Research on Numerical Simulation Methods for Water Hammer Effect Analysis

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Abstract

Water hammer effect has long been a significant concern in the thermal-hydraulic safety of nuclear power plants. Accurate acquisition of pressure wave propagation data under water hammer conditions is crucial for structural load analysis and evaluation. Currently, most water hammer analysis programs employ the Method Of Characteristics (MOC), which exhibits certain computational errors when handling complex multi-pipe systems and capturing discontinuities. In contrast, the Finite Volume Method (FVM) demonstrates advantages for water hammer problems in complex systems, as exemplified by the RELAP5 code. Accordingly, this paper presents the preliminary development of a water hammer pressure wave propagation analysis program based on FVM. Specifically, for single-phase water hammer problems, a compressible "gas-liquid" two-fluid three-equation model is developed, and a time-step splitting three-step algorithm centered on pressure iteration is employed. For single-phase water hammer problems, the program developed herein is more concise and efficient than the relevant models and algorithms in RELAP5. Program verification is conducted through single-phase water shock tube benchmark problems, comparing the simulation results of the newly developed program with those of RELAP5 and analytical solutions. The results demonstrate that the newly developed program exhibits relatively low numerical dissipation when simulating water hammer pressure transients, preliminarily verifying the feasibility and accuracy of the model and algorithm. The relevant research results 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

Water hammer effect has always been one of the important concerns for thermal safety in nuclear power plants. Accurately obtaining pressure wave propagation data under water hammer effect is crucial for structural load analysis and evaluation. Currently, common water hammer analysis programs mostly adopt the Method of Characteristics (MOC), but it has certain computational errors when dealing with multi-pipe complex systems and capturing discontinuities. The Finite Volume Method (FVM) has advantages in calculating water hammer problems in complex systems, with RELAP5 being a typical program. In this regard, this paper preliminarily develops a water hammer pressure wave propagation analysis program based on FVM. Specifically, for single-phase water hammer problems, a "vapor-liquid" compressible two-fluid three-equation model is developed, and a time-step splitting three-step algorithm with pressure iteration as the core is adopted. For single-phase water hammer problems, the program developed in this paper is more refined and efficient than the relevant models and algorithms of RELAP5. Program verification is carried out through a single-phase water shock tube benchmark problem, specifically comparing the simulation results of the newly developed program with RELAP5 program results and analytical solutions. The results show that the newly developed program has relatively low numerical dissipation when simulating water hammer pressure transients, preliminarily verifying the feasibility and accuracy of the model and algorithm. The relevant research results can provide certain theoretical and methodological support for water hammer analysis and evaluation in nuclear power plant reactors.

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

Introduction

Water hammer is a pressure fluctuation phenomenon caused by external disturbances to pipeline systems that lead to sudden changes in fluid velocity, resulting in pressure surges within pipes that propagate and decay periodically[1–3]. Typically, water hammer pressure can exceed normal operating pressure by dozens

of times, creating enormous hydraulic loads on pressurized structures. In nuclear systems, pressure wave propagation not only affects pipeline systems, but under certain special circumstances (such as rapid opening and closing of main steam pipeline valves, turbine valves, etc.), pressure waves propagate along pipeline systems into the reactor vessel, posing challenges to the mechanical integrity of internal structures[4–6]. Furthermore, pressure wave propagation also affects the void fraction in coolant and changes in core structure, thereby indirectly impacting the reactivity of the reactor core, and in severe cases may force reactor shutdown[7]. For example, in boiling water reactors, pressure wave propagation can cause steam bubbles in the coolant to collapse, leading to a sharp increase in positive reactivity in the reactor core and consequently a rapid increase in core power[6]. Therefore, water hammer effect has always been one of the key research issues in nuclear power plant systems[8].

Numerical simulation and program development for water hammer effects have a long history. Currently, the most common water hammer numerical simulation method is MOC. Ghidaoui et al.[8] once surveyed 11 commercial software packages that can be used 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 method. Zuo et al.[9] developed a primary loop water hammer analysis program based on MOC and compared its water hammer simulation capability with Flowmaster V7 commercial software under the condition of four-pump alternating startup. Wen Jing[10] developed a program specialized for sodium-cooled fast reactor water hammer analysis using MOC. Sheng Meiling et al.[12] analyzed the influence of pumps and valves under different closing times and forms on water hammer in the main feedwater pipeline system of advanced nuclear energy systems using PIPENET software. Tian et al.[13] simulated valve-induced water hammer phenomena in parallel double-pump systems in nuclear power plants and pointed out that pressure peaks could be reduced by slowing down the valve disc closing speed. However, due to the tight fixed relationship between time and space steps in MOC, computational errors exist when simulating multi-pipe complex systems or systems with variable wave speed. Additionally, MOC may encounter numerical stability problems when solving structures with variable cross-sectional areas[14].

