VALIDATION OF CATHENA MOD-3.5c/Rev0 FOR SINGLE-PHASE WATER HAMMER

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ABSTRACT

This paper describes work performed to validate the system thermalhydraulics code CATHENA MOD-3.5c/Rev0 for single-phase water hammer. Simulations were performed and are compared quantitatively against numerical tests and experimental results from the Seven Sisters Water Hammer Facility to demonstrate CATHENA can predict the creation and propagation of pressure waves when valves are opened and closed. Simulations were also performed to show CATHENA can model the behaviour of reflected and transmitted pressure waves at area changes, dead ends, tanks, boundary conditions, and orifices in simple and more complex piping systems. The CATHENA results are shown to calculate pressure and wave propagation speeds to within 0.2% and 0.5% respectively for numerical tests and within 3.3% and 5% for experimental results respectively. These results are used to help validate CATHENA for use in single-phase water hammer analysis. They also provide assurance that the fundamental parameters needed to successfully model more complex forms of water hammer are accounted for in the MOD-3.5c/Rev0 version of CATHENA, and represent the first step in the process to validate the code for use in modelling two-phase water hammer and condensation-induced water hammer.

1. INTRODUCTION

CATHENA is a system thermalhydraulics code developed by Atomic Energy of Canada Limited (AECL) primarily for analysis of postulated Loss Of Coolant Accident (LOCA) events in CANDU® reactors [1]. One of the phenomena CATHENA will be used to analyze is water hammer. Water hammer can, and does occur in nuclear power plants under normal as well as shutdown conditions. Some water hammer events can be averted by making design modifications or by changing operating procedures. However, under certain circumstances it may not be possible to avoid the conditions which lead to water hammer. For example, water hammer may be unavoidable during emergency core cooling of a reactor. In such cases, the potential for water hammer and its impact can only be assessed through numerical simulation, and it is important to have a validated tool at hand to perform these simulations.

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This paper summarizes the effort to validate CATHENA MOD-3.5c/Rev 0 for single-phase water hammer. In this work, CATHENA simulation results are compared with numerical solutions to analytical problems (tests) and experimental data obtained from the Seven Sisters Water Hammer Facility. These results provide a basis on which validation of more complex two-phase and condensation-induced water hammer can be conducted.

2. WATER HAMMER

Water hammer is defined as the change in pressure that occurs in a fluid system as a result of a change in the fluid velocity. The magnitude of the pressure change can be sufficient to cause mechanical failure of a system. This pressure change is a result of the conversion of kinetic energy into pressure, which creates compression waves, or the conversion of pressure into kinetic energy, which creates rarefaction waves. In single-phase water hammer, the water is initially in the liquid state, and remains in the liquid state for the duration of the water hammer event.

When water hammer occurs, a pressure wave is generated and passes through the piping system. Accurate prediction of the magnitude of the pressure waves and their propagation velocity are two essential fundamental requirements in a thermalhydraulic code qualified to perform water hammer analysis. In addition, any obstructions, changes in area, dead ends, tanks, or orifices located in the flow path can cause reflections of the oncoming pressure waves. As the wave passes through the area change, part of the wave is reflected back, and part is transmitted, travelling further along the initial path. The two resulting waves travel in opposite directions, and the pressure behind both is the same. Accurate prediction of these phenomena is also required in a code used for water hammer analysis.

3. THE CATHENA CODE

The acronym CATHENA stands for Canadian Algorithm for THErmalhydraulic Network Analysis. The CATHENA code was developed by Atomic Energy of Canada Limited (AECL) at Whiteshell Laboratories (WL) in Pinawa, Manitoba [1]. The CATHENA code was developed primarily for analysis of postulated LOCA events in CANDU reactors, although it has been applied to a wide range of thermalhydraulic problems. CATHENA uses a transient, one-dimensional two-fluid representation of two-phase flow in piping networks. In the thermalhydraulic model, the liquid and vapour phases may have different pressures, velocities, and temperatures. The thermalhydraulic model consists of solving six partial differential equations for the conservation of mass, momentum and energy for each phase. Interface mass, energy and momentum transfer between the liquid and vapour phases are specified using constitutive relations obtained either from the literature or developed from separate-effect experiments. The code uses a staggered-mesh, one-step, semi-implicit, finite-difference solution method, that is not transit time limited. The extensive wall heat transfer package includes radial and circumferential conduction, solid-solid contact, thermal radiation, pressure tube deformation and the zirconium-steam reaction. The heat transfer package is general and allows the connection of multiple wall surfaces to a single thermalhydraulic node. The code also includes component models required to complete loop simulations, such as pumps, valves, tanks, break discharge, separators and an extensive control system modelling capability.

4. NUMERICAL TESTS

In this section, results generated by CATHENA MOD-3.5c/Rev 0 are compared with numerical solutions to analytical problems. It is essential to show that CATHENA is capable of modelling the fundamental propagation of water hammer pressure waves and both the reflected and transmitted pressure waves created by obstructions, changes in area, or dead ends, tanks, or orifices since models of any reactor will contain these features.

The CATHENA MOD-3.5c/Rev 0 simulations were executed on the WU28 HP-UX 9000/800 computer. All numerical validation tests were performed using simple pipe geometries with no wall friction to compare the simulated results with the analytical solutions which also assumed the absence of wall friction. The only minor losses considered were due to pipe expansion or contraction or the presence of a valve or orifice as noted. The time step size was set to a maximum of 1.0×10^{-5} sec, the minimum time step to 1.0×10^{-7} sec, and the maximum length per node was 1 m or smaller. Unless otherwise noted, the only non-default setting used in these simulations was the removal of the wall friction.

4.1 Instantaneous Valve Closure, Constant Pressure Boundary Condition

The objective of this test is to assess the ability of CATHENA to simulate the abrupt pressure changes exhibited by a travelling pressure wave generated by a water hammer in a simple pipe geometry. Both the magnitude of the pressure change and the propagation velocity of a pressure wave generated as a result of an instantaneous valve closure are examined.

The problem is depicted in Figure 1. It consists of an 80 m long, 2.54 cm internal diameter (ID) horizontal pipe. Infinite volume pressure reservoirs are attached to the ends of the pipe, and a valve is located between the pipe and the right hand reservoir. The pipe is filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right through the pipe at a velocity of 1 m/s at a nominal pressure of 2 MPa and a temperature of 25°C. There is no wall friction, and the only minor loss occurs through the valve. At the beginning of the test, the valve is instantaneously closed, causing a water hammer pressure excursion to travel back and forth in the pipe without diminishing.

The CATHENA model of this test is depicted in Figure 2. It consisted of an 2.54 cm ID pipe 80 m long, divided into 80 nodes. A pressure boundary condition was attached to each end of the pipe, and the pressures were set such that the flow occurred from left to right in the pipe. A valve was located between the pipe and the right-hand boundary condition. A steady state was first established with the valve open, the liquid temperature set at 25°C and the right hand pressure boundary condition set at 2 MPa. The left-hand pressure boundary condition was set at 2.0013409 MPa to establish a steady flow at a velocity of 1 m/s in the pipe. At the start of the transient the valve was instantaneously shut, thus rapidly decelerating the flow and creating a water hammer pressure excursion.

Figure 3 shows the analytical [2] and simulated pressure histories at the pipe node closest to the valve. The water hammer wave velocity and peak pressure were predicted within 0.5% and 0.07% of the analytical solution respectively. This shows that CATHENA is capable of modelling the velocity and magnitude of a water hammer pressure wave resulting from the closure of a valve.

4.2 Instantaneous Valve Closure, Tank Boundary Condition

This case is identical to the case discussed in Section 4.1 with the exception of the presence of the tank at the left hand boundary of the pipe instead of the pressure boundary condition. Replacing the pressure boundary condition with a tank should not affect the results. The objective of this case is to ensure a tank can successfully be used as part of a CATHENA simulation involving water hammer. Both the magnitude of the pressure change and the propagation velocity of a pressure wave generated as a result of an instantaneous valve closure will be examined as it reflects off a dead end (closed valve) at one end of the pipe, and a large tank at the other.

The problem is depicted in Figure 4. It consists of an 80 m long, 2.54 cm ID horizontal pipe. A 10 m diameter, 12 m high tank is attached to the left end of the pipe, and a pressure reservoir to the right end. A valve is located between the pipe and the right hand reservoir. The tank and pipe are filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right through the pipe at a velocity of 1 m/s at a nominal pressure of 2 MPa and a temperature of 25°C. There is no wall friction, and the only minor loss occurs through the valve. At the beginning of the test, the valve is instantaneously closed, causing a water hammer pressure excursion to occur which travels back and forth in the pipe without diminishing.

The CATHENA model of this test is depicted in Figure 5. It consisted of a 2.54 cm ID pipe 80 m long, divided into 80 nodes. A 10 m diameter, 12 m high vertical tank filled with light water to a level of 10 m was attached to the left end of the pipe, and a pressure boundary condition to the right. A pressure boundary condition was attached to the top of the tank, and a numeric option was added to eliminate the effects of condensation within the tank. A valve was located between the pipe and the right-hand boundary condition, and the pressures were set such that the flow occurred from left to right in the pipe.

A steady state was established with the valve open, the liquid temperature set at 25°C, and the right hand pressure boundary condition set at 2 MPa. The pressure boundary condition attached to the top of the tank was adjusted to 1.9040237 MPa to establish a steady flow at a velocity of 1 m/s in the pipe toward the valve. At the start of the transient the valve was instantaneously shut, thus rapidly decelerating the flow and creating a water hammer pressure excursion.

Figure 6 shows the analytical [2] and simulated pressure histories at the pipe node closest to the valve. The water hammer wave velocity and peak pressure were predicted within 0.5% and 0.06% of the analytical solution respectively. This shows that CATHENA is capable of modelling a water hammer pressure wave resulting from the closure of a valve. When compared to the simulation of

Section 4.1, these results show that both constant pressure boundary conditions, as well as tanks can be used in water hammer simulations.

4.3 Wave Transmission and Reflection at an Expansion

The objective of this case is to assess the ability of CATHENA to simulate the reflected and transmitted waves created when a water hammer pressure excursion passes through an expansion in a simple pipe geometry. In this case, the magnitude of the water hammer pressure wave before and after reflection and transmission at the expansion are examined.

