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Numerical Investigation of Water-Hammer Mitigation in Restrictive Pipelines Using a Dipping Tube Tank

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ABSTRACT

Water hammer is a severe hydraulic transient phenomenon that generates destructive pressure surges in pressurized pipeline systems, especially in the presence of flow restrictions. This study aims to evaluate the performance of a compact Dipping Tube Tank (DTT) as an effective passive device for mitigating water hammer in restrictive pipeline systems. A high-resolution numerical model based on the Method of Characteristics (MOC) was developed in MATLAB to simulate transient pressure wave propagation. The system under investigation consists of a 50 m long, 1-inch Polyvinyl Chloride (PVC) pipeline subjected to rapid flow interruption, and pressure responses are analyzed at key locations along the pipeline. The unprotected system exhibited a pressure rise of approximately 6 bar and a severe pressure drop to −55 bar, indicating a high risk of cavitation. With the inclusion of the DTT, the maximum pressure was reduced to 2.5 bar, while the minimum pressure increased to −0.6 bar, effectively suppressing cavitation and significantly improving transient stability. The study presents an integrated numerical framework that captures the coupled dynamics of transient flow and air–water interaction within a compact DTT. The proposed DTT offers a compact, efficient, and cost-effective solution for protecting small-diameter pipelines, making it highly suitable for practical engineering applications where conventional surge protection devices are not feasible.

1. INTRODUCTION

Water hammer is one of the most critical transient phenomena encountered in pressurized pipeline systems, arising from rapid variations in flow momentum caused by sudden valve closure, pump shutdown, or localized hydraulic restrictions. These disturbances generate pressure waves that propagate along the pipeline at acoustic velocity, generating high positive pressure waves followed by significant negative-pressure transients. Such oscillatory pressure fluctuations may lead to vapor cavity formation, liquid column separation, structural fatigue, leakage at pipe joints, and, in extreme cases, catastrophic pipeline failure. Therefore, accurate prediction and effective mitigation of hydraulic transients remain essential challenges in hydraulic engineering [1, 2].

The theoretical framework governing transient flow in pipelines has been extensively developed in the literature. The Method of Characteristics (MOC), originally formulated by Wylie et al. [1], remains the most widely used numerical technique for solving unsteady flow equations. Chaudhry [2] further extended this framework by incorporating complex boundary conditions, cavitation effects, and wave reflections. The influence of fluid–structure interaction on transient pressure propagation was investigated by Tijsseling [3], while Bergant et al. [4] provided a comprehensive analysis of column separation and cavitation phenomena during severe transient events.

Significant efforts have been devoted to improving the accuracy of transient flow modeling. Pezzinga [5] introduced advanced formulations for unsteady flow behavior in pipelines, while Duan et al. [6] comprehensively reviewed unsteady friction models and numerical approaches for improving the prediction of hydraulic transients. More recent studies have highlighted the importance of accurate friction representation in transient simulations, particularly under rapidly varying flow conditions [7].

In parallel with modeling developments, various mitigation techniques have been proposed to control hydraulic transients. Experimental investigations demonstrated that flexible bypass systems can effectively reduce pressure surges in pipeline systems [8]. Other studies showed that optimized valve closure strategies and surge tank installations can significantly attenuate transient pressure peaks [9]. Hydro-pneumatic tanks have been widely recognized as one of the most effective protection devices for mitigating water hammer and suppressing pressure oscillations in pipeline systems [10].

Vardy [8] comprehensively reviewed the major damping mechanisms affecting pressure-wave propagation in water-hammer systems, while Meniconi et al. [9] examined pressure-wave interactions in complex pipe networks. Numerical approaches for transient modeling were presented by Arefi et al. [11], while Tjuatja et al. [12] comprehensively reviewed transient flow modeling, numerical methods, parameter calibration, and surge-control strategies in viscoelastic pipeline systems. Pipeline column separation is a critical phenomenon associated with severe hydraulic transients [13]. Air vessels are widely used for surge mitigation in pressurized pipeline systems [14]. Recent studies have shown that the selection of an appropriate unsteady friction model plays a significant role in improving the accuracy of transient pressure prediction in pipeline systems [15]. Kriaa et al. [16] experimentally investigated water-hammer mitigation in uPVC pipelines using flexible bypass tubes and demonstrated that compliant bypass elements can reduce pressure surges in plastic pipe systems. Recent studies have improved surge-tank sizing methods for hydraulic transient protection in long-distance pipeline systems [17]. Wang et al. [18] demonstrated the effectiveness of air vessels in mitigating water hammer in long-distance water supply systems using the Method of Characteristics. Zhang et al. [19] investigated water-hammer characteristics in long-distance dual-pipe water supply systems and demonstrated that surge tanks and extended valve-closure times effectively mitigate hydraulic transients. Bergant et al. [20] investigated the parameters affecting water-hammer wave attenuation, wave shape, and timing characteristics, demonstrating the importance of accurately representing transient-wave behavior when evaluating surge-mitigation strategies in pipeline systems. In addition, Hamed and Abdulaziz [21] experimentally and numerically confirmed that pressurized air vessels can significantly reduce pressure oscillations and improve system stability.

