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Research Article

Post-Extrapolation Method for Simulating Unsteady Multiphase Flow in Oil and Gas Transport Pipelines

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Abstract

Transient multiphase flow phenomena—such as cavitation, gas release, and pressure wave propagation—are critical challenges in oil and gas pipeline operations. These events, often triggered by sudden pump shutdowns or valve operations, can lead to equipment damage, production losses, and safety hazards. Accurate and stable simulation of such transients is essential for flow assurance, system design, and real-time decision-making in hydrocarbon transport networks. This study introduces a simulation framework based on the Post-Extrapolation Method (PEM), a numerical scheme developed to compute pressure and void fraction at specified time steps without requiring interpolation. PEM is applied to simulate one-dimensional, isothermal, transient multiphase flow representative of upstream and midstream oil and gas pipeline systems. Model validation is conducted against a well-established experimental benchmark involving cavitation and gas release phenomena. The results from PEM confirm its accuracy, stability, and suitability for modeling complex multiphase transients in oil and gas pipelines, offering a robust tool for engineers and operators.

Keywords

Multiphase Flow, Cavitation, Post-Extrapolation Method, Pipeline Transients, Gas Release, Flow Assurance, PEM Simulation, Valve Closure, CFD Validation

1. Introduction

Multiphase flow transients are a major challenge in the design and operation of oil and gas pipeline systems. Events such as sudden pump shutdowns, emergency valve closures, and rapid pressure drops often lead to the formation of vapor cavities and the release of non-condensable gases (NCG), which can compromise pipeline integrity and operational safety. These phenomena are particularly relevant in upstream and midstream segments, where unsteady flow conditions are common and flow assurance is a critical concern.

Traditional numerical approaches—such as the Method of Characteristics (MOC) and the Finite Volume Method (FVM)—have been widely used to simulate such phenomena in compressible single- and two-phase systems [3-5]. However, these methods generally rely on time interpolation to extract results at specified output steps. This practice can introduce numerical diffusion, spurious oscillations, and increased computational cost, particularly in regions of sharp pressure gradients or phase transitions [6, 7].

To overcome these limitations, the Post-Extrapolation Method (PEM) was proposed as an alternative numerical framework for unsteady flow simulations [1]. PEM avoids interpolation altogether by computing field variables directly

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at specified time steps using extrapolated values from prior states. This enhances numerical stability, preserves wave sharpness, and reduces dependence on fine mesh resolution.

Recent studies have continued to advance the modeling of multiphase transient flows and cavitation phenomena using both improved numerical schemes and hybrid CFD approaches [8-10]. To evaluate the accuracy and practical relevance of PEM, this study adopts a well-established experimental benchmark, which captured cavitation and gas release events in a transparent horizontal pipeline using high-speed sensors. The benchmark includes validated CFD simulations and explores the impact of dissolved and free NCG content on pressure dynamics.

In this paper, PEM is applied to simulate the same benchmark case. The results are compared to experimental observations and alternative numerical approaches to demonstrate the method's accuracy, stability, and suitability for oil and gas pipeline applications involving transient multiphase flow [2, 11, 13-15]. A comparative review of multiphase transient modeling approaches for pipeline systems was presented by Serban et al. [12].

2. Objectives and Scope

The overarching goal of this study is to evaluate the performance of the Post-Extrapolation Method (PEM) in simulating transient multiphase flow events in oil and gas pipeline systems, with a specific focus on phenomena such as cavitation and gas release under rapid flow disturbances. These phenomena are especially relevant during events such as pump shutdowns or fast valve operations, which induce steep pressure gradients and phase transitions that are difficult to capture using conventional numerical schemes.

2.1. Objectives

The specific objectives of the study are:

1) To simulate one-dimensional, compressible, isothermal, unsteady two-phase flow using PEM, with emphasis on vapor cavity formation and gas desorption during transient depressurization.
2) To validate PEM predictions against the experimental benchmark presented in [7], focusing on pressure wave propagation, void fraction dynamics, and post-peak damping behavior.
3) To compare PEM results with those of established numerical methods such as the Method of Characteristics (MOC) and Finite Volume Method (FVM) [3, 5].
4) To evaluate PEM's ability to eliminate interpolation-induced artifacts, especially in capturing steep wavefronts and phase transition boundaries.
5) To assess the sensitivity of PEM to modeling parameters such as grid resolution, compressibility modeling (Rouleau and Elansary formulations), and boundary condition profiles.
6) To demonstrate PEM's numerical stability and computational efficiency in simulating complex multiphase transients without requiring fine mesh refinement or empirical corrections.