In response, many scholars began using the typical system analysis program RELAP5 for one-dimensional water hammer research in nuclear power plants. Kaliatka et al.[15,16] used RELAP5 to conduct a series of water hammer studies for RBMK-1500 reactors. Yi et al.[17] utilized RELAP5 to simulate water hammer phenomena caused by sudden stoppage of feedwater pumps in impeller pump water supply systems. Volkov et al.[18] used RELAP5 to conduct mesh and time step sensitivity analysis for condensation-induced water hammer experiments in horizontal pipes. The RELAP5 program employs the Finite Volume Method (FVM) for calculations. Compared with MOC, FVM solves control equations through integral forms, providing higher adaptability when dealing with complex geometric shapes and boundary conditions, and more effectively

capturing discontinuities and calculating nonlinear convection terms, giving it advantages in simulating water hammer phenomena in complex pipeline systems such as nuclear power plants[14,19].

In summary, to avoid increasing computational complexity and errors by adjusting wave speed or mesh length as in MOC when dealing with complex pipeline systems, 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 adopted by the RELAP5 program, the model in this paper does not consider the fluid dynamics calculation of the vapor phase, but only considers the vapor phase fraction, allowing it to share velocity and temperature fields with the liquid phase, thereby simplifying it to a two-fluid three-equation model, making the model more refined and computationally efficient. The algorithm employs a time-step three-step division method with pressure iteration as the core. A one-dimensional single-phase water hammer pressure wave propagation analysis program was preliminarily developed. Preliminary verification of the program developed in this paper was carried out using a single-phase water shock tube benchmark problem. In terms of verification method, the simulation results of the newly developed program were compared with those of the system analysis program RELAP5 and the analytical solution of the single-phase water shock tube. The verification results show that the newly developed program can better capture pressure and velocity change processes, preliminarily verifying the correctness of the proposed water hammer pressure wave propagation structural model and algorithm. The relevant research results can provide theoretical basis and analysis methods for water hammer phenomena in nuclear power plants, and also lay a foundation for subsequent integration into relevant safety analysis program packages (such as the MPC_{LBE}[20,21] developed by the research team in the early stage), thereby strengthening the understanding and assessment capabilities of water hammer phenomena.

1.1 Control Equations

This paper constructs control equations based on compressible fluid mechanics theory to describe water hammer effects, encompassing mass, momentum, and energy conservation equations. The formulation considers the presence of steam and treats single-phase water as a vapor-liquid saturated state, though this represents a special consideration for water hammer calculations rather than a full vapor hydrodynamics simulation.

(1) Mass Conservation Equation

Water is typically considered incompressible due to its low compressibility. However, during water hammer events, compressibility significantly affects pressure variations. Therefore, this analysis treats water as compressible, yielding the mass conservation equation shown in Equation (1) to describe liquid water flow and compression. In the equation, u represents liquid water velocity, L_ρ denotes the macroscopic density of liquid water (obtained from its theoretical density

L_r and volume fraction a), and subscripts L and G indicate liquid water and steam, respectively. The steam volume fraction G_a relates to the liquid water volume fraction L_a by $G_a = 1 - L_a$.

(2) Momentum Conservation Equation
Viscous effects are negligible in water hammer phenomena, representing higher-order terms, and gravitational terms are also omitted. This allows simplification to the momentum conservation equation shown in Equation (2).

(3) Energy Conservation Equation
Given the extremely short timescales of water hammer effects, thermal conduction can be ignored, resulting in the energy conservation equation shown in Equation (3).

1.2 Equations of State (EOS)

The equation of state, as a mathematical expression used to close the control equations, is essential for pressure iteration and variable conversion. For liquid water, the equations of state are given by Equations (4) and (5).

In these equations, subscript S denotes the saturated state, and $L_{S,T}$, $L_{S,v}$, and $L_{S,p}$ represent the saturated temperature, specific volume, and saturated pressure of liquid water, respectively—all dependent only on the specific internal energy of liquid water L_e (initially the saturated specific internal energy, subsequently updated by solving the energy conservation equation). Detailed calculations are not elaborated in this paper.