Recent investigations have also explored advanced modelling and optimization strategies for water-hammer protection. Burgos-Méndez et al. [22] evaluated simulation tools and machine-learning approaches for hydro-pneumatic tank applications. Furthermore, Zhou et al. [23] proposed interpretable machine-learning techniques for optimizing the configuration and operation of water-hammer protection devices.

Although these recent contributions have significantly improved the understanding and mitigation of hydraulic transients, a critical assessment of the literature reveals that several challenges remain unresolved. Most recent studies have concentrated on conventional Dipping Tube Tank (DTT) protection devices, including surge tanks, hydro-pneumatic tanks, bypass systems, and pressurized air vessels. While these approaches have demonstrated effective surge attenuation, they often require additional installation space, increased system complexity, or higher operational costs. Furthermore, relatively limited attention has been devoted to compact protection devices for restrictive small-diameter Polyvinyl Chloride (PVC) pipelines subjected to rapid flow interruption. Consequently, the applicability of such protection strategies in space-constrained pipeline systems remains insufficiently explored. The present study addresses this gap by investigating a compact DTT, a surge-mitigation device specifically intended for restrictive small-diameter PVC pipelines where conventional protection systems may be impractical due to space or cost limitations.

Despite the considerable progress achieved in hydraulic transient analysis and surge-mitigation technologies, several limitations remain. Most previous investigations have focused on large-scale transmission pipelines and conventional protection devices such as surge tanks, air vessels, and bypass systems. Although these techniques are effective in large installations, their application in restrictive small-diameter pipelines is often limited by space requirements, installation complexity, and economic considerations. Furthermore, only a limited number of studies have examined compact air–water interaction devices capable of simultaneously suppressing positive surge pressures and severe negative pressure waves under highly restrictive flow conditions. In addition, the transient behavior of DTT systems has received limited attention in recent water-hammer mitigation studies when compared with the extensive research devoted to surge tanks, air vessels, and hydro-pneumatic protection systems. Furthermore, their application in restrictive PVC pipeline systems subjected to rapid flow interruption remains largely unexplored. Therefore, a clear research gap exists regarding the development and numerical evaluation of compact surge-mitigation devices specifically designed for small-scale restrictive pipelines.

To address this gap, the present study proposes and investigates a compact DTT as a passive surge-protection device for restrictive pipeline systems. Unlike conventional surge tanks and air vessels, the proposed DTT utilizes a confined air–water interaction mechanism within a compact configuration, making it particularly suitable for installations where space and cost constraints prevent the use of larger protection systems. The novelty of this work lies in integrating a high-resolution MOC model with a dynamic DTT formulation for detailed evaluation of transient pressure-wave attenuation, cavitation suppression, and pressure stabilization at multiple locations throughout the pipeline.

Unlike conventional surge-protection devices, the proposed DTT provides transient-pressure mitigation through a compact air–water interaction mechanism operating within a simplified configuration. This feature enables effective hydraulic-energy absorption and pressure-wave attenuation without the large installation requirements commonly associated with surge tanks or hydro-pneumatic protection systems. Consequently, the proposed device offers a practical alternative for restrictive small-diameter PVC pipeline systems where space and economic constraints limit the applicability of conventional surge-protection technologies.

The main contributions of the present study can be summarized as follows:

(1) Development of a numerical transient-flow model based on the MOC for restrictive pipeline systems.

(2) Formulation of a compact DTT model incorporating air–water interaction effects.

(3) Quantitative assessment of surge-pressure attenuation and cavitation suppression achieved by the DTT.

(4) Multi-location evaluation of transient pressure-wave propagation and damping performance.

(5) Demonstration of the suitability and practical applicability of compact DTT systems for protecting small-diameter restrictive pipelines where conventional surge-protection devices may not be feasible.

The remainder of this paper is organized as follows. Section 2 presents the mathematical formulation and numerical methodology, including the MOC and the DTT model. Section 3 discusses the transient simulation results and evaluates the surge-mitigation performance of the proposed DTT. Finally, Section 4 summarizes the main findings and conclusions of the study.

2. METHODOLOGY

This study adopts a numerical methodology to assess the transient hydraulic response of a restrictive pipeline system with and without the DTT. The approach integrates the classical water-hammer equations, the MOC, and a dynamic air–water interaction model for the DTT. The methodology comprises pipeline modeling, restriction modeling, DTT formulation, and transient simulation configuration.

2.1 Governing equations

Transient flow in pressurized pipelines is governed by the one-dimensional unsteady continuity and momentum equations, Eqs. (1) and (2):

Continuity equation:

$$\frac{dH}{dt} + \left(\frac{a^2}{g}\right)\left(\frac{dV}{dx}\right) = 0 \tag{1}$$

Momentum equation:

$$\frac{\mathrm{dV}}{\mathrm{dt}} + \mathrm{g}\left(\frac{\mathrm{dH}}{\mathrm{dx}}\right) + \frac{(\mathrm{fV|V|})}{(2\mathrm{D})} = 0 \tag{2}$$

where,

H is the piezometric head; V is the flow velocity; a is the wave speed; D is the pipe diameter; f is the Darcy–Weisbach friction factor.

The Darcy–Weisbach friction factor, f, was used to represent head-loss effects during transient flow. For turbulent flow conditions, the friction factor was estimated using the Swamee–Jain approximation, whereas for laminar flow conditions it may be expressed as $f = 64/\mathrm{Re}$, where Re is the Reynolds number. Since the present study considers water flow in a small-diameter PVC pipeline operating under practical engineering conditions, turbulent flow behavior was assumed throughout the simulations.