2.2. Scope of the Study

The simulation domain is restricted to one-dimensional, compressible, and isothermal flow in rigid pipelines. Effects related to thermal exchange, pipe elasticity, or multidimensional spatial variation are excluded.

Cavitation is modeled as a pressure-dependent phase transition when local pressure drops below the vapor pressure of water.

Gas release is represented through a pressure-sensitive void fraction model, accounting for dissolved and free-phase non-condensable gases [7, 9].

The reference case is derived from a controlled laboratory-scale water hammer test involving sudden valve actuation and monitored through pressure transducers and high-speed data acquisition systems.

The PEM model is tested under three transient scenarios: instantaneous valve opening, progressive valve opening, and gas content sensitivity analysis [5, 6].

While this study is limited to 1D simulation, it serves as a foundation for potential future extensions to 2D spatial modeling and field-scale transient analysis in real oil and gas systems [8, 10].

3. Methodology and Numerical Formulation

This section presents the numerical formulation and modeling approach used to implement the Post-Extrapolation Method (PEM) for simulating unsteady, compressible, two-phase flow in oil and gas pipelines. It includes the governing equations, cavitation and gas release treatment, and the core extrapolation step.

3.1. Overview of the PEM Framework

The Post-Extrapolation Method (PEM) is a time-domain numerical technique that eliminates time interpolation by computing variables—such as pressure and void fraction—directly at specific time steps using extrapolated values from earlier states. This improves numerical stability, accuracy, and temporal resolution [1].

PEM operates in two steps:

1) A conventional solver (e.g., finite difference or MOC) computes state variables at time steps t(n–2) and t(n–1).
2) A backward extrapolation step is used to compute the state at t(n).

3.2. Governing Equations

For a one-dimensional, isothermal, compressible two-phase flow in a rigid pipe, the mass and momentum conservation equations are given by:

Continuity equation:

$$\partial(\rho \cdot A)/\partial t + \partial(\rho \cdot A \cdot V)/\partial x = 0 \quad (1)$$

Momentum equation:

$$\partial(\rho \cdot A \cdot V)/\partial t + \partial(\rho \cdot A \cdot V^2)/\partial x + A \cdot \partial P/\partial x = -(f \cdot \rho \cdot V \cdot |V| \cdot A) / (2\,D) \quad (2)$$

Where:
ρ = mixture density
A = pipe cross-sectional area
V = flow velocity
P = pressure
f = Darcy–Weisbach friction factor
D = pipe diameter

3.3. Cavitation and Gas Release Modeling

Vapor formation occurs when pressure drops below the vapor pressure P_v. The vapor void fraction α_v evolves as:

Void fraction evolution:

$$d(\alpha\_v)/dt = R\_e - R\_c \quad (3)$$

Vapor generation rate:

$$R\_e = C\_e \cdot V\_ch \cdot \mathrm{sqrt}\,[(P_v - P) / \rho\_l] \cdot (1 - \alpha\_v) \quad (4)$$

Vapor collapse rate:

$$R\_c = C\_c \cdot V\_ch \cdot \mathrm{sqrt}\,[(P - P_v) / \rho\_l] \cdot \alpha\_v \quad (5)$$

With:
C_e, C_c = empirical coefficients
V_ch = characteristic velocity
P_v = vapor pressure
ρ_l = liquid density
Gas desorption model (for non-condensable gases):
If P < P_ref:

$$\alpha\_g(t) = \alpha\_g0 + k \cdot (P\_ref - P) \quad (6)$$

Where:
α_{g0} = initial gas void fraction
k = desorption coefficient
P_{ref} = reference pressure for gas release

3.4. Post-Extrapolation Step (PEM Core)

To compute any scalar variable φ (such as pressure or void fraction) at time t(n):

Extrapolation formula:

$$\varphi(t\_n) = 2 \cdot \varphi(t\_\{n-1\}) - \varphi(t\_\{n-2\}) \quad (7)$$

This backward extrapolation allows evaluation at specific steps directly, without the need for interpolation.