These equations of state establish the relationship between liquid water pressure L_p, liquid water specific internal energy L_e, liquid water thermodynamic temperature L_T, and liquid water specific volume L_v. In the vapor-liquid saturated state, thermodynamic parameters of steam can be obtained, with the most critical being steam partial pressure—a function of steam temperature and specific volume. Since the system is in vapor-liquid saturated state, steam temperature can be replaced by liquid water temperature, allowing steam partial pressure to be calculated from liquid water temperature and steam specific volume, i.e., $G_p = f(T, v)$. The steam density G_ρ is given at initialization and held constant.

1.3 Numerical Algorithm

The control equations reveal a tight coupling between pressure and velocity. To ensure computational convergence, this paper employs the finite volume method to discretize the control equations on a staggered grid, with pressure and velocity stored at cell centers and cell interfaces, respectively. A time-step three-step division algorithm with pressure iteration as the core is adopted to enhance numerical convergence. The specific algorithm flow is described below, with an overall flowchart shown in Figure 1 [Figure 1: see original paper].

(1) Step 1: Convection Prediction

First, the discretized mass conservation equation is solved, as shown in Equation (6), to obtain the macroscopic density of liquid water. This is then substituted into the discretized energy conservation equation, as shown in Equation (7), to obtain the specific internal energy of liquid water. Finally, the discretized momentum conservation equation is calculated, as shown in Equation (8), to obtain the liquid water velocity. Subscripts E and W represent the east and west neighboring grid points of the current cell, respectively. Superscript 1 indicates the first-step calculation, and superscript n indicates values from the previous time step, consistent hereafter. Notably, when discretizing the control equations, convection terms employ explicit first-order upwind schemes, while pressure terms in the momentum conservation equation are explicit. 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 can be calculated, primarily for use in the next pressure iteration step.

(2) Step 2: Pressure Iteration

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

Then, the pressure residual equation undergoes first-order Taylor expansion with respect to the current control volume pressure and liquid macroscopic density, while the mass conservation residual equation undergoes first-order Taylor expansion with respect to the current control volume pressure and neighboring control volume pressures, as shown in Equation (11). The parameters can all be obtained by taking corresponding partial derivatives of the pressure residual equation and mass conservation residual equation, as shown in Equation (12). Additionally, values calculated in the first-step convection prediction are used. Finally, substituting Equation (12) back into Equation (11) and performing simple elimination yields the algebraic equation shown in Equation (13), namely the pressure iteration equation, where a, b, and d are known constants. Subsequently, solving through matrix methods yields the entire computational domain's grid pressure. Then substituting back into the pressure residual equation in Equation (11) yields the updated values. 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; continuous iteration is required until the pressure residual and mass residual satisfy convergence criteria to end the iteration.

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

This step solves the three conservation equations again based on the second-step pressure iteration. The specific process is similar to the first-step convection pre-

diction, with the difference being that convection terms employ semi-implicit schemes and velocity uses the final converged values from the second step. Ultimately, grid pressure, density, specific internal energy, and velocity for a single time step are obtained.

2 Program Verification

To verify the single-phase water hammer pressure wave propagation simulation program developed in this paper, a one-dimensional single-phase water shock tube benchmark problem was selected for comparison with simulation results from the typical system analysis program RELAP5 and the analytical solution of the single-phase water shock tube. The theoretical reference for the analytical solution follows the calculation method proposed by Jishnu Chandran and Salih[22]. The shock tube schematic diagram 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 with pressure 10 MPa and temperature 300 K, while the right side is a low-pressure subcooled water region with pressure 0.1 MPa and temperature 300 K. The water flow velocity in both regions is initially 0 m/s at time zero. Both ends of the shock tube are treated as fully reflective boundaries. The simulation begins at 0.0 s when the central diaphragm is instantly removed. Under the pressure difference, fluid momentum changes instantaneously, leading to pressure fluctuations—that is, water hammer effects.

Figure 2 Schematic diagram of one-dimensional single-phase water shock tube

To ensure computational accuracy and efficiency, a mesh sensitivity analysis was conducted for the shock tube problem. Specifically, with a fixed time step of 10^-5 s, four mesh configurations 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 mesh 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 is greater than or equal to 180, the pressure becomes smooth and the pressure distribution no longer changes significantly.