These equations capture wave propagation, fluid compressibility, and pipe elasticity.

The numerical model was developed under the following assumptions: (i) one-dimensional transient flow, (ii) uniform pipe diameter and material properties, (iii) constant water density, (iv) negligible heat transfer effects, and (v) turbulent flow conditions throughout the simulation period. These assumptions are commonly adopted in hydraulic transient analysis and are considered appropriate for the present investigation.

2.2 Numerical solution-Method of Characteristics

The partial differential equations are transformed into ordinary differential equations along characteristic lines:

$$C^{+} dV + (g/a)dH + ((fV|V|dx))/((2Da)) = 0 \tag{3}$$

$$C^{-} dV - (g/a)dH + ((fV|V|dx))/((2Da)) = 0 \tag{4}$$

The pipeline was discretized with a spatial step Δx satisfying the Courant condition:

$$\Delta t \leq a\Delta x$$

This ensures numerical stability and high-resolution capture of pressure waves during sudden closure. The complete numerical scheme, including the characteristic equations and boundary updates, was implemented in MATLAB to compute the transient flow and pressure fields.

2.3 Restriction (choke) modeling

The restrictive element is represented by the standard orifice relation:

$$Q = CdA\sqrt{(2g|Hup - Hdown|)} * sgn(Hup - Hdown) \tag{5}$$

$$sgn(x) = +1 \; if \; x > 0$$
$$sgn(x) = -1 \; if \; x < 0$$
$$sgn(x) = 0 \; if \; x = 0$$

The restriction equation controls how much water flows through the throttling element and in which direction during transient conditions. The sign function switches the flow direction automatically whenever the pressure difference changes sign. This enables the restriction to react immediately to rapid pressure changes on either side, creating a surge when the flow is suddenly stopped, and allowing reverse flow when a negative wave arrives. Therefore, this equation is essential for representing the sharp pressure changes and flow reversals that occur during water-hammer events in restrictive pipelines.

2.4 Dipping Tube Tank model

The DTT is modeled as an air–water energy-absorbing chamber governed by the polytropic relation:

$$Pa * V_a^{\gamma} = constant \tag{6}$$

with γ typically between 1.2 and 1.4.

The flow entering the dipping tube is expressed as:

$$Q_{DTT} = CdA_0\sqrt{\left(2g\left|H_p - H_{DTT}\right|\right)} * sgn\left(H_{up} - H_{down}\right) \tag{7}$$

The DTT governs a pressure-responsive water exchange between the pipe and the air-cushioned chamber. During a surge, excess pressure drives water into the tank, compressing the air and absorbing hydraulic energy. When pressure drops, the compressed air returns water to the pipe, preventing sub-atmospheric conditions. This mechanism moderates both positive and negative waves, ensuring a substantially more stable transient response.

2.5 Transient simulation setup

The model represents a 50-m, 1-inch PVC pipeline operating at 0.6 L/s under atmospheric initial head. An instantaneous downstream closure (<2 ms) initiates pressure waves propagating at 1000–1200 m/s. The pressure-wave speed was selected within the range of 1000–1200 m/s, which is consistent with values commonly reported in the literature for PVC pipelines. The wave speed depends on both fluid compressibility and pipe-wall elasticity and can be estimated using the classical water-hammer relationship. The selected range reflects typical engineering values reported in the literature for small-diameter PVC pipeline systems. Boundary conditions include an upstream reservoir, a sudden downstream closure, and, for the protected case, a dynamic air–water DTT boundary. The upstream reservoir was modeled as a constant-head boundary condition to represent a sufficiently large water source whose hydraulic head remains essentially unchanged during the transient event. This assumption is commonly adopted in hydraulic-transient simulations and provides a stable reference condition for pressure-wave propagation analysis.

The instantaneous downstream closure was adopted to represent a worst-case transient scenario and to evaluate the maximum surge-mitigation capability of the proposed DTT. Although practical valve operations generally require a finite closure time, rapid closure conditions are frequently employed in water-hammer studies to investigate the most severe pressure-wave responses and assess the robustness of surge-protection devices.

All simulations were carried out in MATLAB, which was used to numerically solve the characteristic equations and evaluate the transient response.

2.6 Model validation

The reliability of the adopted numerical methodology was assessed by comparison with the experimentally validated study reported by Hamed and Abdulaziz [21]. In their work, transient flow in a pressurized pipeline system was modeled using the MOC and validated against laboratory measurements obtained from a rapid valve-closure test rig equipped with a pressurized air vessel. The reported comparison showed excellent agreement between numerical and experimental results, with maximum deviations of 3.42% for the unprotected case and 4.39% for the protected case.

Since the present study employs the same MOC framework for solving the transient continuity and momentum equations, the successful validation reported in this study [21] provides additional confidence in the accuracy and physical consistency of the adopted numerical approach. Furthermore, both studies investigate transient pressure-wave propagation and mitigation using air-cushioned protection devices operating through air–water interaction mechanisms.