The problem is depicted in Figure 7. It consists of an 80 m long, 2.54 cm ID horizontal pipe section connected to an 80 m long, 1.27 cm ID horizontal pipe section. Pressure reservoirs are attached to the open ends of the pipes, and a valve is located between the pipe and the right hand reservoir. The pipe is filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right through the pipe at a velocity of 0.66944 m/s in the smaller pipe segment at a nominal pressure of 2 MPa and a temperature of 25°C. There is no wall friction, and the only minor loss occurs through the valve and the area change. At the beginning of the test, the valve is instantaneously closed, causing a water hammer pressure excursion to travel from right to left in the pipe, reflecting off the expansion.

The CATHENA model of this test is depicted in Figure 8. It consisted of a 2.54 cm ID pipe segment 80 m long, divided into 80 nodes, connected to a 1.27 cm ID pipe segment 80 m long, divided into 80 nodes. Pressure boundary conditions were attached to the pipe ends, and the pressures were set such that the flow occurred from left to right in the pipe. A valve was located between the pipe and the right-hand boundary condition. A steady state condition was established in which the valve was open with the liquid temperature set at 25°C. The right hand pressure boundary condition was set at 2 MPa, and the left hand pressure boundary condition at 2.000127 MPa to establish a steady flow rate at a velocity of 0.66944 m/s in the smaller pipe segment. At the start of the transient, the valve was instantaneously shut, thus rapidly decelerating the flow and creating a water hammer pressure excursion.

Figures 9 and 10 show the analytical [2] and simulated axial pressure profiles in the pipe before and after reflection at the expansion respectively. Both the initial pressure of the water hammer wave, as well as the reflected and transmitted pressures were predicted within 0.2% of the analytical solution. This shows that CATHENA is capable of modelling the effect a pipe expansion has on a water hammer pressure wave.

4.4 Wave Transmission and Reflection at a Contraction

The objective of this case is to assess the ability of CATHENA to simulate the reflected and transmitted waves created when a water hammer pressure excursion passes through a contraction in a simple pipe geometry. In this case, the magnitude of the water hammer pressure wave before and after reflection and transmission at the contraction are examined.

The problem is depicted in Figure 11. It consists of an 80 m long, 1.27 cm ID horizontal pipe section connected to an 80 m long 2.54 cm ID horizontal pipe section. Pressure reservoirs are attached to the ends of the pipe, and a valve is located between the pipe and the right hand reservoir. The pipe is filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right through the pipe at a velocity of 0.41412 m/s in the larger pipe segment at a nominal pressure of 2 MPa and a temperature of 25°C. There is no wall friction, and the only minor loss occurs through the valve and the area change. At the beginning of the test, the valve is instantaneously closed, causing a water hammer pressure excursion to travel from right to left in the pipe, reflecting off the expansion.

The CATHENA model of this test is depicted in Figure 12. It consisted of a 1.27 cm ID pipe segment 80 m long, divided into 80 nodes, connected to a 2.54 cm ID pipe segment 80 m long, divided into 80 nodes. Pressure boundary conditions were attached to the pipe ends, and the pressures were set such that the flow occurred from left to right in the pipe. A valve was located between the pipe and the right-hand boundary condition. A steady state was established in which the valve was open with the liquid temperature set at 25°C. The right hand pressure boundary condition was set at 2 MPa, and the left hand pressure boundary condition at 2.0001 MPa to establish a steady flow with a velocity of 0.41412 m/s in the larger pipe segment. At the start of the transient the valve was instantaneously shut, thus rapidly decelerating the flow and creating a water hammer pressure excursion.

Figures 13 and 14 show the analytical [2] and simulated axial pressure profiles in the pipe before and after reflection at the contraction respectively. Both the initial pressure of the water hammer wave, as well as the reflected and transmitted pressures were predicted within 0.2% of the analytical solution. This shows that CATHENA is capable of modelling the effect a pipe contraction has on a water hammer pressure wave.

4.5 Wave Reflection at a Dead End

The objective of this case is to assess the ability of CATHENA to simulate the reflected wave created when a water hammer pressure excursion reflects off a dead end in a simple pipe geometry. In this case, the pressure of the water hammer wave before and after reflection at the dead end are examined.

The problem is depicted in Figure 15. It consists of a 160 m long, 2.54 cm ID horizontal pipe. The left end of the pipe is a dead end, and a pressure reservoir is attached to right end. The pipe is filled with quiescent (i.e. no flow) light water at a temperature of 25°C and a pressure of 2 MPa. At the beginning of the test, the pressure in the boundary condition is set to 3.5 MPa, causing a water hammer pressure excursion to travel from right to left in the pipe, reflecting off the dead end.

The CATHENA model of this test is depicted in Figure 16. It consisted of a 2.54 cm ID pipe segment 160 m long, divided into 160 nodes. The flow of 25°C light water in the pipe was set to zero and the pressure was set to 2.0 MPa. A pressure boundary condition was attached to the right end of the pipe, which was set to 3.5 MPa at the beginning of the simulation, thus creating a water hammer pressure excursion.

Figures 17 and 18 show the analytical [2] and simulated axial pressure profiles in the pipe before and after reflection at the dead end respectively. Both the initial pressure of the water hammer wave, as well as the reflected and transmitted pressures were predicted within 0.2% of the analytical solution. This shows that CATHENA is capable of modelling a water hammer pressure wave as it is reflected off a dead end in a pipe.

4.6 Wave Transmission and Reflection at an Orifice

The objective of this case is to assess the ability of CATHENA to simulate the reflected and transmitted waves created when a water hammer pressure excursion passes through an in-line orifice in a simple pipe geometry. In this case, the pressure of the water hammer wave before and after reflection and transmission at the orifice are examined.

The problem is depicted in Figure 19. It consists of two 80 m long, 2.54 cm ID horizontal pipe sections connected by an orifice with a flow area equal to 1/32 of the flow area of the pipes. Pressure reservoirs are attached the ends of the pipes. The pipes are filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right. The pressure is 2.2 MPa upstream of the orifice and 2.0 MPa downstream of the orifice. The water temperature is 25°C. There is no wall friction, and the only minor loss occurs at the orifice. At the beginning of the test, the pressure at the left-hand reservoir is instantaneously increased to 2.3 MPa, causing a water hammer pressure excursion to travel from left to right in the pipe, reflecting off the orifice.

The CATHENA model of this test is depicted in Figure 20. It consisted of a 2.54 cm ID pipe segment 80 m long, divided into 80 nodes, connected to another 2.54 cm ID pipe segment which is also 80 m long and divided into 80 nodes. Pressure boundary conditions were attached to the pipe ends, and the pressures were set such that the flow of 25°C light water occurred from left to right in the pipe. An orifice with a flow area equal to 1/32 the area of the pipe was inserted between the two pipe segments.

A steady state was established in which the left-hand pressure boundary condition was set to 2.2 MPa and the right-hand pressure boundary condition was set to 2.0 MPa. At the start of the transient the left-hand pressure boundary condition was set to 2.3 MPa, thus creating a water hammer pressure excursion which travelled from left to right towards the orifice.

Figures 21 and 22 show the analytical [2] and simulated axial pressure profiles in the pipe before and after reflection at the orifice respectively. Both the initial pressure of the water hammer wave, as well as the reflected and transmitted pressures were predicted within 0.05% of the analytical solution. This shows that CATHENA is capable of modelling a water hammer pressure wave as it is reflected off and transmitted through an orifice in a pipe.

4.7 Wave Transmission and Reflection at an Orifice at a Pipe End

The objective of this case is to assess the ability of CATHENA to simulate the reflected and transmitted waves created when a water hammer pressure excursion passes through an orifice located at the end of a pipe in a simple pipe geometry. In this case, the pressure of the water hammer wave before and after reflection at the orifice are examined.

The problem is depicted in Figure 23. It consists of a 160 m long, 2.54 cm ID horizontal pipe. Pressure reservoirs are attached to the ends of the pipe. The pipe is filled with light water, and the pressure differential across the pipe is adjusted such that the water is flowing from left to right through the pipe. The pressure upstream of the orifice is 2.2 MPa and 2.0 MPa downstream of the orifice. The water temperature is 25°C. There is no wall friction, and the only minor loss occurs at the orifice. The flow area of the orifice is 1/32 the area of the pipe. At the beginning of the test, the pressure at the left-hand reservoir is instantaneously increased to 2.3 MPa, causing a water hammer pressure excursion to travel from left to right in the pipe, reflecting off the orifice.

The CATHENA model of this test is depicted in Figure 24. It consisted of a 2.54 cm ID pipe segment 160 m long, divided into 160 nodes. Pressure boundary conditions were attached to the ends of the pipe, and the pressures were set such that the flow of 25°C light water occurred from left to right in the pipe. An orifice which had a flow area equal to 1/32 the area of the pipe was inserted between the right-hand end of the pipe and the right-hand pressure boundary condition.

A steady state was established in which the left-hand pressure boundary condition was set to 2.2 MPa and the right-hand pressure boundary condition was set to 2.0 MPa. At the start of the transient, the left-hand pressure boundary condition was set to 2.3 MPa, thus creating a water hammer pressure excursion which travelled from left to right towards the orifice.

Figures 25 and 26 show the analytical [2] and simulated axial pressure profiles in the pipe before and after reflection at the orifice respectively. Both the initial pressure of the water hammer wave, as well as the reflected and transmitted pressures were predicted within 0.005% of the analytical solution. This shows that CATHENA is capable of modelling a water hammer pressure wave as it is reflected off an orifice located at the end of a pipe.

5. EXPERIMENTAL TESTS: SEVEN SISTERS WATER HAMMER FACILITY

The Seven Sisters Water Hammer Facility was located in the Manitoba Hydro Seven Sisters Generating Station. It was operated to provide water hammer data to be used for code validation. The test facility configuration used for single-phase water hammer tests is shown schematically in Figure 27. In the single-phase water hammer tests, valve MV13 was open, and valve MV2 was closed for the duration of the experiment. Valve MV1 was initially open. After establishing a desired flow and pressure in the system, MV1 was rapidly closed. The initial system pressure and flow conditions were set such that the system stayed in the single-phase liquid state for the duration of the resulting water hammer.

Two tests were chosen for CATHENA validation: tests O6FC04 and O1FC02. Test O6FC04 had the lowest initial flow and the longest valve closing time, and therefore produced the smallest water hammer pressure wave. Conversely, test O1FC02 had the highest initial flow and the shortest valve closing time, and therefore produced the largest water hammer pressure wave.