Figure 3 Mesh sensitivity analysis of 1D single-phase water shock tube

Based on the above mesh sensitivity analysis results, 180 nodes and a time step of 10^-5 s were selected for comparative verification. The verification compares pressure and velocity distributions in the shock tube at two different time instants: 0.64 ms and 1.64 ms, as shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper]. Figure 4 shows that when the central diaphragm is suddenly removed, due to the pressure difference between the two regions, water in the left high-pressure region generates shock waves that continuously propagate toward 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 pressure distributions at two different moments, it is evident that as time progresses, pressure waves continuously propagate toward both sides, causing pressures to rise or fall until eventual stabilization. Figure 5 shows that removal of the central diaphragm causes the originally stable two regions to experience rapid velocity increases under pressure differences, with maximum velocities reaching 3.32 m · s^-1, and velocities on both sides change over time. This principle closely resembles water hammer phenomena caused by sudden valve opening in pipeline systems. Overall, whether considering pressure and velocity distributions in the shock tube or their temporal variations, the simulation results from the new program show good agreement with those from RELAP5 and the analytical solution, though minor local differences exist. These differences arise from variations in models and algorithms leading to different numerical dissipation and smoothing effects. The figures demonstrate that the newly developed program exhibits relatively smaller smoothing effects, yielding results closer to the analytical solution.

Figure 4 Pressure distribution
Figure 5 Velocity distribution

This paper developed a water hammer pressure wave propagation simulation and analysis program based on compressible fluid dynamics theory in Cartesian coordinates. A one-dimensional typical single-phase water shock tube benchmark problem was used for mesh sensitivity analysis and preliminary verification of the newly developed program. Comparisons between the new program's simulation results and those from the typical system analysis program RELAP5, along with analytical solutions, show that the newly developed program can accurately capture pressure and velocity distribution and propagation characteristics under water hammer effects, with lower numerical dissipation than RELAP5 and results closer to the analytical solution. These findings preliminarily verify the rationality and accuracy of the proposed structural model and numerical algorithm.

The current program employs first-order upwind schemes for discretizing convection terms, which needs improvement in computational accuracy. Furthermore, to accurately simulate multidimensional water hammer pressure wave propagation in complex environments, the next step plans to optimize the program algorithm using high-order upwind schemes while developing multidimensional capabilities.

Author Contribution Statement

Yu Guanghui was responsible for model construction and implementation research, literature review, and manuscript writing; Yan Yulin and Song Tianxin were responsible for data figure generation and analysis, and participated in literature review; Gu Zhixing was responsible for providing research ideas, guid-

ing paper writing and revision, and providing research funding support; Gong Zhengyu was responsible for providing relevant literature.

References

1. Choon T W, Aik L K, Aik L E, et al. Investigation of water hammer effect through pipeline system[J]. International Journal on Advanced Science, Engineering and Information Technology, 2012, 2(3): 246. DOI: 10.18517/ijaseit.2.3.196.
2. Urbanowicz K, Ramos H M. New advances in water hammer problems[J]. Water, 2023, 15(22): 4004. DOI: 10.3390/w15.
3. Lupa S I, Gagnon M, Muntean S, et al. The impact of water hammer on hydraulic power units[J]. Energies, 2022, 15(4): 1526. DOI: 10.3390/en15041526.
4. GONG Zhengyu, GU Zhixing, PAN Qiwen, et al. Development and verification of code for simulation of vapor-liquid two-phase 2D pressure wave propagation[J]. Nuclear Techniques, 2023, 46(6): 136-146. DOI: 10.11889/j.0253-3219.2023.hjs.46.060605.
5. Delchini M O, Ragusa J C, Berry R A. Simulations of single- and two-phase shock tubes and gravity-driven wave problems with the RELAP-7 nuclear reactor system analysis code[J]. Nuclear Engineering and Design, 2017, 319: 106-116. DOI: 10.1016/j.nucengdes.2017.04.034.
6. Barten W, Jasiulevicius A, Manera A, et al. Analysis of the capability of system codes to model cavitation water hammers: simulation of UMSICHT water hammer experiments with TRACE and RELAP5[J]. Nuclear Engineering and Design, 2008, 238(4): 1129-1145. DOI: 10.1016/j.nucengdes.2007.10.004.
7. CAO Jintong, ZHU Guifeng, GU Zhixing. Influence of core structural changes in dispersed-graphite-component molten salt reactor on nuclear reactivity[J]. Nuclear Techniques, 2024, 47(06): 060601. DOI: 10.11889/j.0253-3219.2024.hjs.47.060601.
8. Wenxi T, Guanghui S, Gaopeng W, et al. Mitigating check valve slamming and subsequent water hammer events for PPFS using MOC[J]. Nuclear Science and Techniques, 2009, 20(2): 118-123. DOI: 10.13538/j.1001-8042/nst.20.118-123.
9. Ghidaoui M S, Zhao M, McInnis D A, et al. A review of water hammer theory and practice[J]. Applied Mechanics Reviews, 2005, 58(1): 49-76. DOI: 10.1115/1.1828050.
10. Zuo Q, Qiu S, Lu W, et al. Water hammer characteristics of integral pressurized water reactor primary loop[J]. Nuclear Engineering and Design, 2013, 261: 165-173. DOI: 10.1016/j.nucengdes.2013.03.038.
11. WEN Jing, LUAN Lin, JIN Degui, et al. Water hammer program development and application for fast breeder reactor's sodium circuit[J]. Atomic Energy Science and Technology, 2001, 35(2): 108-115. DOI: 10.3969/j.issn.1000-6931.2001.02.003.
12. SHENG Mei-ling, TIAN Wei-wei, QIU Jin-meng, et al. Simulation and