The transient responses predicted by the present model exhibited physically realistic behavior consistent with published experimental observations. In the unprotected pipeline, rapid valve closure generated severe pressure fluctuations, including high positive pressure surges and significant negative-pressure development. After installation of the DTT, the maximum pressure was reduced from approximately 5.8–6.0 bar to 2.5 bar, while the minimum pressure increased from approximately −55 bar to −0.6 bar. In addition, pressure oscillations decayed more rapidly, and the system reached a stable condition within a shorter period.

The agreement between the transient-response characteristics observed in the literature and those predicted by the present model supports the reliability of the adopted numerical methodology and confirms its suitability for evaluating the surge-mitigation performance of the proposed DTT system.

2.7 Evaluation strategy

Transient behavior is assessed at four locations, focusing on peak surge, minimum pressure, oscillation amplitude, and flow reversal. The unprotected system experiences severe instability—positive surges of ~6 bar and negative pressures near –55 bar—whereas the DTT reduces them to ~2.5 bar and ~–0.6 bar. These reductions confirm the DTT's strong damping capability and its effectiveness in stabilizing the entire transient event.

3. RESULT AND DISCUSSION

The transient behavior of the pipeline system was investigated by analyzing pressure and mass-flow responses at both the inlet and outlet of the restriction. Before presenting the transient simulation results, it is useful to compare the proposed DTT with conventional surge-mitigation devices commonly employed in pipeline systems. Such a comparison helps clarify the distinctive features of the proposed configuration and highlights its suitability for restrictive small-diameter pipelines where installation space and economic considerations are critical. Table 1 summarizes the main characteristics of the DTT relative to traditional surge-control alternatives.

Table 1. Validation reference and comparison with the present study

Item	Hamed and Abdulaziz [21]	Present Study
Numerical method	Method of Characteristics (MOC)	MOC
Validation approach	Experimental measurements	Literature-based comparison
Protection device	Pressurized air vessel	Dipping Tube Tank (DTT)
Maximum deviation between numerical and experimental results	3.42% (unprotected), 4.39% (protected)	—
Pressure-wave attenuation	Observed	Observed
Negative-pressure suppression	Observed	Observed
Oscillation damping	Observed	Observed
System stabilization	Improved	Improved

The analysis compares the hydraulic response of the system under two configurations: an unprotected pipeline and a pipeline equipped with the proposed DTT. Particular attention is given to the formation of the leading pressure surge, the development of extreme negative pressures, and the damping performance of the DTT. The results are presented through time histories of pressure and flow rate, allowing clear identification of the mechanisms responsible for surge amplification and transient attenuation.

3.1 Water-hammer formation at the inlet of the restriction without Dipping Tube Tank

Figure 1 illustrates the instantaneous pressure response at the inlet of the restriction in a pipeline operating without any surge-mitigation device. The pressure trace clearly demonstrates the formation of a strong water-hammer surge in the unprotected system. Under steady operating conditions, the pressure remains close to 1 bar. However, the sudden valve closure at t ≈ 0.20 s abruptly stops the moving water column, producing a sharp pressure rise that reaches approximately 6 bar.

To highlight the advantages of the proposed protection device, Table 2 compares the proposed DTT with conventional surge-mitigation devices based on key technical and operational characteristics.

Table 2. Comparison between Dipping Tube Tank (DTT) and conventional surge-mitigation devices

Feature	Surge Tank	Air Vessel	Bypass System	Proposed DTT
Installation Space	Large	Medium	Medium	Small
Construction Cost	High	High	Medium	Low
Maintenance	Low	Medium	High	Low
Air–Water Interaction	Limited	Moderate	No	Direct
Suitability for Small PVC Pipelines	Limited	Moderate	Moderate	Excellent
Cavitation Suppression	Good	Good	Moderate	Excellent
Restrictive Pipeline Application	Limited	Limited	Moderate	Specifically Designed
Surge Pressure Mitigation	High	High	Moderate	High

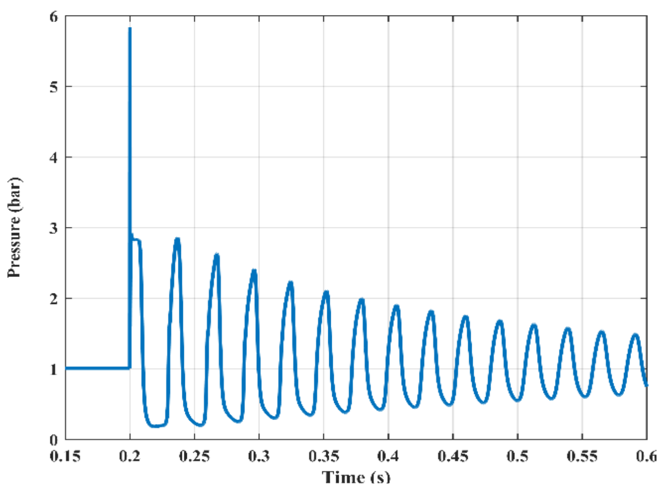

Figure 1. Pressure at the restriction inlet without Dipping Tube Tank (DTT)

Following the initial surge, the pressure rapidly decreases and enters a sequence of repeated oscillations ranging between approximately 0.2 and 2.8 bar. These oscillations persist because the pipeline lacks any damping mechanism, allowing compression and rarefaction waves to continuously reflect between system boundaries.

This pressure pattern represents a classical unprotected water-hammer response characterized by a strong primary surge, rapid pressure collapse, and sustained oscillatory behavior, confirming the highly unstable transient conditions in the absence of surge-mitigation devices.