The CATHENA idealization of the Seven Sisters Water Hammer Test Facility used to model both the O6FC04 and O1FC02 tests is shown Figure 28. No non-default settings were used in these simulations. The maximum time step was set to 1.0×10^{-5} sec, the minimum time step to 1.0×10^{-7} sec, and the maximum length per node was 1 m. The CATHENA MOD-3.5c/Rev 0 simulations were executed on the WU28 HP-UX 9000/800 computer.

5.1 Test O6FC04

Measured and simulated pressures at valve MV1 are shown in Figure 29. The error bars indicate the uncertainty in the measured values according to the manufacturer's quoted instrument accuracy.

Generally, the salient features of the experimental pressure excursions caused by the water hammer were present in the CATHENA simulation. CATHENA calculated the timing of the pressure increase in the system resulting from the initial closing of the valve to within 2 ms. The peak pressures of the initial pressure excursion were within 1.3% of the experimental values and within experimental error. The period of the pressure excursions (time between pressure excursions, as measured from the first to the second pressure excursion) was calculated to within 5%.

The overall decay of the experimentally measured pressure excursions was considerably faster than the simulated decay. This may be a result of CATHENA not including energy dissipation due to fluid/structure interactions.

5.2 Test O1FC02

Measured and simulated pressures at valve MV1 are shown in Figure 30. The error bars indicate the uncertainty in the measured values according to the manufacturer's quoted instrument accuracy.

Generally, the salient features of the experimental pressure excursions caused by the water hammer were present in the CATHENA simulation. CATHENA calculated the timing of the pressure increase in the experimental system resulting from the initial closing of the valve to within 2 ms. Peak pressures of the initial pressure excursion were within 3.3% of the experimental values and were within experimental error. The period of pressure excursions (time between pressure excursions, as measured from the first to the second pressure excursion) was simulated to within 5%.

As in the previous test results, the overall decay of the experimentally measured pressure excursions was considerably faster than the simulated decay. This may be a result of CATHENA not including energy dissipation due to fluid/structure interactions.

5.3 Sensitivity Analysis

A sensitivity analysis was conducted for both test O6FC04 and O1FC02 to examine the effect of uncertainties in the measured initial steady state flow and system temperature. The results indicated that neither a ±0.55% change in the fluid flow rate nor a ±1°C change in the system temperature had a significant influence on the simulated water hammer pressure waves.

6. SUMMARY AND CONCLUSIONS

Seven numerical tests were simulated using CATHENA MOD-3.5c/Rev. 0, including a water hammer pressure wave generated via an instantaneous valve slam, reflection and transmission of a pressure wave from at an area change (both expansion and contraction) and an orifice located in the middle of a pipe, and reflection of a pressure wave from a dead end and an orifice located at the end of a pipe. The simulation results from all tests showed that the single-phase water hammer pressure wave velocity was calculated to within 0.5% of the analytical solution, and pressure was calculated to within 0.2% of the analytical solution for the numerical tests examined.

Two Seven Sisters Water Hammer Facility single-phase water hammer tests were simulated using CATHENA MOD-3.5c/Rev 0. These tests represent the bounding cases of the experimental conditions examined. In one test the initial flow was the lowest and the valve was closed the slowest (O6FC04), and in the other test the flow was the highest and the valve closing time was the fastest (O1FC02) of all tests conducted. The CATHENA results showed that the peak pressures of the experiments were simulated within experimental error. The peak pressure of the initial water hammer pressure excursion on valve closure was calculated to within 3.3%, and the wave propagation speed was calculated to within 5%. A sensitivity analysis showed that the predicted results were not sensitive to the uncertainty in the fluid flow rate and the system temperature.

7. ACKNOWLEDGEMENTS

Thanks goes out to R. Swartz for his help and cooperation.

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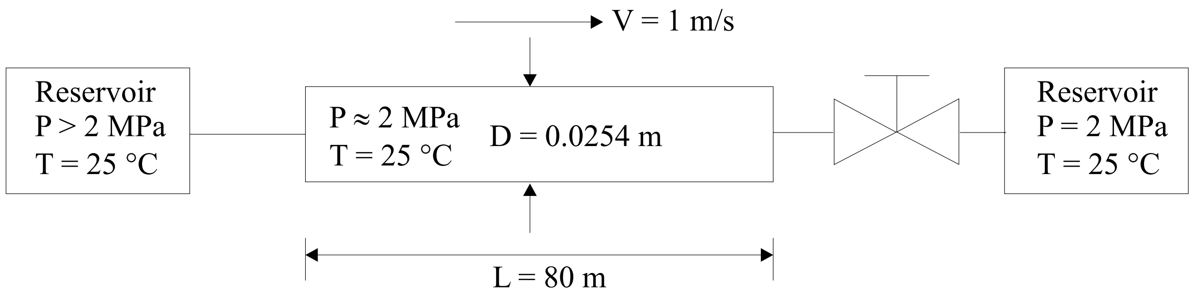

FIGURE 1: Test of instantaneous valve closure with constant pressure boundary conditions.

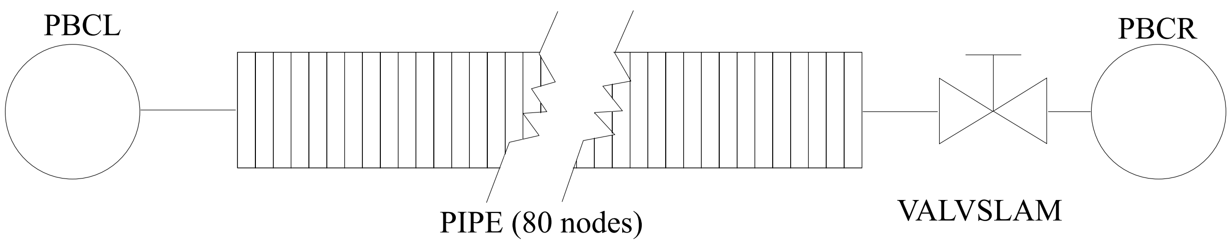

FIGURE 2: CATHENA model of instantaneous valve closure test with constant pressure boundary condition.

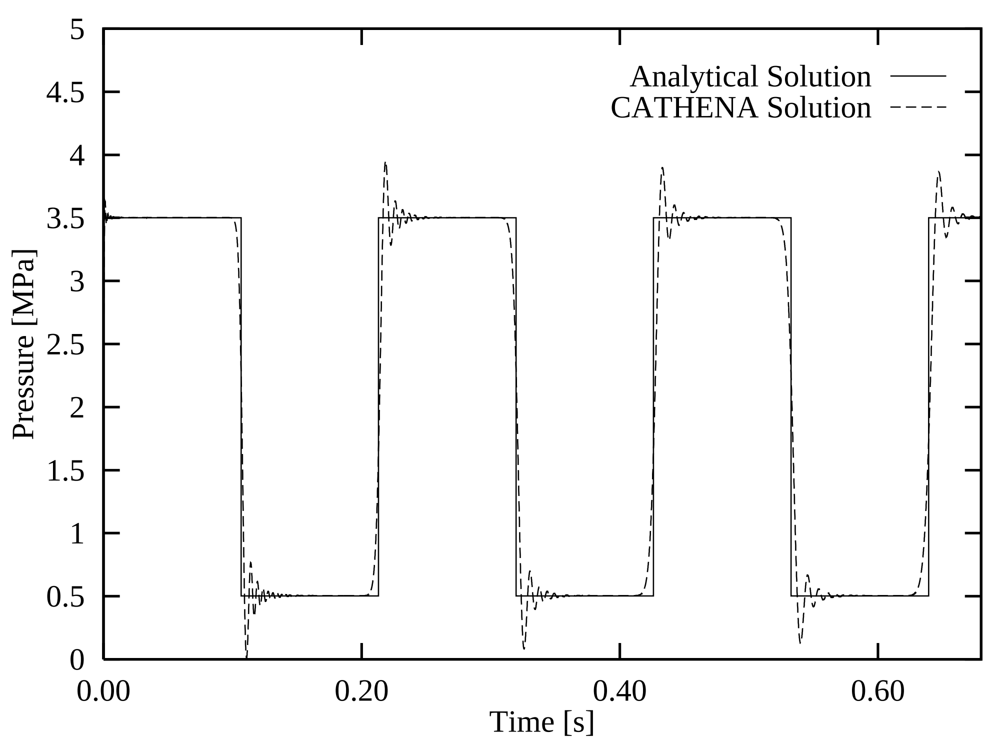

FIGURE 3: Analytical and simulated pressure histories of instantaneous valve closure test with constant pressure boundary condition.

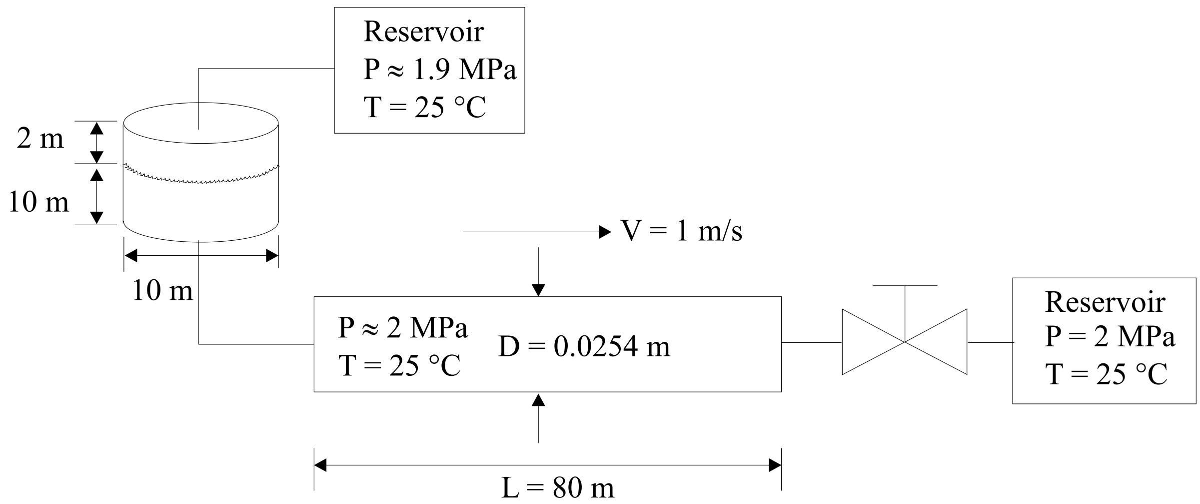

FIGURE 4: Instantaneous valve closure test with tank boundary condition.

