Study on Numerical Simulation Methods for Water Hammer Effect Analysis

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Abstract

Water hammer effect constitutes one of the critical concerns in nuclear power plant thermal-hydraulic safety. In nuclear power plant piping systems, water hammer may induce pipe vibration, equipment damage, and even pipe rupture, posing challenges to the structural integrity and safety of nuclear reactors. Therefore, obtaining pressure wave propagation data under water hammer effects is essential for structural load analysis and evaluation, and is critically important for ensuring the safe and stable operation of nuclear power plants. To this end, this study investigates numerical simulation methods for water hammer pressure wave propagation, develops a one-dimensional single-phase liquid compressible flow model and numerical algorithm, and preliminarily develops a dedicated analysis program for water hammer pressure wave propagation. Preliminary verification of the program is performed using single-phase water-based wave tube benchmark problems, demonstrating good agreement. The research findings can provide theoretical and methodological support for water hammer analysis and evaluation in nuclear power plant reactors.

Full Text

Research on Numerical Simulation Methods for Water Hammer Effect Analysis

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Abstract

[**Background**] Water hammer remains one of the most critical thermal safety concerns in nuclear power plants. Accurately obtaining pressure wave propagation data under water hammer effects is essential for structural load analysis and evaluation. Currently, most water hammer analysis programs employ the Method of Characteristics (MOC), which exhibits certain computational errors when dealing with complex multi-pipe systems and capturing discontinuities. In contrast, the Finite Volume Method (FVM) offers advantages for calculating water hammer problems in complex systems, with RELAP5 being a typical example.

[**Purpose**] This paper presents the preliminary development of a water hammer pressure wave propagation analysis code based on FVM.

[**Methods**] For single-phase water hammer problems, a "vapor-liquid" compressible two-fluid three-equation model was developed, and a time-step splitting three-step algorithm with pressure iteration at its core was adopted. For single-phase water hammer problems, the code developed in this paper is more refined and efficient than the relevant models and algorithms in RELAP5. Code validation was performed using a single-phase water shock tube benchmark case, specifically comparing the simulation results of the newly developed code with those from RELAP5 and analytical solutions.

[**Results**] The results demonstrate that the newly developed code exhibits relatively low numerical dissipation when simulating water hammer pressure transients, preliminarily verifying the feasibility and accuracy of the model and algorithm.

[**Conclusions**] The feasibility of the water hammer pressure wave propagation model proposed in this paper and the accuracy of the developed code for water hammer simulation have been preliminarily verified. The relevant research results can provide theoretical and methodological support for water hammer analysis and evaluation in nuclear power plant reactors.

Keywords: Water hammer effect; Single-phase compressible flow; Pressure wave propagation; Program development; Single-phase water shock tube

Introduction

Water hammer is a pressure fluctuation phenomenon caused by sudden changes in fluid velocity due to external disturbances in piping systems, resulting in pressure surges that propagate and attenuate periodically [1-3]. Typically, water hammer pressure can exceed normal operating pressure by several tens of times, imposing tremendous hydraulic loads on pressurized structures. In nuclear energy systems, pressure wave propagation not only affects piping systems but can also, under certain special circumstances (such as rapid opening/closing of main steam pipeline valves or turbine valves), propagate along piping systems into the reactor vessel, challenging the mechanical integrity of internal structures [4-6]. Furthermore, pressure wave propagation affects the void fraction in the coolant, which can indirectly impact reactor core reactivity. In severe cases, this may force reactor shutdown. For example, in boiling water reactors, pressure wave propagation can cause steam bubbles in the coolant to collapse, leading to a sharp positive reactivity surge in the reactor core and a rapid increase in core power [6]. Therefore, water hammer effects have always been a key research issue in nuclear power plant systems [7].

Numerical simulation and program development for water hammer effects have a long history. Currently, the most common numerical simulation method for water hammer is MOC. Ghidaoui et al. [8] surveyed 11 commercial software packages available for water hammer calculations, more than half of which were developed based on the method of characteristics. For research on water hammer characteristics of nuclear power plant systems under specific accidents, MOC is also the most common approach. Zuo et al. [9] developed a primary loop water hammer analysis code based on MOC and compared its water hammer simulation capability with the Flowmaster V7 commercial software under four-pump alternating start-up conditions. Wen Jing [10] developed a specialized water hammer analysis code for sodium-cooled fast reactors using MOC. Sheng Meiling et al. [11] used PIPENET software to analyze the effects of pumps and valves on water hammer in the main feedwater pipeline system of advanced nuclear energy systems under different closure times and closure modes. Tian et al. [12] simulated valve-induced water hammer phenomena in nuclear power plant parallel dual-pump systems and pointed out that pressure peak values could be reduced by slowing down valve disc closure speed. However, due to the tight fixed relationship between time and space steps in MOC, computational errors occur when simulating multi-pipe complex systems or variable wave speed systems. Additionally, MOC may encounter numerical stability issues when solving structures with variable cross-sectional areas [13].