3.2 Flowrate behavior at the restriction inlet without Dipping Tube Tank

The mass flow rate at the restriction inlet remains nearly constant at approximately 0.056 kg/s during steady-state operation, indicating stable hydraulic conditions prior to the transient event Figure 2. At the instant of valve closure (t ≈ 0.20 s), the flow rate drops abruptly to zero, representing an instantaneous cessation of fluid motion.

This sudden interruption confirms that, without a DTT, the moving water column behaves as a rigid body with no mechanism available to absorb its momentum. Consequently, the kinetic energy of the flowing water is converted directly into a pressure surge, generating a severe water-hammer event. The absence of oscillations or gradual recovery in the flow-rate response indicates a rigid hydraulic behavior and highlights the vulnerability of the unprotected system to transient loading.

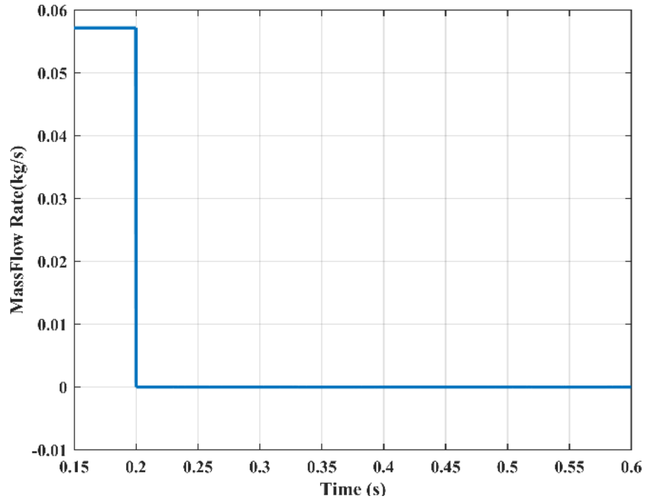

Figure 2. Flowrate at the restriction inlet without Dipping Tube Tank (DTT)

3.3 Water-hammer formation at the outlet of the restriction without Dipping Tube Tank

Figure 3 presents the transient pressure response at the downstream side of the restriction. The most severe water-hammer signature appears immediately after valve closure (t ≈ 0.20 s), where the pressure drops sharply to approximately −55 bar. Following this extreme negative surge, the pressure gradually returns toward zero and exhibits relatively small oscillations. This behavior indicates that the outlet region experiences the most severe tensile stresses within the pipeline. Such conditions significantly increase the likelihood of cavitation, pipe-wall fatigue, and structural damage in the absence of any surge-mitigation mechanism.

It should be noted that the predicted minimum pressure of approximately −55 bar in the unprotected case should not be interpreted as a physically sustainable liquid pressure. Rather, it represents the theoretical response of the adopted transient-flow model under rapid valve-closure conditions and indicates a strong tendency toward liquid-column separation and cavitation. In practical systems, pressures approaching vapor pressure would normally trigger cavitation and vapor-cavity formation, thereby limiting further pressure reduction. Therefore, the reported negative-pressure magnitude should be regarded as an indicator of the severity of the transient event rather than a physically sustainable operating condition. Similar observations have been reported in the hydraulic-transient literature under severe water-hammer conditions and cavitation-prone flow regimes [4, 7, 20].

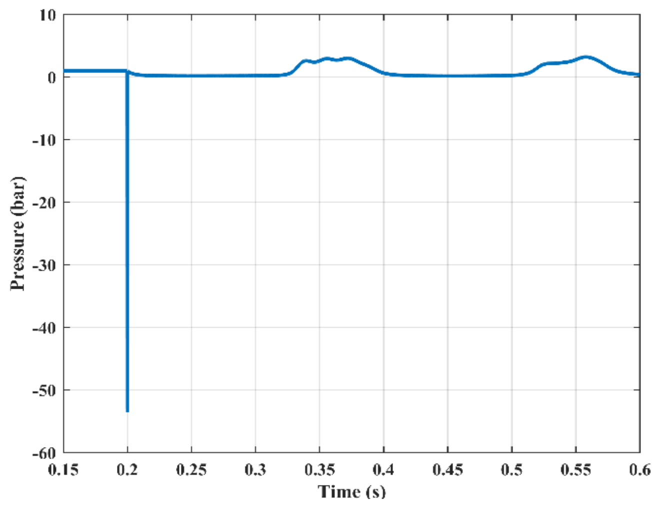

Figure 3. Pressure at the outlet restriction without Dipping Tube Tank (DTT)

3.4 Flowrate behavior at the restriction outlet without Dipping Tube Tank

The mass flow rate at the restriction outlet also exhibits a sharp transient response at the moment of valve closure Figure 4. Prior to the closure event, the outlet flow rate remains approximately –0.056 kg/s, where the negative sign indicates downstream discharge.

At t ≈ 0.20 s, the flow rate drops almost instantaneously to zero, indicating a complete interruption of discharge. This abrupt change confirms that the restriction behaves as a rigid hydraulic boundary incapable of absorbing fluid momentum.

Because the downstream section lacks compliance or damping, the kinetic energy of the moving water column cannot dissipate through flow adjustment and is instead transformed into a strong tensile pressure wave. This explains the extremely low pressure observed in the outlet region and confirms the highly destructive nature of water-hammer events in unprotected restrictive systems.

