CATHENA STUDY OF TWO-PHASE WATER HAMMER INTER-PEAK TIMING

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ABSTRACT

A development effort is underway to prepare CATHENA for use as a two-phase water hammer simulation tool. Preliminary investigations have shown that although although the basic physics of water hammer is being modelled correctly by CATHENA, the inter-peak timing between pressure excursions in CATHENA simulations can be much larger than shown in the experimental data. In this paper, an effort is made to identify possible factors influencing the inter-peak timing, and their influence on the simulation results. The results show that the wall shear stress calculation in CATHENA must be adjusted to properly account for unsteady wall shear stress under accelerating and decelerating flow conditions.

1. INTRODUCTION

In nuclear generating plants, water hammer can potentially lead to severe damage to plant components and piping systems. It represents an important safety issue as well as a serious economic concern since it can lead to costly forced outages.

Performing in-situ water hammer experiments to assess the potential conditions under which water hammer may occur is not an option in an operating reactor. Out-of-reactor tests are time-consuming and expensive, and cannot always completely model the conditions found in a reactor. As a result, it becomes important to have a validated modelling tool which can be used to assess the potential for water hammer through numerical simulation.

2. THE CATHENA CODE

CATHENA (Canadian Algorithm for THErmalhydraulic Network Analysis) is a one-dimensional, two-fluid thermalhydraulic computer code designed for the analysis of two-phase flow and heat transfer in piping networks. The CATHENA thermalhydraulic code was developed by AECL, Whiteshell Laboratories, primarily for the analysis of postulated accident conditions in CANDU® reactors.

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The thermalhydraulic model in CATHENA is a one-dimensional, non-equilibrium two-fluid model consisting of six partial differential equations for mass, momentum and energy conservation – three for each phase. A first-order finite-difference representation is used to solve the differential equations, utilizing a semi-implicit one-step method in which the time step is not limited to the material Courant number [1]. This solution method is theoretically capable of modelling two-phase water hammer.

Heat transfer models are also available to model conductive, convective, and radiative heat transfer to and from pipe walls and fuel. Flexible system control models are available to control the operation of the code and the models it offers (pump, valve, etc.). All features of CATHENA are available through the input control file without the need to re-compile the code.

Work on preparing CATHENA as a generalized tool for use in two-phase water hammer simulations of CANDU reactors is currently underway. Preliminary investigations have shown that although there are no major impediments for CATHENA to perform two-phase water hammer, the temporal progression of water hammer peaks may not always be captured accurately [2]. In this paper, an attempt will be made to identify the conditions under which this discrepancy occurs, and suggest actions to remedy it.

3. INSTANTANEOUS VALVE CLOSURE

An analytical solution accredited to Joukowsky in 1898 is available in the case of an instantaneous single-phase water hammer. The fundamental relationship between fluid velocity and pressure in a single-phase system can be expressed as:

$$\Delta P = \rho v a \tag{1}$$

where ρ is the density of the liquid, v is the velocity of the liquid, and a is the speed of sound in the liquid. The relationship shown in equation 1 describes the maximum increase in pressure ΔP which can be expected to occur when a liquid flowing with velocity v is brought to rest. This change in pressure ΔP travels through the system at the speed of sound. Joukowsky originally derived equation 1 in 1898 from continuity considerations as well as through the energy equation [3]. Today, it has become more conventional to derive equation 1 from the principle of conservation of momentum [4].

Comparison to this solution gives an indication of the ability of the code to model the pressure changes exhibited in a travelling pressure wave generated by a single-phase water hammer in a simplified pipe geometry. As shown in Figure 1, although the CATHENA numerical model cannot precisely match the instantaneous pressure increase encountered in an instantaneous valve slam single-phase water hammer, the magnitude of the pressure pulses generated are well predicted. More importantly for the this study, the temporal progression of the travelling pressure waves is accurately predicted.

4. SEVEN SISTERS WATER HAMMER FACILITY

This facility is located at Manitoba Hydro's Seven Sisters Generating Station, close to the Whiteshell Laboratories of Atomic Energy of Canada Limited (AECL) in Manitoba. The facility is operated by AECL under CANDU Owners Group (COG) sponsorship, and consists of a complex network of piping which can easily be modified to investigate water hammer in a wide range of geometries.