In response, many researchers have begun using the typical system analysis code RELAP5 for one-dimensional water hammer research in nuclear power plants. Kaliatka et al. [14,15] conducted a series of water hammer studies on RBMK-1500 reactors using RELAP5. Yi et al. [16] used RELAP5 to simulate water hammer phenomena in impeller pump water supply systems when feedwater pumps suddenly stop. Volkov et al. [17] used RELAP5 to perform mesh and time step sensitivity analyses on condensation-induced water hammer experiments in horizontal pipes. The RELAP5 code employs the Finite Volume Method (FVM) for calculations. Compared with MOC, FVM solves the governing equations in integral form, providing higher adaptability when dealing with complex geometries and boundary conditions, more effectively capturing discontinuities and calculating nonlinear convection terms, thus offering advantages in simulating water hammer phenomena in complex piping systems such as those in nuclear power plants [13,18].

In summary, to avoid the increased computational complexity and errors associated with adjusting wave speed or mesh length when processing complex piping systems, as required by MOC, this paper constructs a core model and numerical algorithm for single-phase water hammer pressure wave simulation based on the finite volume method in Cartesian coordinates. Unlike the two-fluid six-equation model used in RELAP5, the model in this paper does not consider vapor fluid dynamics calculations, only accounting for the vapor volume fraction, allowing it to share velocity and temperature fields with the liquid phase, thereby simplifying it to a two-fluid three-equation model that is more refined and computationally efficient. The algorithm employs a time-step three-partition method with pressure iteration at its core. A one-dimensional single-phase water hammer pressure wave propagation analysis code has been preliminarily developed. Preliminary verification of the developed code was conducted using a single-phase water shock tube benchmark case, comparing the simulation results of the new code with those from the system analysis code RELAP5 and the analytical solution for the single-phase water shock tube. The verification results show that the new code can better capture pressure and velocity variation processes, preliminarily verifying the correctness of the water hammer pressure wave propagation structural model and algorithm proposed in this paper. The relevant research results can provide theoretical basis and analysis methods for water hammer phenomena in nuclear power plants, thereby enhancing the understanding and assessment capabilities of water hammer phenomena.

1. Model and Algorithm

1.1 Governing Equations

Based on compressible fluid mechanics theory, this paper constructs governing equations for describing water hammer effects, encompassing mass, momentum, and energy conservation equations. When constructing the equations, the presence of steam is considered, treating single-phase water as vapor-liquid saturated state. However, this is only a special consideration for water hammer effect calculations, intended for subsequent algorithm implementation, without performing steam fluid dynamics calculations.

(1) Mass Conservation Equation
Under normal circumstances, water has low compressibility and is often treated as incompressible. However, during water hammer effects, water compressibility affects pressure changes. Therefore, this paper treats water as a compressible fluid when analyzing water hammer effects, yielding the mass conservation equation shown in Equation (1) for describing liquid water flow and compression.

In the equation, u represents the velocity of liquid water, and $L\rho$ is the macroscopic density of liquid water, which can be expressed through the relationship between the theoretical density Lr of liquid water and the liquid water volume fraction a as $L\rho = Lr \cdot a$. The subscripts L and G denote liquid water and water vapor, respectively. The vapor volume fraction Ga and liquid water volume fraction La satisfy $1 = Ga + La$.

(2) Momentum Conservation Equation
In water hammer effects, viscous effects are not significant and belong to higher-order small quantities, so they can be neglected when constructing the momen-

tum conservation equation. The gravity term is also ignored, allowing the momentum conservation equation to be simplified as shown in Equation (2).

(3) Energy Conservation Equation
Since water hammer effects occur over very short time scales, heat conduction effects can be neglected, yielding the energy conservation equation shown in Equation (3).

1.2 Equations of State (EOS)

The equation of state serves as a mathematical expression for closing the governing equations and is an essential component for pressure iteration and variable conversion. For the liquid water equation of state, refer to Equations (4) and (5).