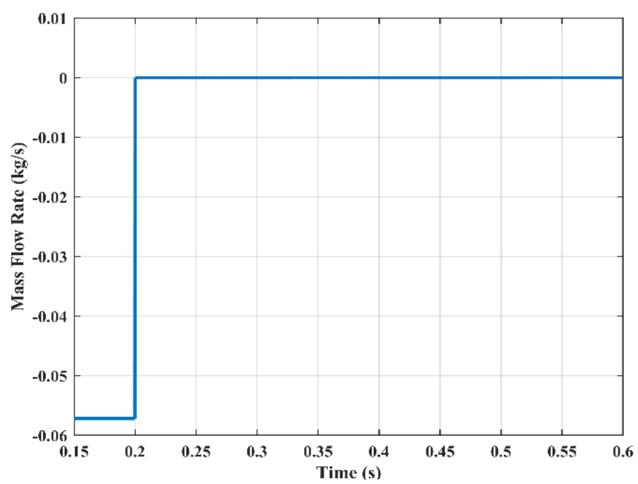

Figure 4. Flowrate at the restriction outlet without Dipping Tube Tank (DTT)

3.5 Water-hammer formation at the inlet of the restriction with Dipping Tube Tank

Figure 5 demonstrates that the installation of the DTT significantly modifies the transient response at the restriction inlet. The pressure surge generated at valve closure is greatly reduced, with the peak pressure limited to approximately 2.52 bar, compared with about 5.8 bar in the unprotected case. Following the initial surge, the pressure exhibits only a mild under-pressure of approximately 0.82 bar and quickly stabilizes near the steady operating pressure of 1 bar. Oscillations are minimal and decay rapidly, indicating that the DTT effectively suppresses wave reflections within the system. This pressure response confirms that the compressible air pocket inside the DTT absorbs part of the transient hydraulic energy, providing strong surge attenuation and rapid damping of pressure oscillations.

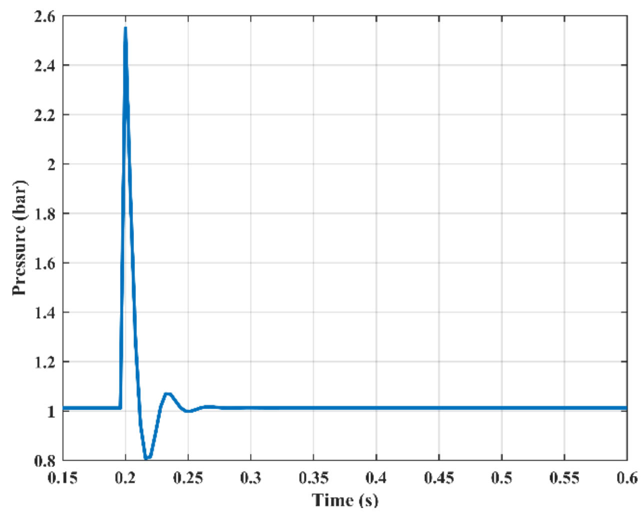

Figure 5. Pressure at restriction inlet with Dipping Tube Tank (DTT)

3.6 Flowrate behavior at the restriction inlet with Dipping Tube Tank

The mass flow rate at the restriction inlet with the DTT installed exhibits a controlled and stable transient response Figure 6. Prior to valve closure, the flow rate remains steady at approximately 0.055–0.056 kg/s.

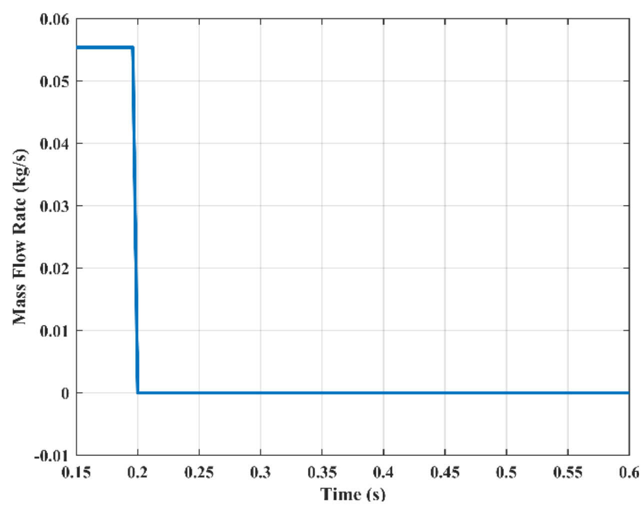

Figure 6. Flowrate at the restriction inlet with Dipping Tube Tank (DTT)

When the valve closes (t ≈ 0.20 s), the flow rate rapidly decreases to zero; however, unlike the unprotected case, no oscillations or flow reversal are observed. The presence of the

DTT provides an immediate energy-absorption pathway, allowing part of the fluid momentum to be transferred to the air-cushioned tank.

This mechanism effectively decouples the upstream flow inertia from the restriction and results in a smooth and stable flow shutdown, demonstrating the strong transient-damping capability of the DTT.

3.7 Water-hammer formation at the outlet of the restriction with Dipping Tube Tank

Figure 7 presents the transient pressure response at the outlet of the restriction when the DTT is integrated into the system. The pressure behavior becomes significantly more stable compared with the unprotected case. The minimum pressure is limited to approximately –0.6 bar, effectively preventing cavitation and eliminating the extreme vacuum conditions observed previously.

