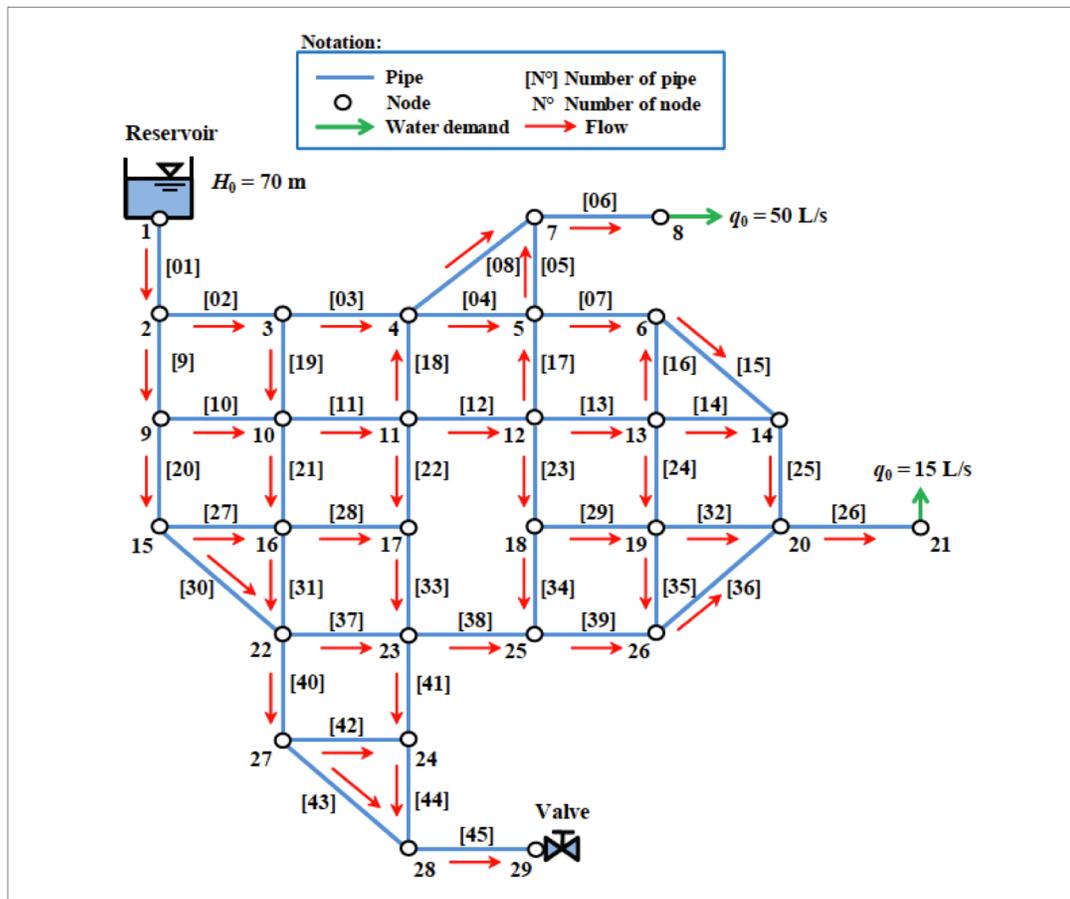


**Figure 1.** Diagram of the network

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## 4. Application example

Figure 2 shows the relative valve openings 2 muestra las aperturas relativas de las válvulas (τ) as a function of time which they will be applied. In all cases the valve closure time is equal to 1.0 (s). Valve closure curves were interpolated using the Newton-Gregory approach with interpolation order equal to 1, which it allows generate more accurate and efficient solutions in computational terms (Twyman, 2018). Figure 3 show what it happens at node 29 when valve closure curve is modelled using the relative valve opening ($\tau$) arrangements shown in Figure 2. Table 1 shows the maximum and minimum pressures in the network according to the simulated type of valve.