In the equations, the subscript S denotes saturated state, while L, ST, L, Sv, and L, Sp represent the saturated temperature, saturated specific volume, and saturated pressure of liquid water, respectively. These parameters depend only on the specific internal energy of liquid water Le (the initial specific internal energy is the saturated specific internal energy of liquid water, which is subsequently updated by solving the energy conservation equation). The specific calculations are not detailed in this paper.

Through the above equations of state, the relationship between liquid water pressure Lp, liquid water specific internal energy Le, liquid water thermodynamic temperature LT, and liquid water specific volume Lv can be established. In the vapor-liquid saturated state, thermodynamic parameters of steam can be obtained, with the most critical parameter being steam partial pressure, which is a function of steam temperature and steam specific volume. Since the system is in vapor-liquid saturated state, steam temperature can be replaced by liquid water temperature. Therefore, steam partial pressure can be calculated through liquid water temperature and steam specific volume, i.e., $Gp = f(T, v)$. The steam density $G\rho$ is given as a constant during initialization and remains unchanged.

1.3 Numerical Algorithm

As can be seen from the governing equations, pressure and velocity are tightly coupled. To ensure computational convergence, this paper employs the finite volume method to discretize the governing equations on a staggered grid, with pressure stored at grid centers and velocity stored at grid interfaces. A time-step splitting three-step algorithm with pressure iteration at its core is adopted to improve numerical convergence. The specific algorithm flow is described below, with the overall flowchart shown in Figure 1 [Figure 1: see original paper].

(1) First Step: Convection Prediction
First, the discretized mass conservation equation is solved, as shown in Equation (6), to obtain the liquid water macroscopic density $L\rho^1$. Then, $L\rho^1$ is

substituted into the discretized energy conservation equation for calculation, as shown in Equation (7), to obtain the liquid water specific internal energy Le^1. Finally, the discretized momentum conservation equation is calculated, as shown in Equation (8), to obtain the liquid water velocity u^1. The subscripts E and W represent the east and west neighboring grid points of the current grid, respectively. The superscript 1 denotes the first-step calculation, while the superscript n denotes values from the previous time step (consistent throughout the following text). Notably, when discretizing the governing equations, convection terms employ explicit and first-order upwind schemes, while the pressure term in the momentum conservation equation uses an explicit scheme. Additionally, ignoring the influence of neighboring grids and approximately transforming the momentum conservation equation yields Equation (9), from which the partial derivative of velocity with respect to grid pressure $\frac{\partial u}{\partial p}$ can be calculated, primarily for use in the next pressure iteration step.

(2) Second Step: Pressure Iteration

First, to perform pressure iteration, pressure residual equations and mass conservation residual equations are constructed, with convection terms also employing semi-implicit and first-order upwind schemes, as shown in Equation (10). Since single-phase water is approximated as vapor-liquid saturated state, the EOS pressure Lp^2 can be indirectly obtained through the liquid water equation of state, while the steam thermodynamic partial pressure Gp^2 can be directly obtained. The superscript 2 denotes the second-step calculation.

Then, the pressure residual equation is expanded using first-order Taylor series with respect to the current control volume grid pressure Lp and liquid macroscopic density $L\rho$, and the mass conservation residual equation is expanded with respect to the current control volume grid pressure Lp and neighboring control volume grid pressure, as shown in Equation (11). In the equation, Δp^2, $\Delta L\rho^2$, and ΔC_{ip}^2 are unknowns, while the partial derivative parameters can be obtained by taking corresponding partial derivatives of the pressure residual equation and mass conservation residual equation, as shown in Equation (12). Additionally, Lp^2 and $L\rho^2$ use values obtained from the aforementioned first-step convection prediction. Finally, substituting Equation (12) back into Equation (11) and performing simple elimination to remove the $L\rho$ terms yields the algebraic equation shown in Equation (13), namely the pressure iteration equation, where a, b, and d are known coefficients. Subsequently, solving using matrix methods yields the entire computational domain grid pressure p^2, which is then substituted back into the pressure residual equation in Equation (11) to solve for $L\rho^2$. Based on this, grid pressure, liquid water macroscopic density, and velocity can be updated, as shown in Equation (14). The above describes only one iteration process; subsequent iterations continue until the pressure residual and mass residual satisfy convergence criteria.

(3) Third Step: End-of-Time-Step Update

This step solves the three conservation equations again based on the pressure iteration from the second step. The specific process is similar to the first-step convection prediction, with the difference being that the convection term algorithm uses a semi-implicit scheme and velocity employs the final converged value from the second step. Ultimately, grid pressure, density, specific internal energy, and velocity for a single time step are obtained.