Subsequent pressure peaks remain moderate, reaching approximately 2.4 bar and 1.8 bar, and rapidly decay with time. Overall, the DTT effectively suppresses negative pressure formation and reduces surge amplification, ensuring a controlled and stable transient response.

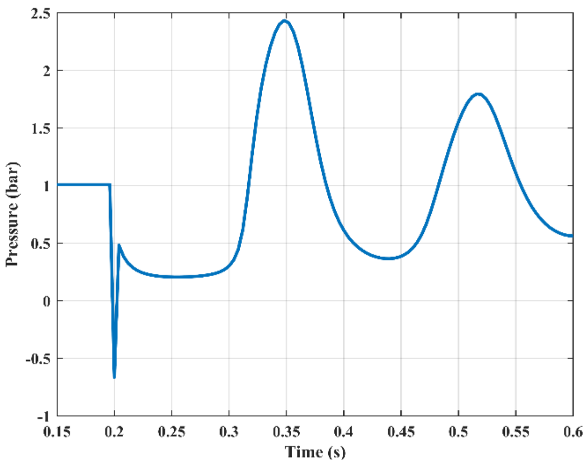

Figure 7. Pressure at restriction outlet with Dipping Tube Tank (DTT)

3.7.1 Quantitative assessment of Dipping Tube Tank performance

To quantitatively evaluate the effectiveness of the proposed DTT, the peak positive and negative pressures obtained from the protected and unprotected systems were compared. To quantitatively evaluate the effectiveness of the proposed DTT, a damping-efficiency ratio (DE) was defined as:

$$DE = \left[\frac{\left(P_{unprotected} - P_{protected}\right)}{P_{unprotected}}\right] \times 100$$

where, $P_{unprotected}$ and $P_{protected}$ represent the characteristic transient pressures before and after installation of the DTT, respectively.

The maximum pressure was reduced from approximately 6 bar in the unprotected system to 2.5 bar when the DTT was installed, corresponding to a pressure-surge reduction of approximately 58.3%. In addition, the minimum pressure increased from approximately −55 bar to −0.6 bar, representing a 98.9% reduction in the magnitude of the negative pressure wave. These results clearly demonstrate the superior damping capability of the proposed DTT and confirm its effectiveness in suppressing both pressure amplification and cavitation-prone conditions in restrictive pipeline systems.

The quantitative performance improvements achieved by the proposed DTT are summarized in Table 3.

Table 3. Quantitative performance improvement achieved by the Dipping Tube Tank (DTT)

Parameter	Without DTT	With DTT	Damping Efficiency
Maximum Pressure (bar)	6.0	2.5	58.3% reduction
Minimum Pressure (bar)	-55.0	-0.6	98.9% reduction
Cavitation Risk	High	Negligible	Significant improvement
Pressure Stability	Poor	Excellent	Enhanced

3.7.2 Practical considerations and implementation aspects

In addition to its transient-pressure mitigation capability, the proposed DTT offers several practical advantages for pipeline protection. Unlike conventional surge tanks and large hydro-pneumatic systems, the DTT requires a relatively compact installation space, making it suitable for restrictive small-diameter pipeline systems where available space may be limited. The simplified configuration of the device also reduces installation complexity and facilitates integration into existing pipeline networks.

From a maintenance perspective, the DTT contains no complex mechanical components or active control systems, which may contribute to reduced maintenance requirements and improved operational reliability. Furthermore, the suppression of severe pressure fluctuations and cavitation-prone conditions may reduce long-term deterioration of pipeline components and associated maintenance costs.

Although a detailed economic analysis was not performed in the present study, the compact geometry and passive operating principle of the DTT suggest potential cost advantages compared with larger conventional surge-protection devices. Future studies may investigate life-cycle cost analysis, long-term durability assessment, and practical field implementation of DTT systems under different operating conditions.

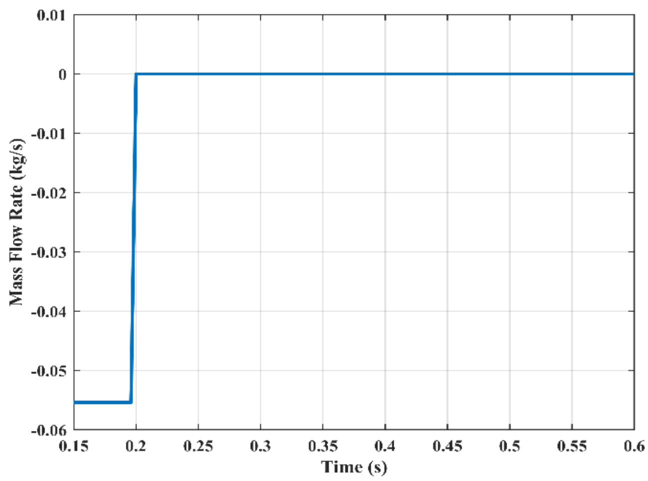

Figure 8. Flowrate at the restriction outlet with Dipping Tube Tank (DTT)

3.8 Flowrate behavior at the restriction outlet with Dipping Tube Tank

With the DTT installed, the outlet mass flow rate decreases smoothly to zero immediately after valve closure without oscillation or flow reversal Figure 8. This behavior confirms that the compressible air cushion within the DTT effectively absorbs the transient hydraulic energy.