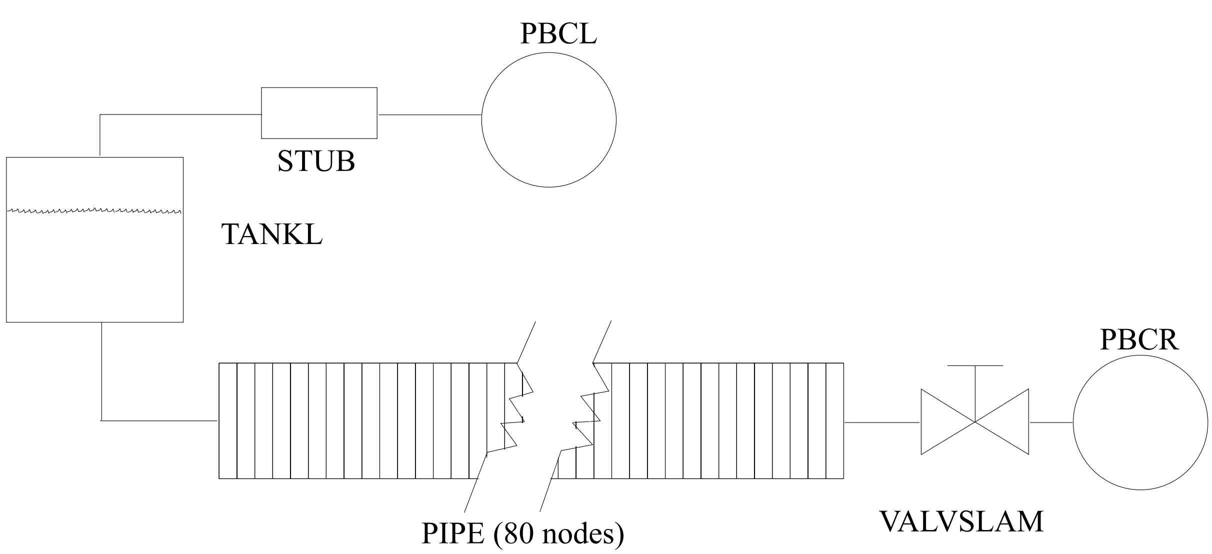

FIGURE 5: CATHENA model of instantaneous valve closure test with tank boundary condition.

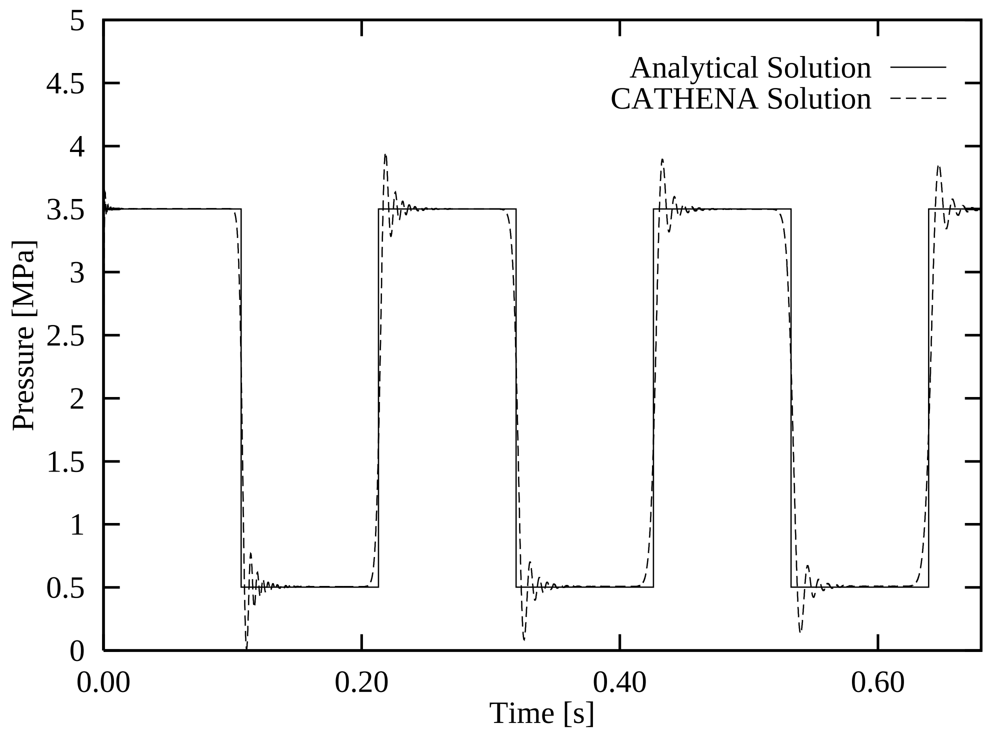

FIGURE 6: Analytical and simulated pressure histories of instantaneous valve closure test with tank boundary condition.

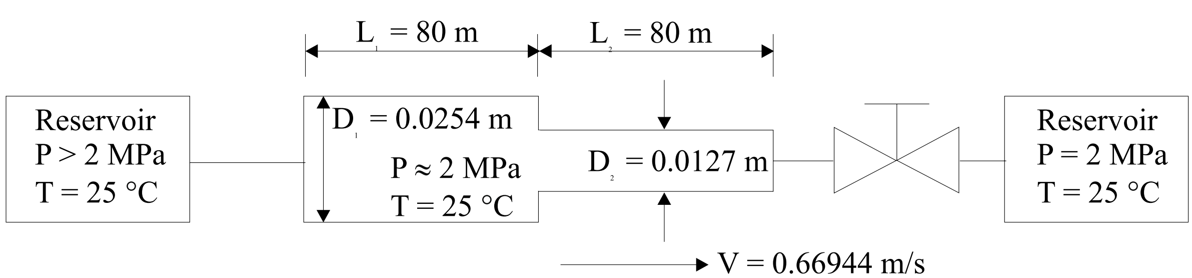

FIGURE 7: Test of wave transmission and reflection at an expansion.

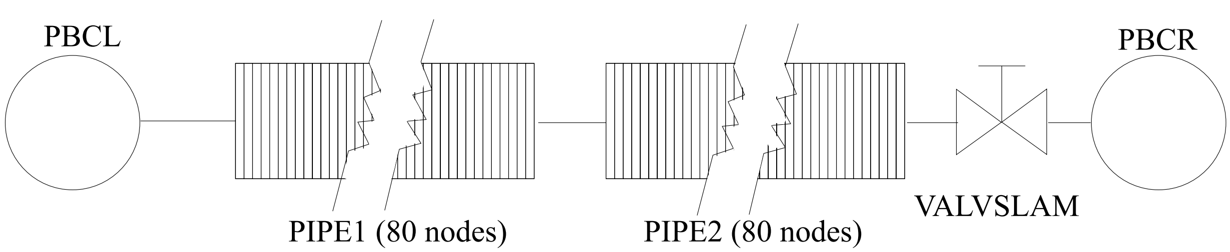

FIGURE 8: CATHENA model of test of wave transmission and reflection at an expansion.

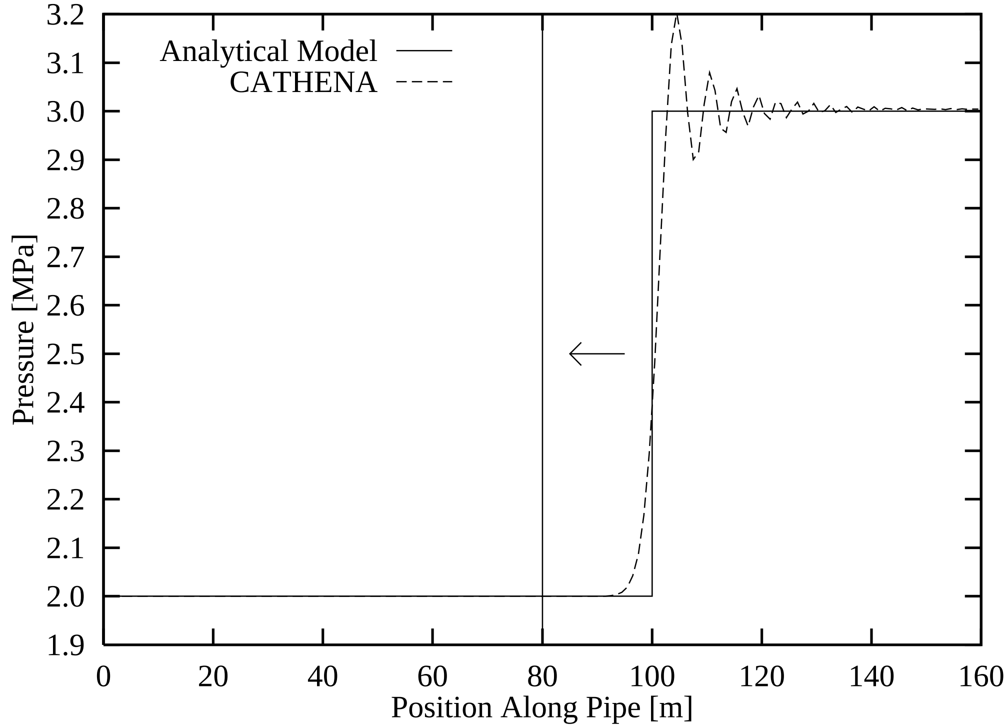

FIGURE 9: Analytical and simulated axial pressure profiles of a water hammer wave prior to reaching an expansion at t = 0.04 s.