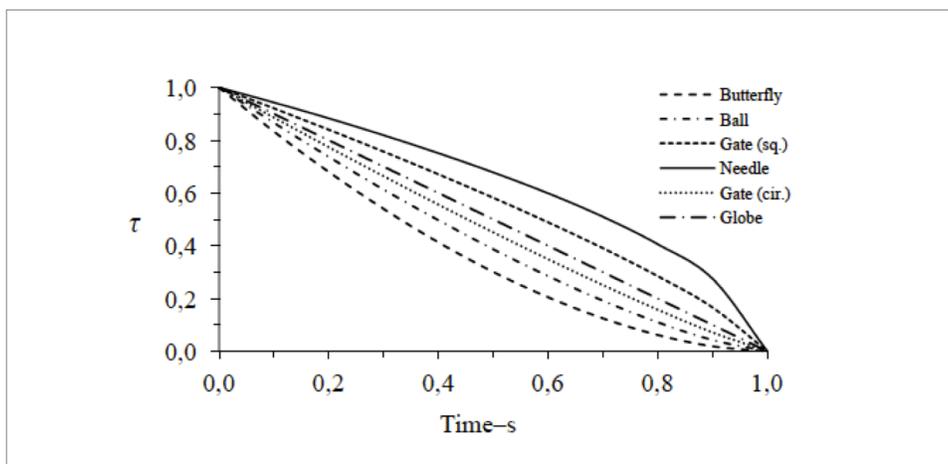


**Figure 2.** relative valve opening () for different type of valves (closure time = 1.0 s).
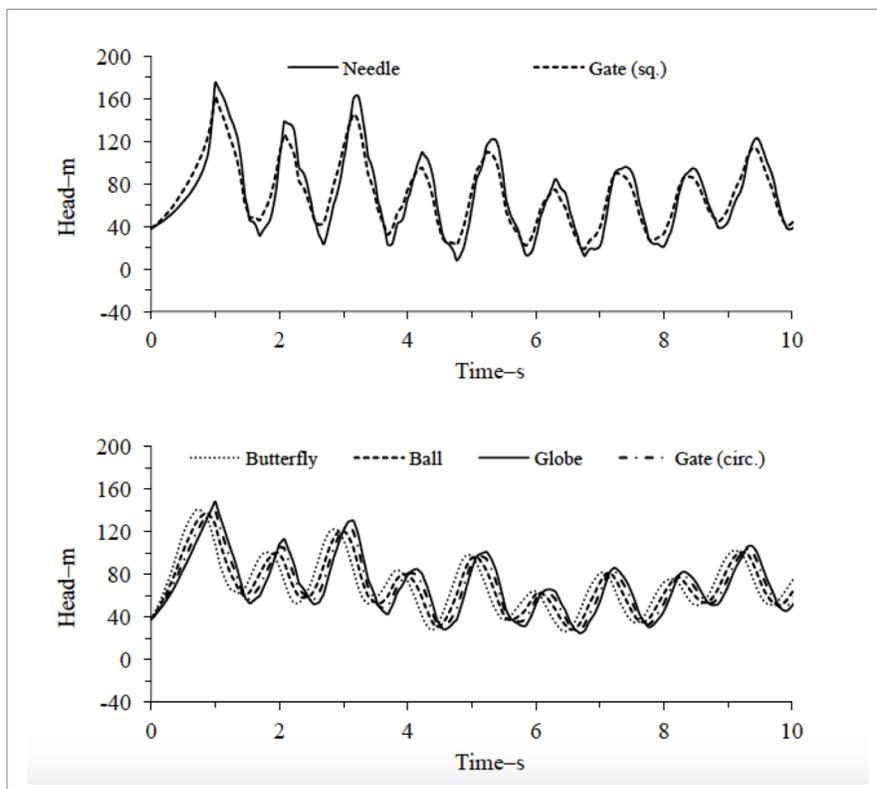


**Figure 3.** pressure as function of time at node 29

Table 1. maximum and minimum head pressures (Max P, Min P)

| Type of valve | Max P (m) | Location | Min P (m) | Location |
|---|---|---|---|---|
| Needle | 183 | Pipe 45 (valve) | 16 | Near the middle section of pipe 42 |
| Gate (sq.) | 169 | Pipe 45 (valve) | 25 | Near the middle section of pipe 42 |
| Butterfly | 148 | Pipe 45 (valve) | 31 | Near the middle section of pipe 42 |
| Uniform | 148 | Pipe 45 (valve) | 20 | Near the middle section of pipe 42 |
| Ball | 145 | Pipe 45 (valve) | 31 | Near the middle section of pipe 42 |
| Gate (circ.) | 139 | Pipe 45 (valve) | 21 | Near the middle section of pipe 42 |