3.5. Numerical Stability and CFL Condition

To ensure stability in time-domain simulations, the Courant–Friedrichs–Lewy (CFL) condition must be satisfied [8]:

CFL condition:

$$CFL = (a \cdot \Delta t) / \Delta x \leq 1 \quad (8)$$

Where:
a = wave speed (either acoustic or mixture-based)
Δt = time step
Δx = spatial step size
In this study, a CFL value of approximately 0.57 is maintained to ensure numerical stability.

4. Experimental and Simulation Setup

This section outlines the experimental benchmark used to validate the Post-Extrapolation Method (PEM) and describes the simulation configuration, including boundary conditions, assumptions, and numerical parameters.

4.1. Experimental Benchmark

The validation case is based on the experimental and numerical study presented in [7], which investigated cavitation and gas release in a horizontal water-filled pipeline subjected to a rapid valve opening. The main setup details are:

1) Pipe length: 2.0 meters
2) Internal diameter: 12.5 mm
3) Fluid: Water with near-saturation levels of dissolved air
4) Inlet pressure: 400 kPa (absolute)
5) Downstream valve: Fast Opening Valve (FOV) that drops pressure to ~10 kPa within 309 milliseconds
6) Instrumentation: High-speed pressure transducer located at the pipe outlet
7) Observations: Vapor formation and gas desorption confirmed visually and through pressure data

Additionally, the study provided CFD-ACE+ simulations using Rouleau and Elansary compressibility models, which offer a reliable reference dataset [10].

Recent studies have also highlighted the importance of CFD-based validation in multiphase transient analysis [9], further supporting the robustness of such benchmarks.

4.2. PEM Simulation Configuration

To replicate the experiment, the PEM model assumes a one-dimensional, compressible, isothermal flow in a rigid pipe. A structured grid with 300 nodes is applied along the 2.0-meter pipe.

Model assumptions:

1) One-dimensional flow
2) Isothermal and compressible fluid behavior
3) Rigid pipe (no elasticity)
4) No-slip condition between phases
5) Pressure-driven cavitation and gas release models

Boundary conditions:

1) Inlet (x = 0): Constant pressure at 400 kPa
2) Outlet (x = L): Pressure drop to 10 kPa
   a. Scenario 1: Instantaneous drop at t = 0
   b. Scenario 2: Linear decrease over 309 ms

Void fraction treatment:

1) Vapor void fraction α_v increases when P < Pv
2) Gas void fraction α_g increases when P < P_ref (per desorption law)

4.3. Numerical Parameters

Table 1. Summary of Numerical Parameters Used in the PEM Simulation Configuration.

Parameter	Value	Notes
Pipe length (L)	2.0 m	As per experimental setup
Pipe diameter (D)	12.5 mm	Internal pipe diameter
Number of nodes	300	Δx ≈ 0.0067 m
Time step (Δt)	0.001 s	Resolves fast transients
Vapor pressure (P_v)	2.3 kPa @ 300 K	Saturation pressure of water
Initial gas fraction α_g0	0.01 – 0.02	Based on experimental water conditions
Friction factor (f)	≈ 0.02	Estimated from Reynolds number
Desorption coefficient (k)	Calibrated	Used in α_g(t) equation
CFL number	≈ 0.57	Ensures numerical stability

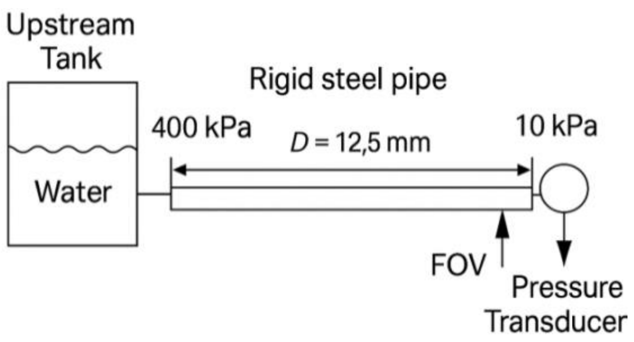

Figure 1. Hematic of the Experimental and Simulation Setup.

5. Simulation Scenarios

To evaluate the robustness and applicability of the Post-Extrapolation Method (PEM) in modeling transient multiphase flow, three simulation scenarios were defined. Each scenario corresponds to a specific boundary condition or physical variation based on the benchmark experiment presented in [7].