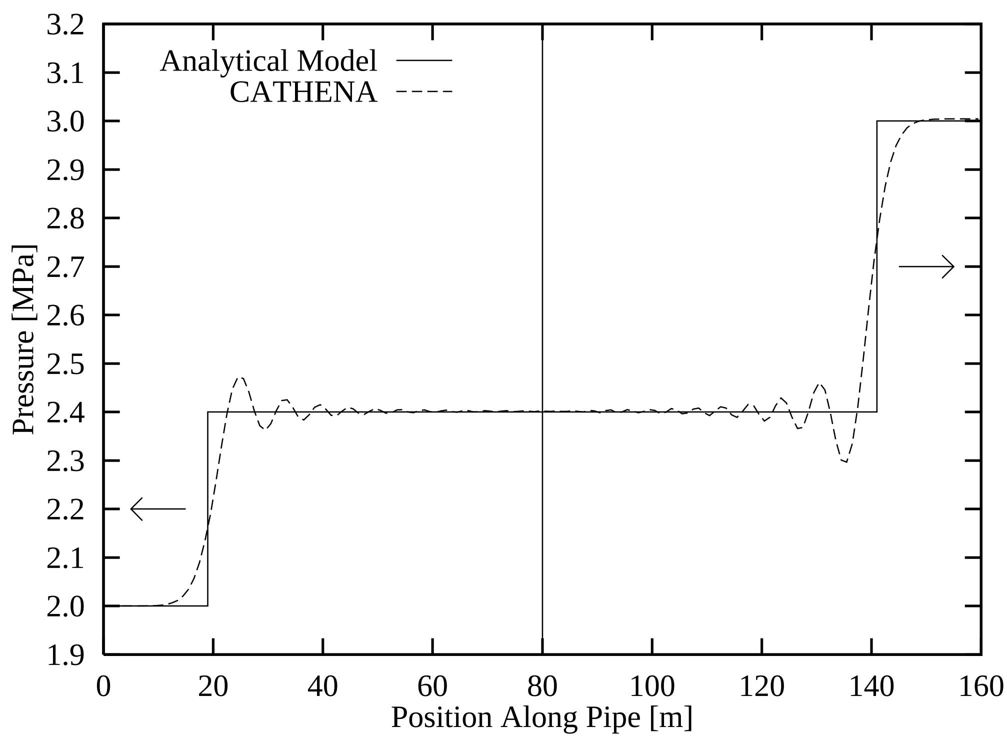

FIGURE 10: Analytical and simulated axial pressure profiles of a water hammer wave after reflecting from an expansion at t = 0.094 s.

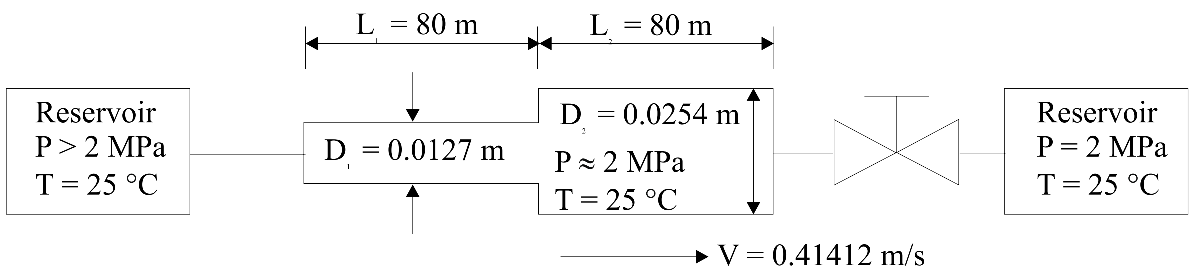

FIGURE 11: Test of wave transmission and reflection at a contraction.

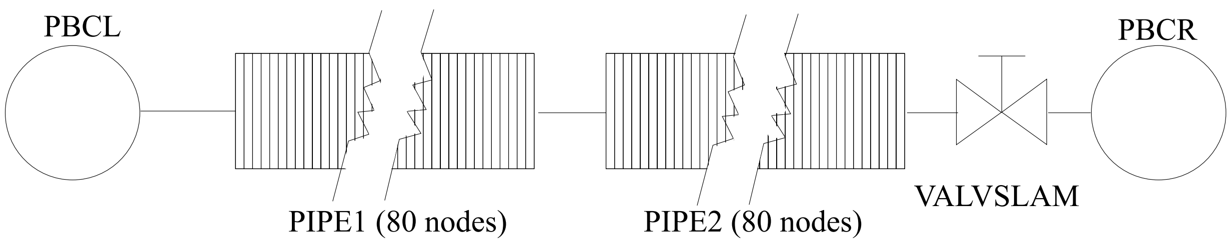

FIGURE 12: CATHENA model of test of wave transmission and reflection at a contraction.

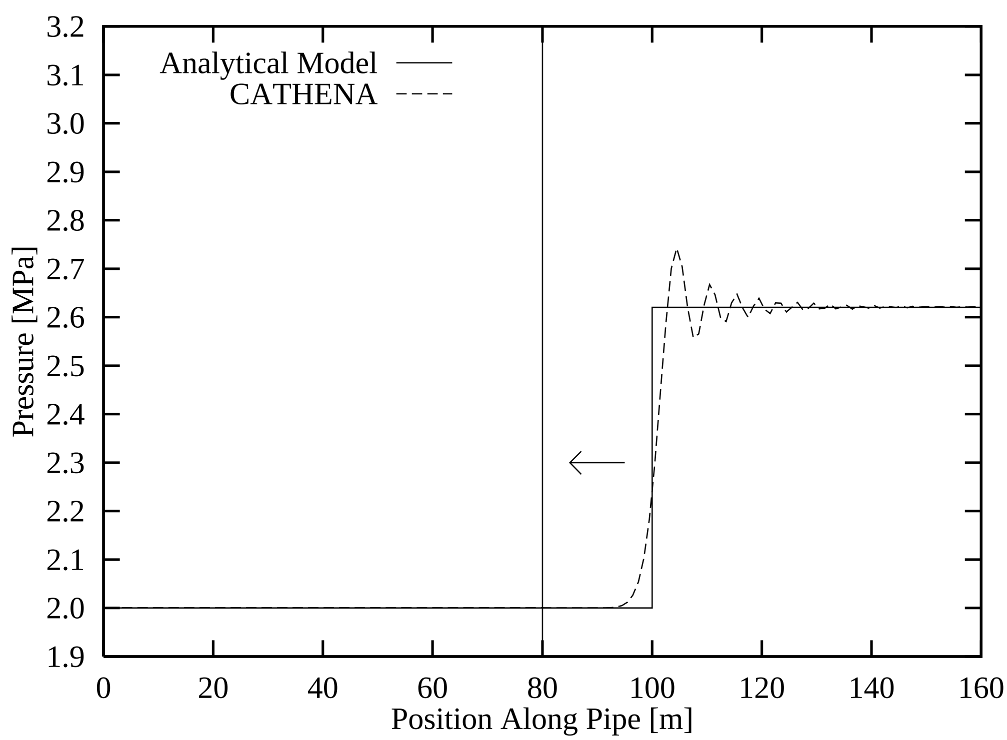

FIGURE 13: Analytical and simulated axial pressure profiles of a water hammer wave prior to reaching a contraction at t = 0.04 s.

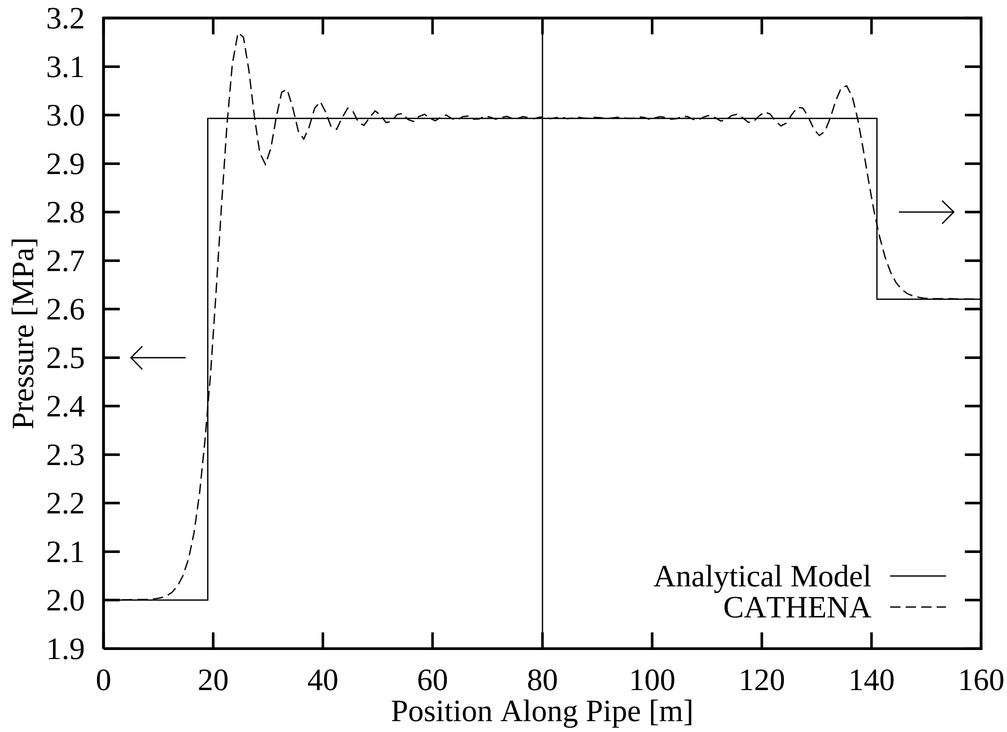

FIGURE 14: Analytical and simulated axial pressure profiles of a water hammer wave after reflecting from a contraction at t = 0.094 s.

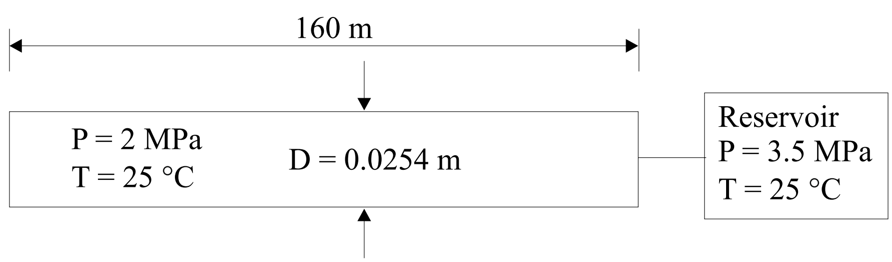

FIGURE 15: Test of wave reflection at a dead end.

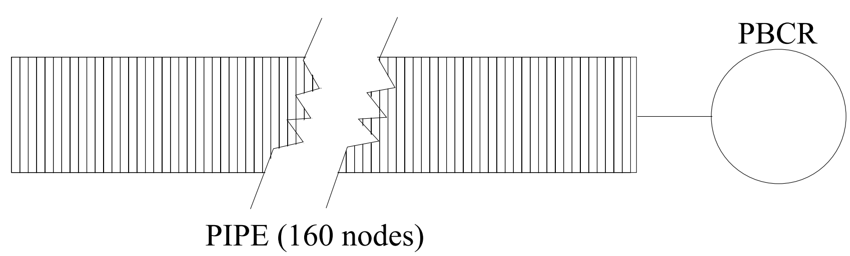

FIGURE 16: CATHENA model of test of wave reflection at a dead end.