# 5. Discussion and conclusions

Figure 3 shows that regardless of the valve type chosen, in all cases the maximum pressure occurred at node where the valve is located and the minimum pressure occurred near the middle section of pipe 42. After 10 (s) of simulation time the pressure continues oscillating without dissipating completely. Despite that pipe network has both a relatively intricate shape and 62% of PVC pipes, where it is expected that PVC flexibility significantly reduces the acoustic velocity and thus the resulting water hammer pressures (Malekpour et al., 2015), it was unable dissipate quickly the transient flow generated by the valve closure. WDS has inability of attenuating waves due to transmission, reflection and superposition effects associated to pressure waves, generating significant maximum and minimum pressures, with risk of exceeding the maximum allowable incidental pressure (expressed as a factor of the nominal pressure class PN) included in some regulations as those mentioned by Pothof and Karney (2013). Another interesting point is that the magnitude of the extreme pressures varies depending on the type of valve which it is being simulated. For example, the maximum pressure registered by needle and gate (square) valve-types is, in average, 21% greater than the maximum pressure registered by the butterfly, globe, ball and gate (circular) valves, the first ones with a concave shape and the latter ones with a convex shape. In the case of needle, gate (square, circular) and globe valves the pressure reaches the first peak value at $t = 1.0$ (s), which it corresponds to the valve closure time; for butterfly and ball valves the pressure reaches the first peak value at $t = 0.9$ (s), value lower than the valve closure time. This result reinforces the importance of the transitory evaluation from the beginning of the closing operation, and not only after the valve has closed. In relation to the minimum pressures, the needle and gate (sq.) valve types register values that are, in average, 19% lower than the minimum pressures registered by the butterfly, globe, ball and gate (circular) valves. This shows that, apart from the closing time of the valve, the shape of the closing curve (concave, convex) exerts an influence on the magnitude of the extreme pressures. According to the results shown in Table 1, the

it yields the most suitable range of extreme pressure head optimum closure is given by the gate (circular) valve because rises, even though the optimum closure arrangement is not unique. This is it because factors such as the pipe wall friction or the maximum prescribed pressure head rise influence the shape of the optimum closure curve, so that for each combination of these variables, there is a different optimum closure curve. Theoretically speaking the system topology and the steady friction are ineffective as pressure dissipation mechanisms, although Karney and Filion (2003) argues that system topology greatly complicates the "micro" transient behaviour of a system by increasing the number of small pressure waves which move quasi-independently to communicate and regulate mass imbalances in the system. It is speculated that this increased hydraulic activity can potentially accelerate the amount of energy dissipated by means of the unsteady component of fluid friction. The capacity of WDSs to tolerate occasional water hammer pressures it is should not be the only consideration during the design stage because if the transient pressures occur quite frequently in the system, an additional check is still required to ensure that the pipes are safe against fatigue. Finally, is important to keep in mind that transient flow modelling is an essential requirement to predict possible damages caused by extreme pressures, it being important that every design engineer understands that equations that govern the transient flow contain limitations, this being an important point to judge the reliability of the results, avoiding misuse of available numerical models. At this point it is relevant to know the advantages, disadvantages and numerical limitations of MOC (and other schemes) when it is used to verify and/or study the operation of a system under transient conditions, or when it is applied to select/dimension the protection elements against the effect of pressure waves. Given the adopted assumptions it is possible to ensure that the result obtained by the MOC is reasonably conservative although less realistic. MOC version applied in this article does not incorporate some effects (unsteady friction, pressure-sensitive demands, air-content in the water, etc.) which they tend to change the magnitude, frequency and shape of the pressure waves. Generally, these pressure changes are described in form of

attenuations, causing pressure waves to tend to decay due to associated energy dissipation mechanisms. For that reason, as future work is propose to model the pipe network relaxing some of the assumptions initially adopted, for example considering that friction is transient, water demand is pressure-sensitive and water contains air.

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