As a result, the downstream section becomes hydraulically stabilized, and the severe flow instabilities associated with water-hammer events are successfully suppressed.

3.9 Cavitation suppression and implications for pipe durability

The results presented in Figure 9 demonstrate that the proposed DTT substantially improves the transient hydraulic performance of the restrictive pipeline system by simultaneously suppressing both positive and negative pressure surges. In the unprotected system, the transient response is characterized by severe pressure fluctuations, with peak pressures approaching approximately 6 bar and minimum pressures reaching approximately −55 bar, indicating a strong tendency toward liquid-column separation and cavitation development. After installation of the DTT, the maximum pressure is reduced to approximately 2.5 bar, while the minimum pressure increases to approximately −0.6 bar, significantly reducing the likelihood of cavitation and associated transient damage.

The marked reduction in pressure-wave amplitudes demonstrates that the confined air chamber inside the DTT effectively absorbs and dissipates transient hydraulic energy through air compression and expansion. As a result, transient oscillations decay more rapidly and pressure-wave reflections are considerably weakened throughout the pipeline system. Since cyclic pressure fluctuations are directly related to repeated stress variations in pipe walls, the attenuation of surge magnitude and oscillation intensity is expected to reduce both the frequency and severity of stress cycles experienced by the pipeline. Consequently, the proposed DTT may contribute to improved long-term structural resilience and reduced fatigue-related deterioration of PVC pipeline systems.

Although a detailed fatigue-life assessment is beyond the scope of the present study, the significant suppression of both positive surge pressures and extreme negative pressure phases demonstrates that the proposed DTT provides an effective passive protection strategy for restrictive small-diameter pipeline systems, thereby improving operational reliability and extending the service life of pipeline infrastructure.

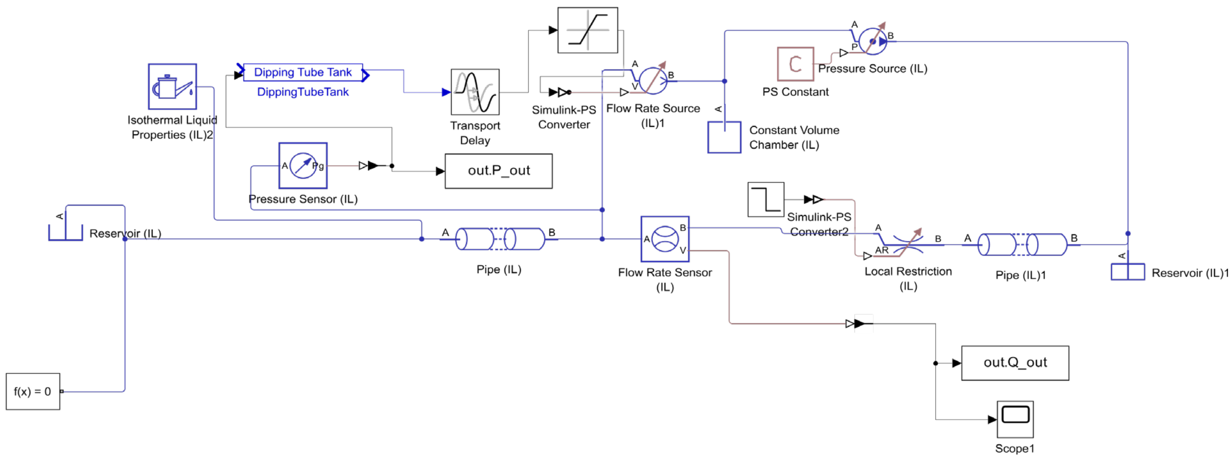

Figure 9. Block diagram of the water-hammer simulation with Dipping Tube Tank (DTT) protection

4. CONCLUSION

This study numerically investigated the hydraulic performance of a compact DTT as a passive surge-mitigation device for restrictive small-diameter pipeline systems using a high-resolution Method of Characteristics (MOC) model. The numerical framework successfully captured transient pressure-wave propagation and the dynamic air–water interaction occurring within the DTT.

The results demonstrate that the DTT effectively suppresses both positive and negative pressure transients by absorbing hydraulic energy through the compression of the confined air volume, resulting in rapid attenuation of pressure oscillations and improved damping performance. This mitigation mechanism effectively reduces the risk of cavitation, stabilizes transient flow behavior, and is expected to improve the long-term durability and operational reliability of PVC pipeline systems.

The main contribution of this study is the demonstration that a compact DTT can provide efficient surge protection in restrictive small-diameter pipelines, where conventional surge-control devices are often impractical because of space and installation constraints. In addition, the proposed numerical framework enables detailed multi-location analysis of transient pressure evolution, providing valuable insight into the dynamic interaction between hydraulic transients and air–water systems. From an engineering perspective, the proposed DTT represents a compact, cost-effective, and easily implementable solution for protecting localized pipeline systems subjected to severe hydraulic transients.

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NOMENCLATURE

a	Pressure-wave speed, m/s
Cd	Discharge coefficient
D	Pipe diameter, m
f	Darcy–Weisbach friction factor
H	Piezometric head, m
Q	Flow rate, m^3/s
V	Flow velocity, m/s