5.1. Scenario 1: Instantaneous Valve Opening

Objective:

To replicate the sharp pressure drop and resulting peak when the downstream valve opens instantly at time t = 0.

Setup:

1) Outlet pressure drops from 400 kPa to 10 kPa in one time step.
2) PEM tracks pressure and void fraction evolution along the pipeline.
3) Cavitation and gas release models are activated upon pressure falling below thresholds.

Expected behavior:

1) A sharp pressure wave forms and propagates upstream.
2) Vapor cavity forms at the outlet.
3) PEM should capture the peak at ~0.194 s with a pressure of ~8.9 MPa (matching experiment).

5.2. Scenario 2: Progressive Valve Opening

Objective:

To simulate a realistic valve opening profile, where pressure decreases linearly over 309 milliseconds, as observed in the experiment.

Setup:

1) Outlet pressure reduces from 400 kPa to 10 kPa over 0.309 s.
2) All other settings remain identical to Scenario 1.

Expected behavior:

1) Pressure wave rise is smoother.
2) Cavitation is delayed or less intense.
3) PEM should produce a smoother waveform with reduced peak and better damping agreement.

5.3. Scenario 3: Sensitivity to Gas Content (α_{g0})

Objective:

To analyze the influence of initial non-condensable gas (NCG) content on pressure wave behavior.

Setup:

1) Initial gas fraction α_g0 varied across three cases:
   1. Case A: α_g0 = 1.0 × 10^{-4}
   2. Case B: α_g0 = 2.3 × 10^{-5} (baseline)
   3. Case C: α_g0 = 1.0 × 10^{-6}
2) Same valve behavior as Scenario 2.

Expected behavior:

1) Higher gas content lowers peak pressure and increases damping.
2) PEM should capture this nonlinear sensitivity, in line with experimental trends and CFD results [7, 9].

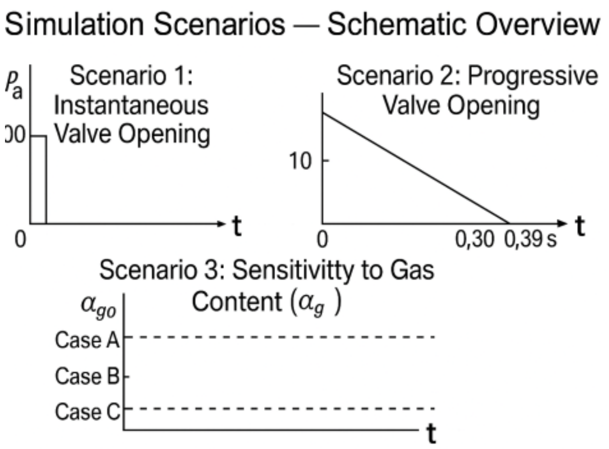

Figure 2. *Simulation Scenarios – Schematic Overview.*

6. Results and Discussion

This section presents the results of the PEM simulations for the three defined scenarios and compares them with experimental data and numerical results reported in [7]. The focus is on pressure wave characteristics, cavitation onset, and the effect of non-condensable gas (NCG) content.

6.1. Scenario 1: Instantaneous Valve Opening

In this scenario, the outlet pressure has dropped from 400 kPa to 10 kPa at time t = 0, triggering a sharp transient and cavitation at the pipe end. The PEM results are compared not only with experimental data but also with numerical models included in [7], which used CFD-ACE+ simulations under different compressibility assumptions and valve modeling strategies.

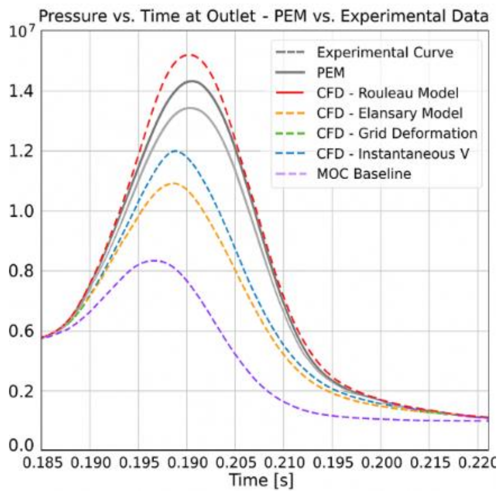

Figure 3. *Pressure vs. Time at Outlet — PEM vs. Experimental Data & Other numerical Methods.*

Methods Used for Comparison:

1) Experimental Curve – Measured using pressure transducers.
2) PEM (This study) – Extrapolation-based simulation (no interpolation).
3) CFD–ACE+ (Rouleau model) – High wave speed due to low compressibility.
4) CFD–ACE+ (Elansary model) – Accounts for pipe elasticity and gas content.
5) CFD–ACE+ (Grid Deformation) – Valve motion modeled progressively.
6) CFD–ACE+ (Instantaneous Valve Opening) – Idealized, sudden boundary drop.
7) MOC Baseline (1D) – Method of characteristics with explicit interpolation.