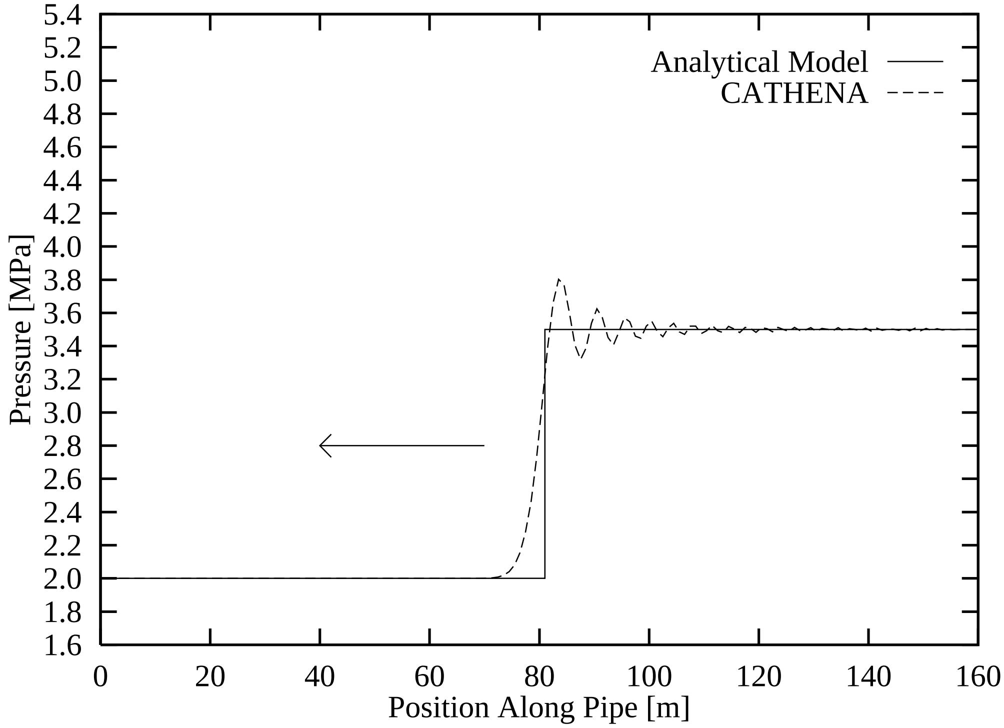

FIGURE 17: Analytical and simulated axial pressure profiles of a water hammer wave prior to reaching a dead end at t = 0.054 s.

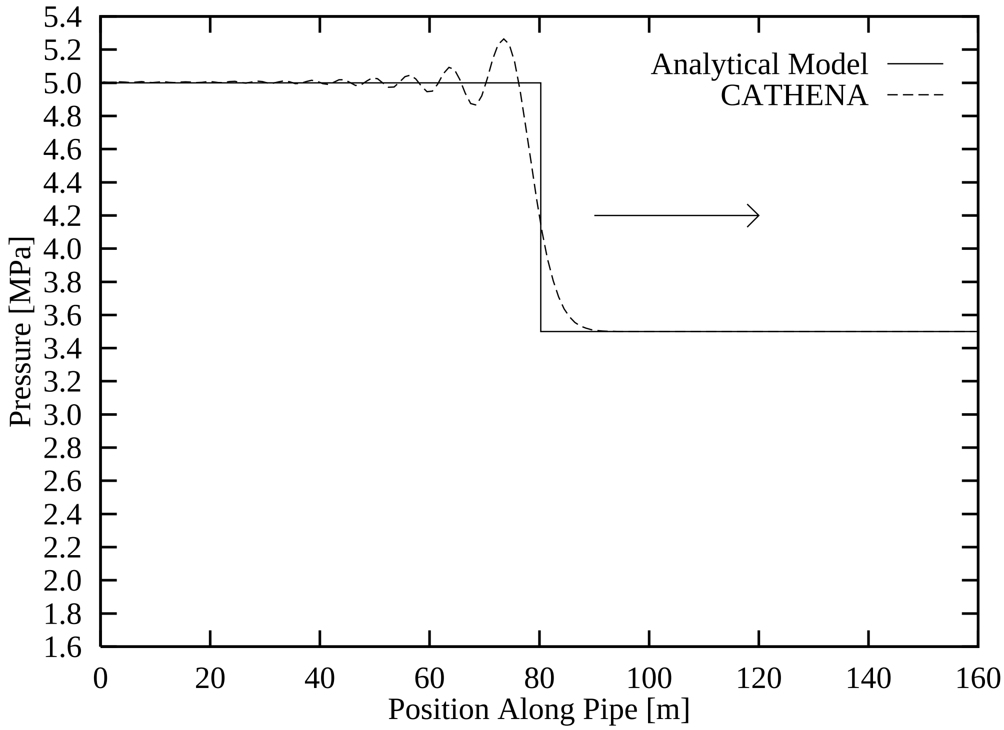

FIGURE 18: Analytical and simulated axial pressure profiles of a water hammer wave after reflecting from a dead end at t = 0.16 s.

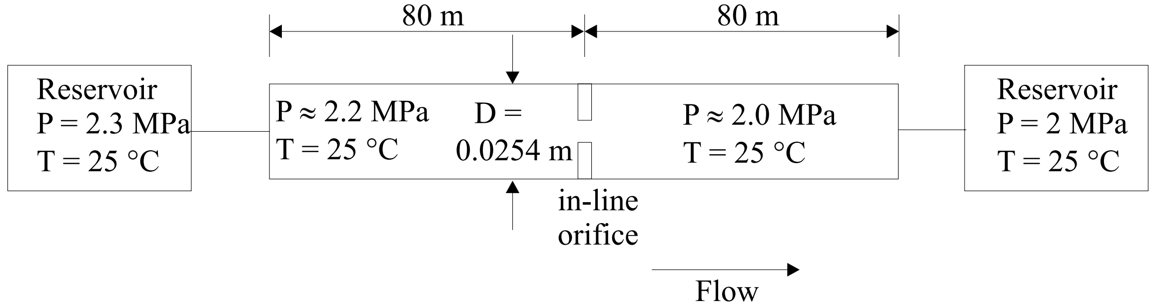

FIGURE 19: Test of wave transmission and reflection at an in-line orifice.

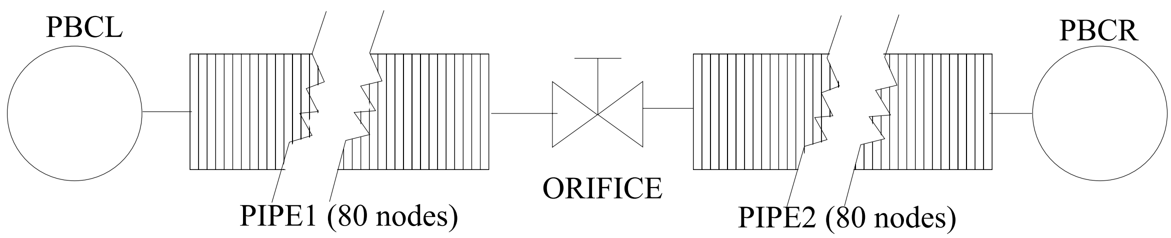

FIGURE 20: CATHENA model of test of wave transmission and reflection at an in-line orifice.

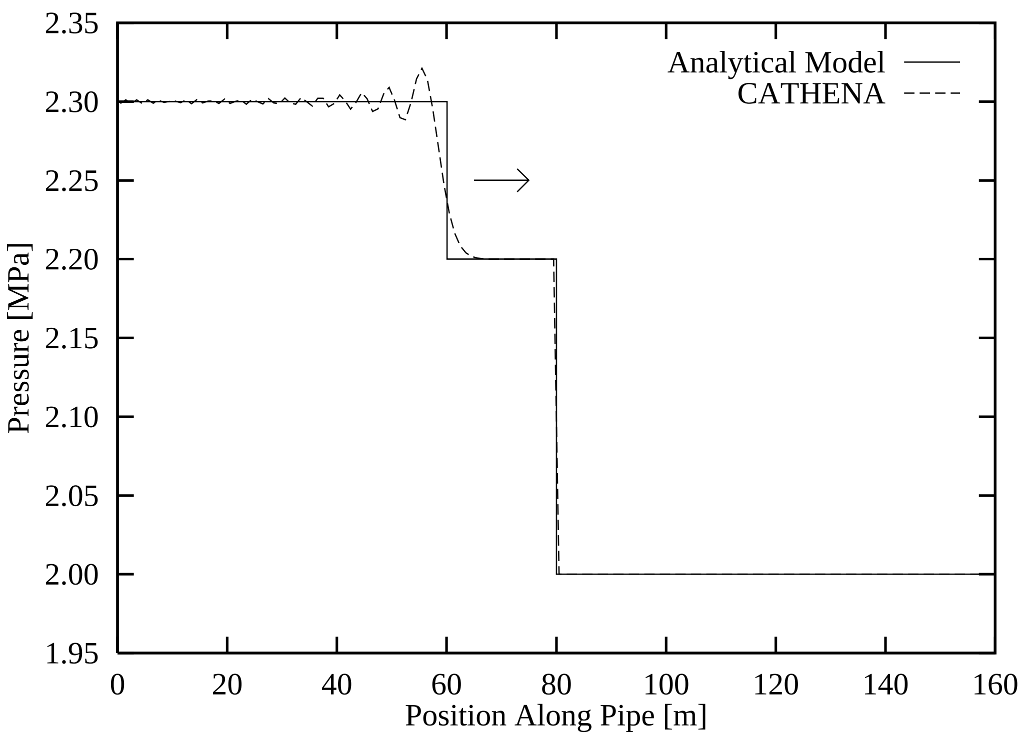

FIGURE 21: Analytical and simulated axial pressure profiles of a water hammer wave prior to reaching an orifice at t = 0.04 s.