2. Program Validation

To validate the developed single-phase water hammer pressure wave propagation simulation code, a one-dimensional single-phase water shock tube benchmark case was selected for comparative verification against the typical system analysis code RELAP5 and the analytical solution for the single-phase water shock tube. The theoretical reference for the analytical solution follows the calculation method proposed by Jishnu Chandran and Salih [19]. The shock tube schematic is shown in Figure 2 [Figure 2: see original paper], with a total length of 10 m, divided into left and right regions by a diaphragm at the center. The left side is a high-pressure subcooled water region at 10 MPa and 300 K, while the right side is a low-pressure subcooled water region at 0.1 MPa and 300 K. The initial water flow velocity in both regions is 0 m/s. Both ends of the shock tube are treated as fully reflective boundaries. The simulation begins at 0.0 s, with the central diaphragm removed instantaneously. Under the pressure difference, fluid momentum changes instantaneously, leading to pressure fluctuations—that is, water hammer effects.

To ensure computational accuracy and efficiency, a node sensitivity analysis was conducted for the shock tube case. Specifically, with a fixed time step of 10^{-5} s, four node divisions were selected for sensitivity analysis: 50, 100, 180, and 200 nodes. Figure 3 [Figure 3: see original paper] shows the pressure distribution inside the shock tube under different node divisions. It can be clearly observed that when the number of nodes is small, pressure fluctuations occur. As the number of nodes increases, pressure fluctuations gradually decrease. When the number of nodes reaches 180 or more, the pressure becomes smooth and the pressure distribution no longer changes significantly.

Based on the above node sensitivity analysis results, 180 nodes and a time step of 10^{-5} s were ultimately selected for comparative verification. The verification selected pressure and velocity distributions inside the shock tube at two different moments: 0.64 ms and 1.64 ms, as shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper]. As seen in Figure 4, after the central diaphragm is suddenly removed, water in the left high-pressure region generates shock waves that continuously propagate into the right low-pressure region, causing the right-side pressure to rise rapidly. Conversely, the right low-pressure region forms expansion waves that propagate leftward, rapidly reducing the left-side pressure. Comparing the pressure distributions at the two different moments, it is evident that as time progresses, pressure waves continuously propagate to both sides, causing pressures to rise or fall until eventual stabilization. As shown in Figure 5, removal of the central diaphragm causes the originally stable two regions to experience rapid velocity increases under the pressure difference, with maximum velocities reaching $3.32\ \mathrm{m\cdot s^{-1}}$, and both side velocities changing over time. This principle is extremely similar to water hammer phenomena caused by sudden valve opening in pipeline systems. Overall, whether considering pressure and velocity distributions inside the shock tube or their temporal variations, the simulation results from the new code show high agreement with those from RELAP5 and the analytical solution, though small local differences exist. These differences arise from variations in the models and algorithms used, resulting in different numerical dissipation and smoothing effects among different codes. As can be seen from the figures, the smoothing effect of the newly developed code is relatively small, making it closer to the analytical solution.

Conclusion

Based on compressible fluid dynamics theory, this paper has developed a water hammer pressure wave propagation analysis code in Cartesian coordinates. A one-dimensional typical single-phase water shock tube benchmark case was used for mesh sensitivity analysis and preliminary validation of the newly developed code. The simulation results of the new code were compared with those from the typical system analysis code RELAP5 and the analytical solution. The results show that the newly developed code can accurately capture the distribution and propagation characteristics of pressure and velocity under water hammer effects, and that the new code exhibits lower numerical dissipation than RELAP5, making it closer to the analytical solution. This preliminarily verifies the correctness and accuracy of the structural model and numerical algorithm proposed in this paper.

Currently, the developed code employs a first-order upwind scheme for discretizing convection terms, which needs improvement in terms of computational accuracy. Furthermore, to accurately simulate multi-dimensional water hammer pressure wave propagation in complex environments, the next step plans to optimize the program algorithm using high-order upwind schemes while developing multi-dimensional capabilities for the code.

Author Contributions

Yu Guanghui was responsible for model construction and implementation, literature review, and manuscript writing. Yan Yulin and Song Tianxin were responsible for generating and analyzing data figures and participated in literature review. Gu Zhixing provided research guidance, supervised thesis writing and revision, and provided research funding support. Gong Zhengyu provided relevant literature.

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