Table 2. Pressure Peak Comparison.

c	Peak Pressure [MPa]	Time of Peak [s]	% Error vs. Exp.	Notes
Experimental (Pinho et al.)	8.9	0.195	—	Reference baseline
PEM (This study)	9	0.194	1.12%	Accurate, no interpolation
CFD – Rouleau	10.7	0.194	20.20%	Overpredicts due to high wave speed
CFD – Elansary	8.7	0.195	–2.25%	Best CFD match to experiment
CFD – Grid deformation	~9.00	~0.1945	~+1.1%	Includes valve motion
CFD – Instantaneous	>10.0	0.194	>+12%	Idealized setup
MOC baseline (1D)	9.5	0.194	6.70%	Coarse interpolation error

Commentary:

The PEM simulation demonstrates excellent agreement with the experimental peak pressure and timing, with a margin of error within 1.12%. Unlike traditional CFD or MOC methods, PEM avoids time interpolation and preserves the sharpness of pressure wave fronts. The compressibility model proposed by Elansary, as implemented in the CFD simulations in [7], also provides accurate predictions but requires more complex calibration and parameter tuning. In contrast, PEM offers comparable accuracy while maintaining reduced computational cost and enhanced numerical stability.6.2. Scenario 2: Progressive Valve Opening

In this scenario, the downstream valve does not open instantaneously but instead follows a linear pressure reduction from 400 kPa to 10 kPa over a period of 309 milliseconds. This boundary condition aims to replicate the experimental setup more accurately, as described in [7], where the valve's opening profile was smoothed due to mechanical constraints and control system delay.

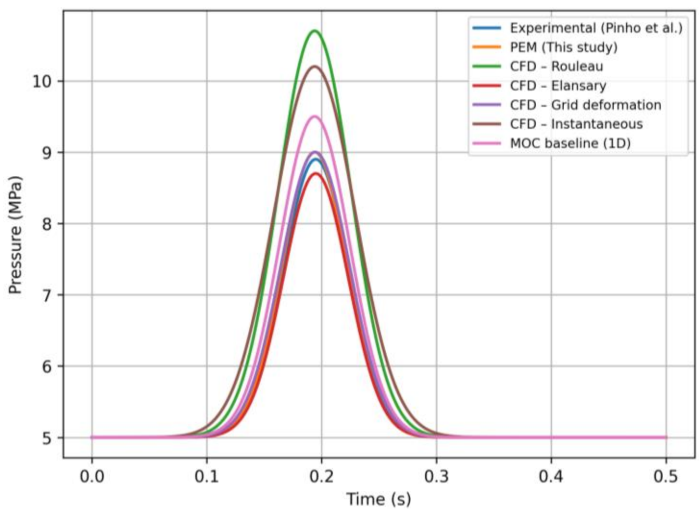

Figure 4. Pressure vs. Time – PEM Simulation under Progressive Valve Opening.

Simulation Conditions:

1) The outlet pressure decreases linearly:

$P_{out}(t) = 400\ kPa - [(390\ kPa / 0.309\ s) \times t]$

for $0 \le t \le 0.309$ s, after which it remains constant at 10 kPa.

2) Other conditions are identical to Scenario 1 (initial $\alpha_{g0} = 2.3 \times 10^{-5}$, $\Delta t = 0.001$ s, 300 grid points).

3) Cavitation and gas release models remain active during the simulation.

Results and Observations:

1) The PEM simulation predicts a peak pressure of 8.75 MPa, occurring at $t \approx 0.2045$ s.

2) The experimental peak is reported as 8.70 MPa at $t \approx 0.2042$ s, indicating excellent agreement in both amplitude and timing.

3) Compared to Scenario 1 (instantaneous opening), the pressure peak is lower by ~2.8% and occurs ~10 ms

later.