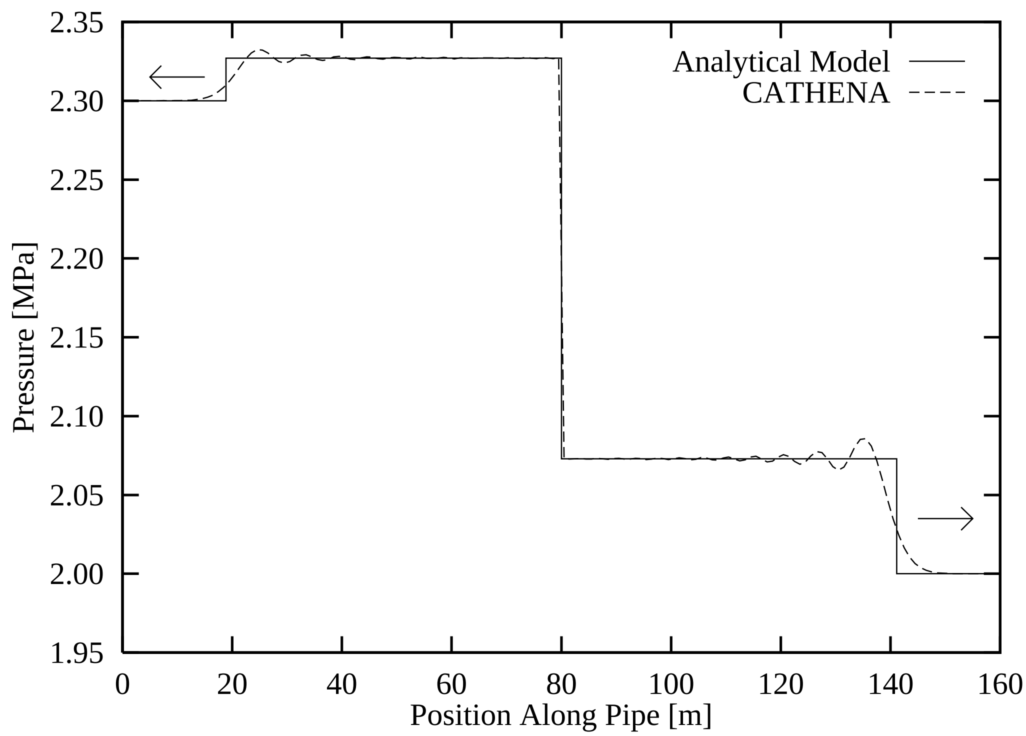

FIGURE 22: Analytical and simulated axial pressure profiles of a water hammer wave after reflecting from an orifice at t = 0.094 s.

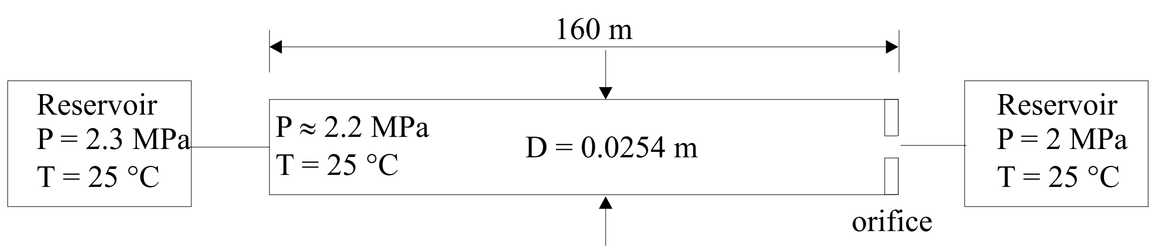

FIGURE 23: Test of wave transmission and reflection at a dead end orifice.

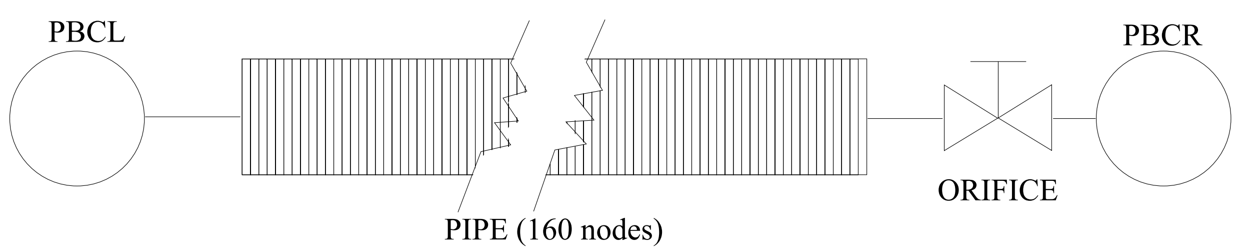

FIGURE 24: CATHENA model of test of wave transmission and reflection at a dead end orifice.

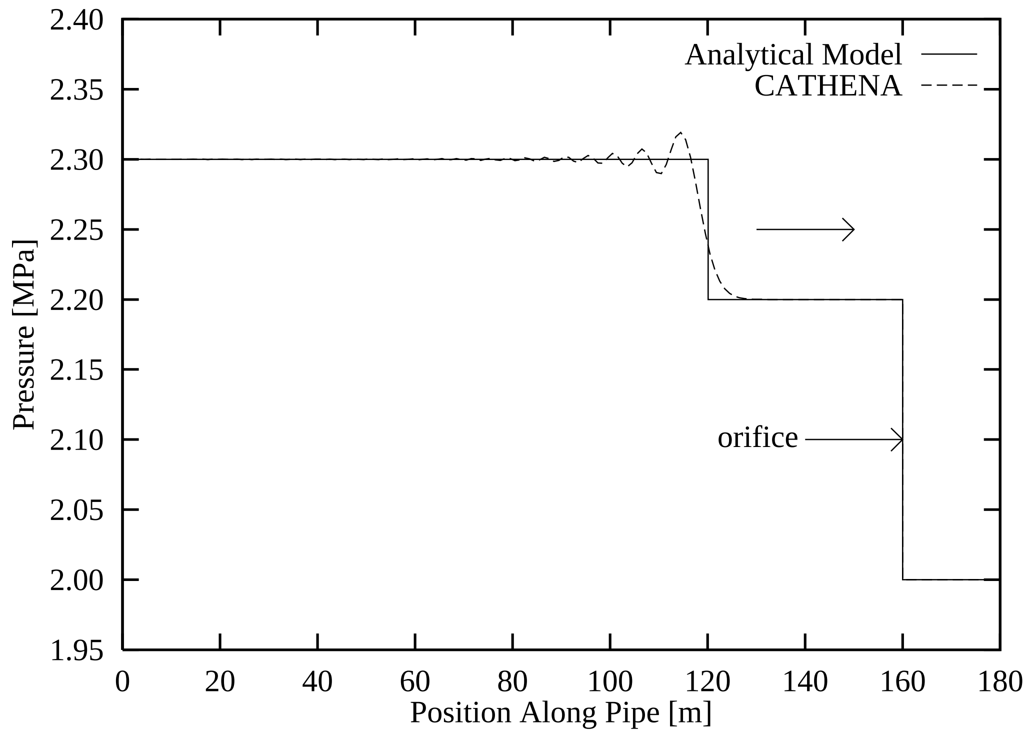

FIGURE 25: Analytical and simulated axial pressure profiles of a water hammer wave prior to reaching a dead end orifice at t = 0.04 s.

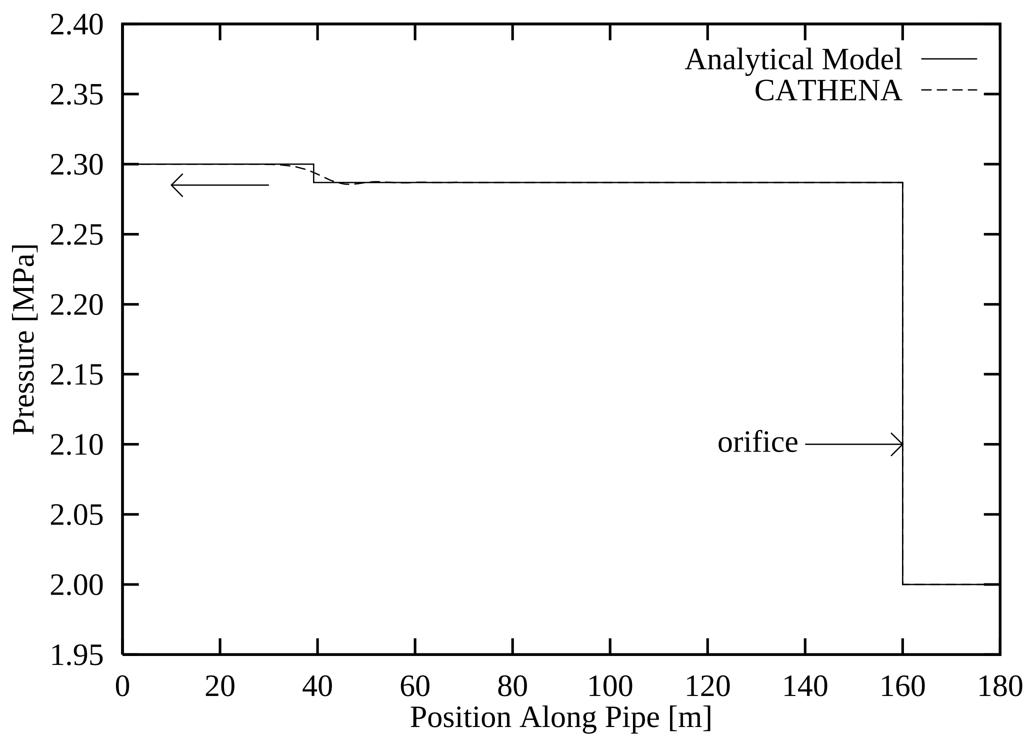

FIGURE 26: Analytical and simulated axial pressure profiles of a water hammer wave after reflecting from a dead end orifice at t = 0.094 s.