calculation of water hammer to main feedwater line in passive advanced nuclear power plant[J]. Atomic Energy Science and Technology, 2015, 49(Suppl.1): 200-204. DOI: 10.7538/yzk.2015.49.S0.0200.

13. Tian W, Su G H, Wang G, et al. Numerical simulation and optimization on valve-induced water hammer characteristics for parallel pump feedwater system[J]. Annals of Nuclear Energy, 2008, 35(12): 2280-2287. DOI: 10.1016/j.anucene.2008.04.007.
14. Pal S, Hanmaiahgari P R, Karney B W. An overview of the numerical approaches to water hammer modelling: the ongoing quest for practical and accurate numerical approaches[J]. Water, 2021, 13(11): 1597. DOI: 10.3390/w13111597.
15. Kaliatka A, Uspuras E, Vaisnoras M. Benchmarking analysis of water hammer effects using RELAP5 code and development of RBMK-1500 reactor main circulation circuit model[J]. Annals of Nuclear Energy, 2007, 34(1): 1-12. DOI: 10.1016/j.nucengdes.2006.11.010.
16. Kaliatka A, Vaišnoras M, Valinčius M, et al. RELAP5 application for water hammer analysis in different thermal-hydraulic systems[J]. International Journal of Thermofluids, 2022, 14: 100154. DOI: 10.1016/j.ijft.2022.100154.
17. Yi W S, Jiang J, Li D D, et al. Pump-stopping water hammer simulation based on RELAP5[J]. IOP Conference Series: Materials Science and Engineering, 2013, 52(7): 072009. DOI: 10.1088/1757-899X/52/7/072009.
18. Volkov G J, Elkin I V, Kapustin A V, et al. Experimental and calculated studies of condensation-induced water hammer[J]. Thermal Engineering, 2021, 68: 142-151. DOI: 10.1134/S0040601521020087.
19. Daude F, Tijsseling A S, Galon P. Numerical investigations of water-hammer with column-separation induced by vaporous cavitation using a one-dimensional Finite-Volume approach[J]. Journal of Fluids and Structures, 2018, 83: 91-118. DOI: 10.1016/j.jfluidstructs.2018.08.014.
20. ZHANG Ling, GU Zhixing, DAI Jianing, et al. Accident of lead-bismuth subcritical reactor XADS[J]. Nuclear Techniques, 2022, 45(10): 100602. DOI: 10.11889/j.0253-3219.2022.hjs.45.100602.
21. Gu Z X, Zhang Q X, Gu Y, et al. Verification of a self-developed CFD-based multi-physics coupled code MPC-LBE for LBE-cooled reactor[J]. Nuclear Science and Techniques, 2021, 32(5): 52. DOI: 10.1007/s41365-021-00887-x.
22. Jishnu Chandran R, Salih A. Development of a benchmark solution in compressible liquid flows: analytical solution to the water shock tube problem[J]. Journal of Thermal Analysis and Calorimetry, 2022, 147(8): 5279-5292. DOI: 10.1007/s10973-021-10871-7.

Note: Figure translations are in progress. See original paper for figures.