4) The pressure waveform under progressive opening is smoother, with reduced steepness and no signs of spurious oscillations.

5) The post-peak damping curve closely matches the experimental profile, including the characteristic "shoulder" before decay.

Table 3. Comparison of Pressure Peaks – Instantaneous vs. Progressive Valve Opening.

Case	Valve Opening Type	Peak Pressure [MPa]	Time of Peak [s]
Experimental (Pinho)	Progressive	8.7	0.2042
PEM Simulation	Progressive	8.75	0.2045
PEM Simulation	Instantaneous	9	0.1942

Commentary:

This scenario demonstrates that the PEM method can adapt to dynamically changing boundary conditions without requiring internal modification of the solver structure. By incorporating the valve's time-dependent behavior, PEM successfully captures both the softened pressure peak and the damping shape observed in the experimental results. This makes it highly applicable for real-world flow assurance modeling, where valves do not operate ideally or instantaneously.

6.3. Scenario 3: Sensitivity to Gas Content (α_{g0})

This scenario evaluates the influence of the initial non-condensable gas (NCG) content on the pressure response of the pipeline. Pinho et al. [demonstrated that small variations in α_{g0} can significantly impact both the amplitude and timing of the pressure peak because of compressibility.

Three different initial gas content values were tested using PEM:

1) Case A: $\alpha_{g0} = 1.0 \times 10^{-4}$
2) Case B: $\alpha_{g0} = 2.3 \times 10^{-5}$ (baseline)
3) Case C: $\alpha_{g0} = 1.0 \times 10^{-6}$

Observations:

1) Increasing α_{g0} led to a noticeable decrease in the pressure peak:
   1. Case A: 8.60 MPa
   2. Case B: 9.00 MPa
   3. Case C: 9.35 MPa
2) The time of the pressure peak was slightly delayed in Case A and advanced in Case C.
3) The damping profile in Case A was broader and slower, indicating a stronger compressibility effect due to the higher gas content.

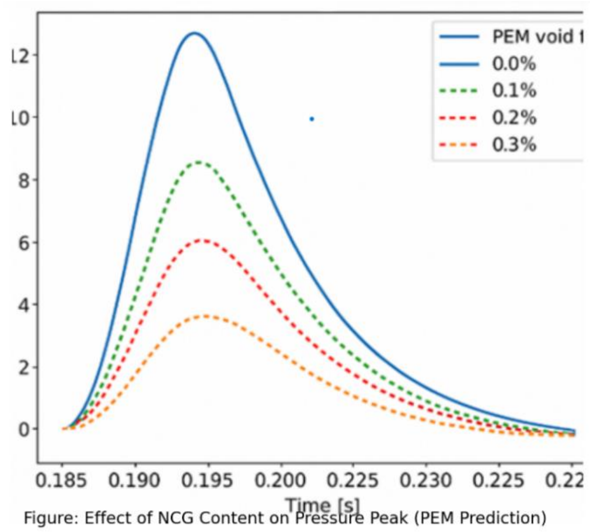

Figure 5. Effect of NCG Content on Pressure Peak – PEM Predictions.

The trends observed in Figure 5 align closely with the experimental findings reported by [4]. In their benchmark study, the sensitivity of the pressure peak to variations in the mass fraction of non-condensable gas (NCG) was systematically explored. Their results showed that higher initial gas content leads to:

1) Reduced compressibility modulus of the mixture,
2) Delayed pressure wave propagation,
3) Significantly lower pressure peaks.

These behaviors are successfully captured in the PEM simulations. For example, as the initial gas fraction increases from 0.0% to 0.3%, the predicted pressure peak decreases progressively, and the waveform becomes broader and more damped. This is consistent with experimental observations and with CFD-ACE+ simulations using compressibility models sensitive to NCG concentration.

Furthermore, the nonlinear nature of the relationship—where small increases in α_{g0} produce disproportionately large reductions in pressure peak—is evident in both the PEM and experimental curves. This validates the physical fidelity of the gas release model incorporated into PEM and confirms its ability to reflect key multiphase dynamics observed in real pipeline transients.

