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Review of Advances and Research Gaps in the Modeling of Transient Phenomena During Emptying Operations in Pressurized Pipelines

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INTRODUCTION & AIM

Pressurized pipelines are critical in water distribution and hydropower systems but remain vulnerable to transient conditions caused by air entrapment and rapid operational changes.

During emptying operations, air inflow and water drainage generate complex two-phase interactions that may result in severe pressure surges or sub-atmospheric conditions, potentially leading to pipe failure. As illustrated in Figure 1, air pockets tend to accumulate at high points along undulating profiles, significantly influencing the transient response and pressure evolution during drainage. Most existing studies focus on filling transients, leaving emptying phenomena comparatively underexplored.

Among the available approaches, Rigid Water Column (RWC) models dominate due to their simplicity, while Elastic Water Column (EWC) formulations offer a more realistic representation by incorporating fluid and pipe-wall compressibility.

This work aims to evaluate the most commonly used techniques and models for studying transient phenomena associated with pipeline emptying operations to identify advances and challenges in this field.

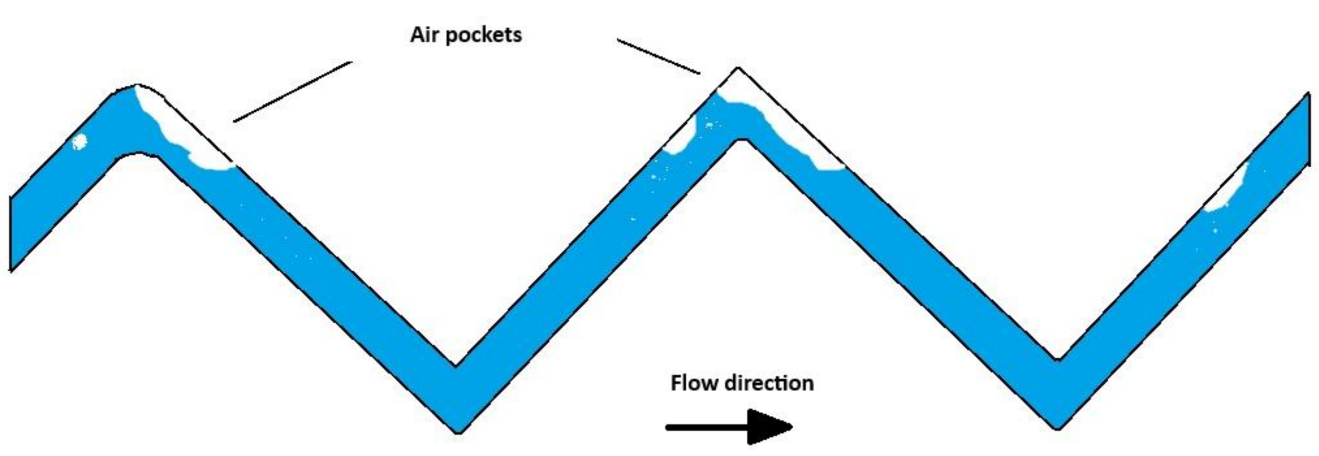

Figure 1. Schematic representation of air accumulation in an undulating pipeline during emptying

METHOD

A systematic literature review was conducted to identify experimental and numerical studies on emptying processes in pressurized pipelines.

The analysis included:

- Classification of modeling approaches: RWC, EWC, and CFD;
- Evaluation of model assumptions, boundary conditions, and validation strategies;
- Bibliometric mapping using VOSviewer, to identify research collaborations and thematic clusters.

A comparative synthesis of key references was then developed, highlighting advances, limitations, and opportunities for integrating elastic and thermodynamic effects in emptying models (Figure 2).

Problem definition	• Identify knowledge gap between filling and emptying transients in pressurized pipelines.
Literature Search	• Retrieve journal articles (2010–2025) from Scopus, Web of Science, and relevant hydraulic databases.
Classification of models	• Rigid Water Column (RWC) models • Elastic Water Column (EWC) models • Computational Fluid Dynamics (CFD) models
Analysis	• Compare assumptions, boundary conditions, and validation strategies.
Bibliometric Mapping	• Use VOSviewer to identify research clusters and collaborations.
Comparative Synthesis	• Summarize main findings and identify knowledge gaps.
Theoretical Framework	• Formulate considerations for extending the Elastic Water Column method to emptying processes.

Figure 2. Flowchart of the literature review and analysis process

RESULTS & DISCUSSION

This section presents a focused part of a broader review on transient hydraulic phenomena, addressing the thermodynamic and elastic behavior of air–water interactions during pipeline emptying. Experimental studies (e.g., [1], [2]) clearly show that during the initial stage of the transient, when air compression occurs within less than one second, the process behaves adiabatically ($m \approx 1.4$). As the event progresses, heat transfer between the air, the surrounding water, and the pipe wall causes the behavior to evolve toward quasi-isothermal conditions ($m \approx 1.0$–1.2). This observation is consistent with the results of [2], who demonstrated that the adiabatic assumption accurately reproduces the first pressure peak but tends to overpredict subsequent cycles once thermal exchange becomes significant.

Emerging methods such as the Virtual Plug Method (VPM) and local-interpolation EWC formulations provide promising foundations for future hybrid elastic models applicable to emptying [3], [4]. Table 1 summarizes some of the most influential studies addressing air–water interactions under transient conditions.

Reference	Model or Method	Application or Context	Key Findings / Relevance for Emptying Modeling
[1] Liu et al. (2011)	Rigid-Plug Elastic-Water Model (EWC)	Transient flow in pipes with entrapped air (elastic coupling)	Demonstrates elastic coupling of air-water phases; forms theoretical basis for extending EWC to emptying.
[2] Zhou et al. (2013a)	Thermodynamic study of air behavior during rapid filling	Comparison of adiabatic and quasi-isothermal air compression *(m=1.0-1.4)*	Identifies time-dependent variation of *m (1.4 to 1.0)* and its influence on pressure prediction.
[4] Zhou et al. (2013b)	Virtual Plug Method (VPM) for air–water interface representation	Simulation of transients involving two entrapped air pockets in a pipeline	Introduces a simplified piston-type formulation for air–water interface motion; potentially adaptable to emptying processes.

Table 1. Representative studies supporting the theoretical adaptation of elastic models to emptying transients.

CONCLUSION / FUTURE WORK

- The emptying process in pressurized pipelines remains a critical yet underrepresented topic in transient flow research.
- Current models do not fully capture the combined elastic, thermodynamic, and multiphase dynamics of these events.
- Further research is required to validate models under real-scale conditions, especially for systems with multiple air pockets and undulating profiles.
- The polytropic coefficient *(m)* should be treated as a dynamic variable, not a fixed constant, to better represent heat transfer and pressure attenuation.
- Future work should focus on developing hybrid elastic models that couple EWC formulations with localized CFD domains, enhancing predictive accuracy and ensuring safer pipeline operation.

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