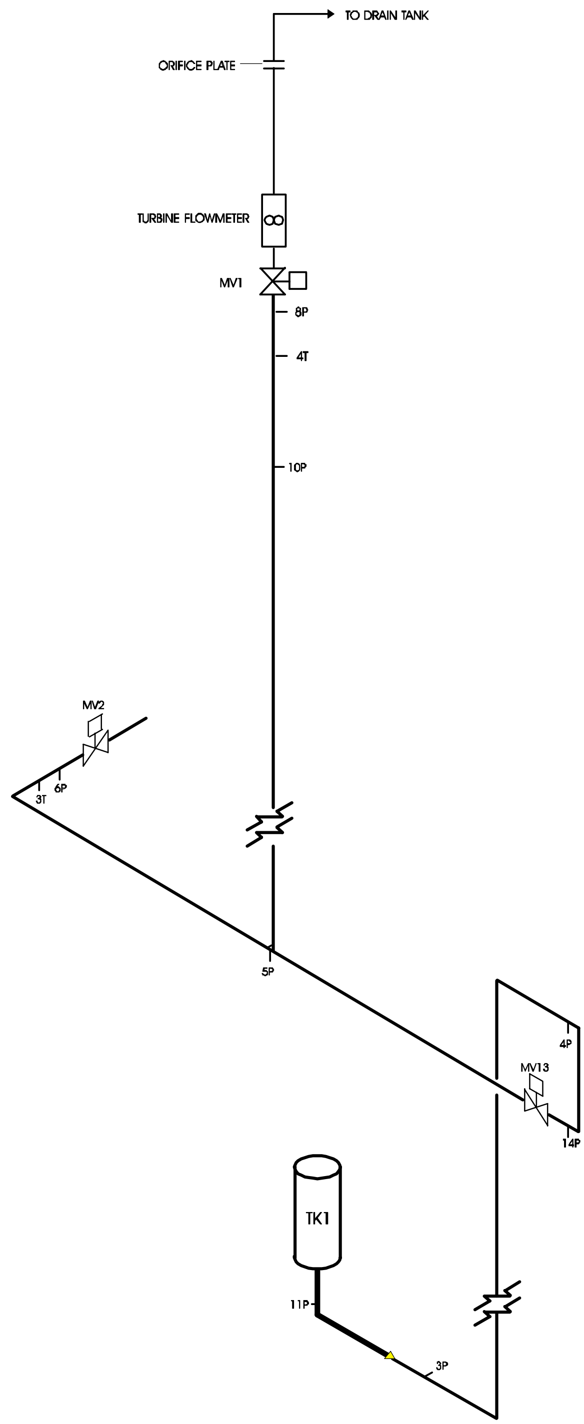

FIGURE 27: Schematic of the Seven Sisters Water Hammer Facility.

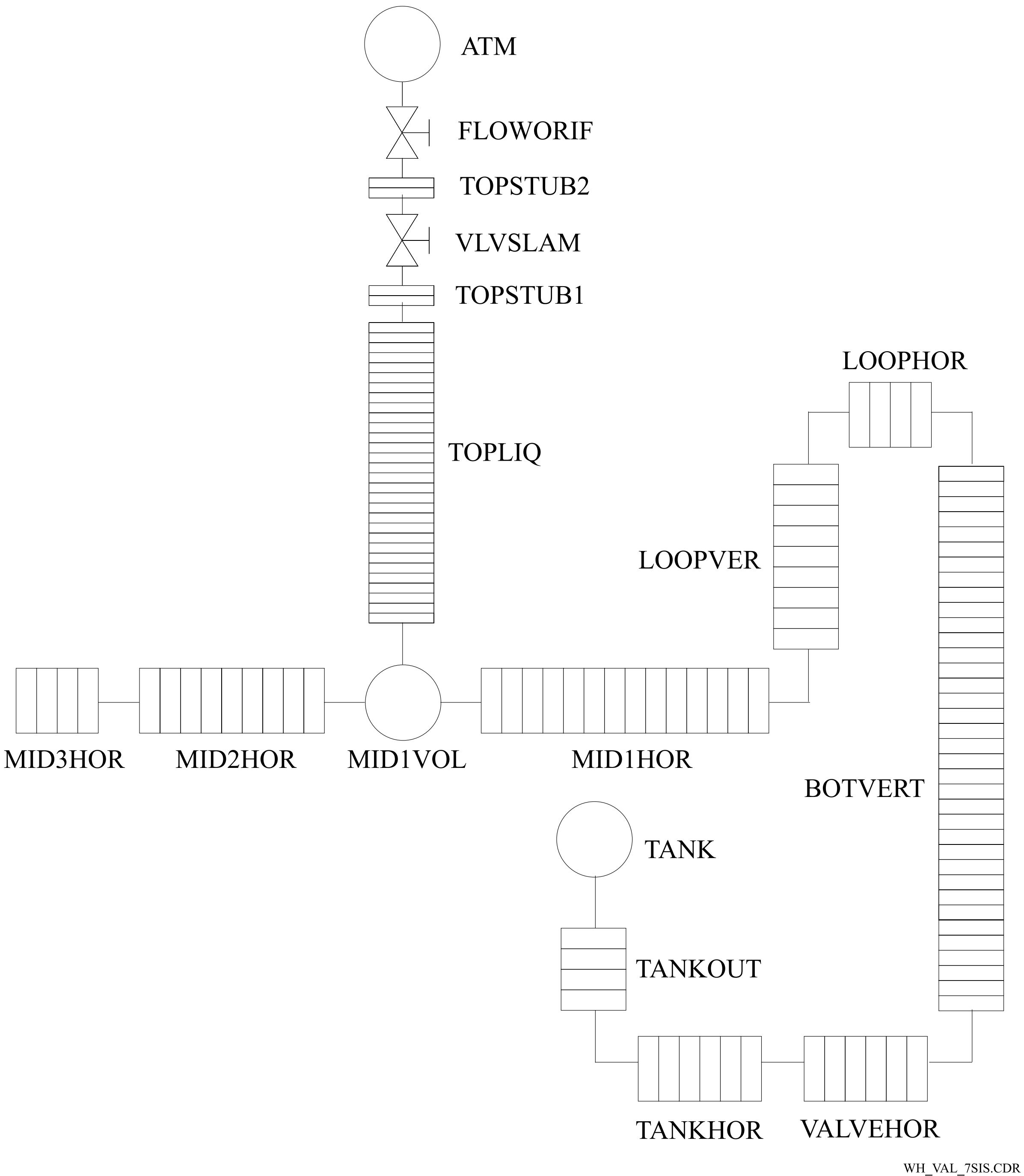

FIGURE 28: CATHENA idealization of the Seven Sisters Water Hammer Facility.

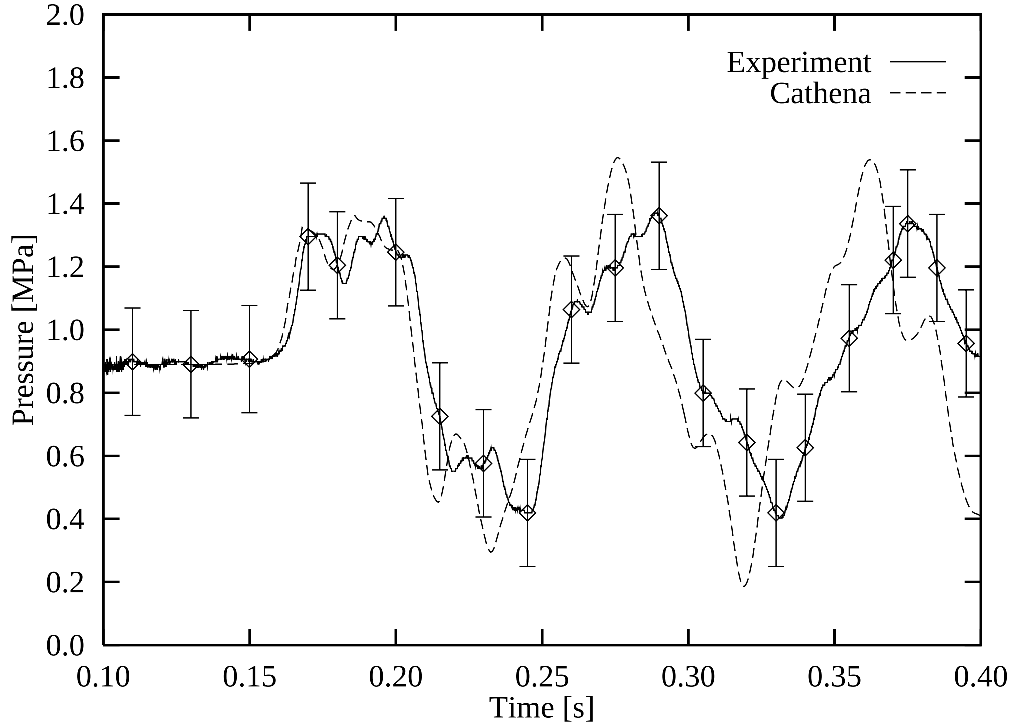

FIGURE 29: Measured and simulated system pressure histories at valve MV1 for Seven Sisters Water Hammer Test O6FC04.

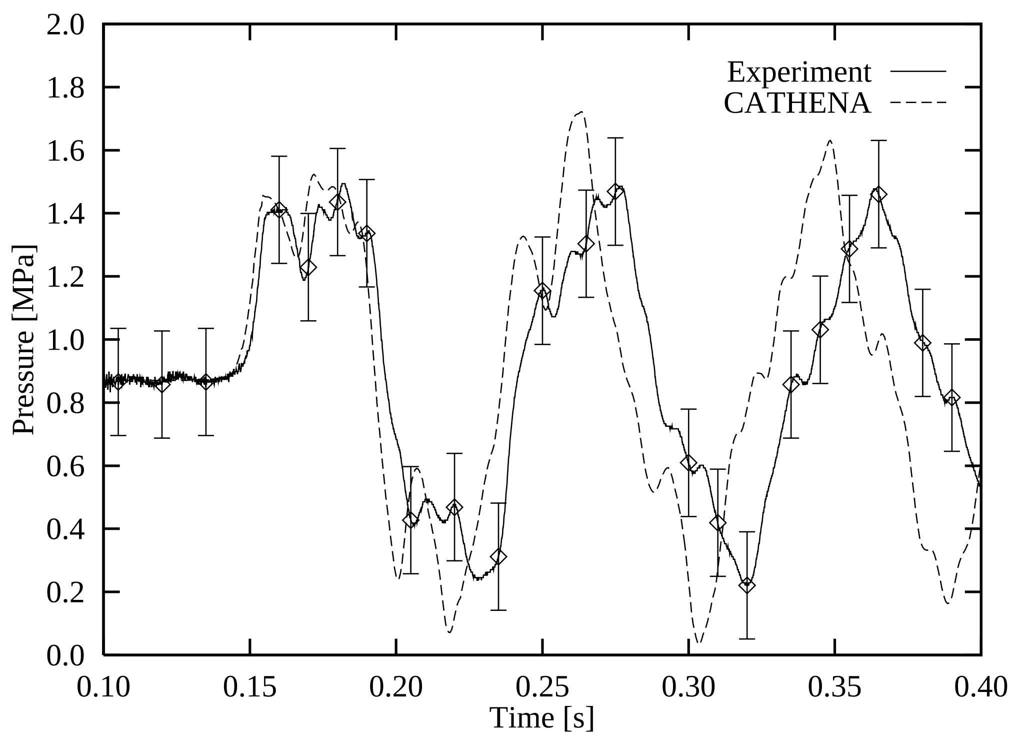

FIGURE 30: Measured and simulated system pressure histories at valve MV1 for Seven Sisters Water Hammer Test O1FC02.