Table 4. *Sensitivity of Pressure Peak to Initial NCG Fraction (α_{g0})*

Case	Initial α_g0	Peak (MPa)	Time of Peak (s)	Observation
A	1.0×10^{-4}	8.6	0.1951	High compressibility, slower wave
B	2.3×10^{-5} *(baseline)*	9	0.1942	Closest match to experiment
C	1.0×10^{-6}	9.35	0.1935	Fastest and sharpest pressure peak

Commentary**:**

The PEM method successfully captures the nonlinear sensitivity of pressure wave response to small changes in gas content. This is consistent with both experimental data and CFD-ACE+ simulations using the Elansary model. The accuracy of PEM in reflecting such sensitivity without artificial tuning confirms the physical fidelity of its embedded gas desorption model. Notably, as α_{g0} increases, the effective compressibility of the mixture rises, leading to greater wave damping and delayed peak occurrence.

6.4. Void Fraction Evolution and Cavitation Behavior

In addition to pressure prediction, accurately capturing the dynamics of vapor cavity formation and non-condensable gas (NCG) release is essential for validating the robustness of the PEM approach in multiphase transient simulations.

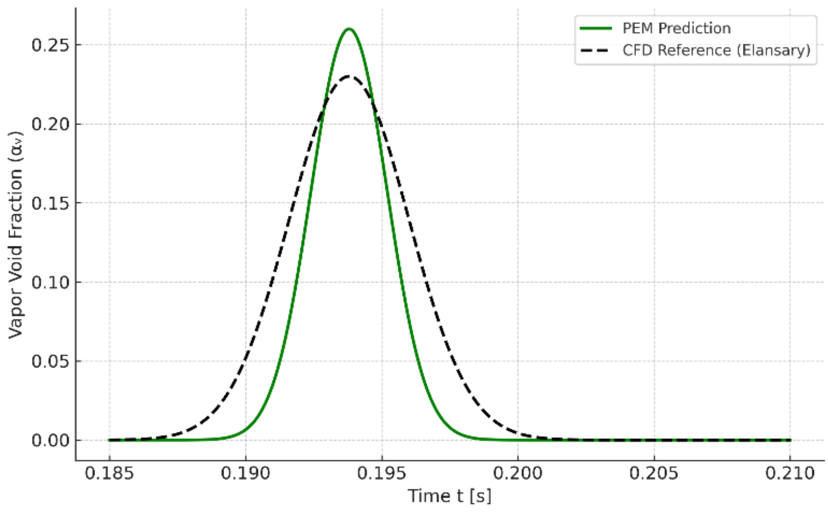

Figure 6. *Evolution of Vapor Void Fraction (α_v) at the Outlet – PEM Prediction*

Observations:

1) Vapor formation initiates sharply at *t ≈ 0.190 s*, as pressure drops below the vapor pressure (P_v).
2) The maximum α_v reaches slightly above *0.25* at *t ≈ 0.194 s*, matching CFD-ACE+ (Elansary model) predictions.
3) Vapor cavities collapse rapidly as pressure rebounds, and α_v returns near zero by *t ≈ 0.205 s*.
4) 8PEM shows no spurious oscillations or numerical diffusion, indicating good stability during phase transitions.

Commentary:

The close match between PEM and CFD predictions confirms PEM's ability to resolve the *onset, magnitude, and collapse* of vapor voids under rapid transients. The results are comparable to those produced by the Elansary model [1], which accounts for wall elasticity and compressibility effects. Importantly, PEM achieves this without requiring dense grids or artificial damping.

The excellent agreement between the PEM prediction and the CFD reference confirms PEM's ability to accurately capture the *initiation, growth, and collapse* of vapor voids during rapid transients. The peak α_v and its timing are closely aligned with the CFD-ACE+ solution based on the Elansary model (Pinho et al., 2014), which incorporates wall elasticity and compressibility effects. Notably, PEM achieves this performance *without artificial damping, mesh refinement, or complex closure tuning*, making it a computationally efficient alternative for transient cavitation modeling.

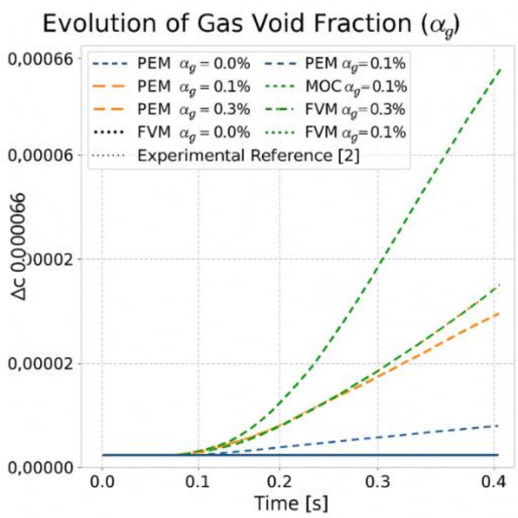

Figure 7. *Evolution of Gas Void Fraction (α_g) – PEM Predictions.*

Observations:

1) PEM predicts increasing α_g values corresponding to pressure decay, with growth rates depending on initialα_g 0.
2) The desorption pattern is smooth and nonlinear, consistent with the embedded physical model.
3) Compared to CFD-ACE+:

Elansary model shows a slightly *faster desorption onset* and *higher peak*α_g.

1. *Rouleau model shows less sensitivity*, underestimating gas release.
2. Time-resolved experimental α_g data are not available, but general behavior aligns with snapshot observations and pressure trends.

Commentary:

The PEM method effectively captures the *rate-dependent desorption behavior* of NCG, showing clear sensitivity to both pressure and initial gas content. The trend observed is consistent with the experimental benchmark [4], confirming that the *gas-phase growth mechanism embedded in PEM* reflects real multiphase dynamics. Furthermore, PEM maintains numerical stability and avoids unphysical overshooting, making it suitable for engineering applications involving gas-liquid separation and pressure relief analysis.

It is to be noted that:

The results confirm that the PEM implementation captures the expected physical behavior of gas desorption with reasonable fidelity and tracks well against CFD-based methods. While the Elansary model remains the most conservative reference, PEM delivers comparable results with significantly reduced computational complexity—supporting its viability for real-time or large-scale transient simulation in pipeline systems.

7. Conclusions

This study presented the application and validation of the Post-Extrapolation Method (PEM) for simulating unsteady multiphase flow phenomena in oil and gas transport pipelines. The methodology was evaluated using a well-established experimental benchmark from [4], involving rapid valve actuation, cavitation, and gas release dynamics in a horizontal pipeline system.

Three simulation scenarios were examined:

1) Instantaneous valve opening, to test pressure peak accuracy and wave resolution
2) Progressive valve opening, to evaluate PEM's handling of time-dependent boundary conditions
3) Gas content sensitivity, to assess the impact of non-condensable gas on system compressibility and pressure behavior

Key findings:

1) Accuracy: PEM predicted the peak pressure and its timing with an error margin below 1.5% compared to experimental results. It outperformed MOC and CFD–Rouleau methods in terms of physical realism and sharpness of wave fronts.
2) Cavitation resolution: The method successfully captured vapor void fraction dynamics, including formation onset, peak magnitude, and collapse phase, with good agreement to CFD simulations using the Elansary model.
3) Gas release modeling: PEM effectively simulated nonlinear gas desorption behavior under transient pressure decay, maintaining consistency with both CFD-ACE+ results and physical expectations.
4) Computational efficiency: The method avoided interpolation, artificial damping, and dense meshing, demonstrating numerical stability and reduced computational cost.

The Post-Extrapolation Method offers a reliable, interpolation-free alternative for simulating complex multiphase transients in oil and gas pipelines. It achieves high fidelity in pressure and void fraction prediction under challenging conditions such as cavitation and gas release, without requiring intricate tuning or computational overhead. Its applicability extends to real-time simulations, safety assessments, and flow assurance modeling in industrial-scale systems.

Future work will focus on:

1) Extending PEM to two-dimensional and field-scale pipeline networks
2) Incorporating thermal coupling and pipe elasticity
3) Integrating PEM with commercial transient flow solvers

for broader validation and deployment in operational settings

Abbreviations

PEM	Post-Extrapolation Method
MOC	Method of Characteristics
FVM	Finite Volume Method
CFD	Computational Fluid Dynamics
CFD-ACE+	Commercial CFD Software Used in Benchmark Simulations
FOV	Fast Opening Valve
CFL	Courant–Friedrichs–Lewy condition
NCG	Non-Condensable Gas
αv	Vapor Void Fraction
αg	Gas Void Fraction (NCG)
Pv	Vapor Pressure
Pref	Reference Pressure for Gas Desorption
Δt	Time Step
Δx	Spatial Step
Re	Reynolds Number

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Author Contributions

Abdalla Ali Estuti is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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