A special series of fast-closing valve-slam-induced water hammer tests was performed to produce both single and two-phase water hammer. In the first series of tests, the initial flow rates were throttled via an orifice downstream of the valve and the system pressure was maximized to ensure that a single-phase water hammer was created by the valve slam. In the second series, the restricting orifice was removed, and different initial system flow rates were set using the initial tank pressure. These experiments resulted in water hammer which generated a void pocket upstream of the slammed valve. The discussion of the CATHENA models of selected results from this series of tests helps to illustrate the ability of CATHENA to perform single and two-phase water hammer tests in more complex piping systems.

5. SINGLE-PHASE VALVE SLAM INDUCED WATER HAMMER

As mentioned above, in this experiment, the initial water flow was throttled using an orifice downstream of the valve, and the pressure in the system was maximized. Figure 2 shows a comparison between the experimental pressure trace for a single-phase valve slam water hammer experiment and the pressure trace modelled by CATHENA. As illustrated here, although the match in the temporal progression of the pressure peaks is not as ideal as in the instantaneous valve slam case shown in Figure 1, the agreement between the model and the experimental data is relatively good.

6. TWO-PHASE VALVE SLAM INDUCED WATER HAMMER

When the tank pressure is decreased, and the intial flow rate of water is increased by removing the orifice downstream of the valve, the water hammer created by slamming the valve creates a void on the upstream face of the valve as well as in the bulk of the rest of the liquid on the return stroke. A series of experiments were performed using different initial tank pressures and hence different initial flow rates.

When a relatively low flow rate is used, the void generated on the upstream side of the valve is small. As a result, the bulk movement of the liquid in the pipes is also small. The pressure trace resulting from such an experiment, and the corresponding CATHENA simulation results are shown in Figure 3. As illustrated here, inter-peak timing between the initial valve slam pressure peak and the second peak generated by void collapse is reasonably good. The inter-peak time between the second, third and fourth modelled peaks grows increasingly longer than the experimental data however.

When the flow is increased by raising the tank pressure, a larger void is generated on the upstream face of the slammed valve, resulting in a larger bulk flow of the liquid in the piping. As shown in Figure 4 the pressure peaks predicted by the CATHENA simulation are now much further apart than those measured in the experiment. The magnitude of the pressure peaks predicted by CATHENA is also significantly larger than those measured in the experiment.

7. EXAMINATION OF FACTORS INFLUENCING INTER-PEAK TIMING

In an attempt to explain the trends shown in Sections 3–6 the high flow case of Section 6 (Figure 4) was chosen to examine the factors influencing inter-peak timing, since it shows the greatest discrepancy with the experimental data in this regard.

Initially, attempts were made to influence the inter-peak timing by changing the bubble diameter (and therefore the condensation rate via the interface area per unit volume), the vapour generation rate and the apparent density in the code. After considerable effort however, it was concluded that none of these factors have a significant effect on the inter-peak timing.

The only remaining factor which could have an effect on the inter-peak timing is flow resistance. When either the wall friction factors are increased by altering the wall roughness, or additional branch or junction resistances are introduced, the CATHENA simulation results match the experimental result more closely as shown in Figure 5. Simply altering the velocity dependent flow resistance factors does not provide the proper correction however. These friction factors were all derived under steady state conditions, and therefore cannot be used to account for the effect of fluid acceleration or deceleration on the flow resistance. This is illustrated in the initial pressure peak caused by the slammed valve. Whereas before, the timing and magnitude of this initial pressure peak is modelled relatively well, as shown in Figure 4, the magnitude of the pressure peak is now under-predicted. This trend is also evident in the second and subsequent peaks caused by void collapse.

8. TRANSIENT PIPE FLOW FRICTION

An examination of the literature shows that a number of authors have considered the problem of measuring and explaining the effect of unsteady flows on flow resistance [5]–[13]. These studies point to the inadequacy of steady state wall friction factors under unsteady flow conditions. Indications are that under accelerating and decelerating flow conditions such as those experienced in water hammer and especially in long thin piping systems such as the one under examination here, there is a significant additional flow resistance which has not been accounted for. Discussions on this topic point to a large modification of the flow profiles in an annular region near the pipe wall under unsteady or transient flow which can have an effect on the skin friction [8, 9]. Analytical models separate the steady and unsteady components of the wall shear stress τ_w as follows:

$$\tau_w = \tau_{ws} + \tau_{wu} \qquad (2)$$

The steady term τ_{ws} is the standard steady-state friction term which is a function of the wall friction f and the velocity U. The unsteady friction term τ_{wu} is typically given as a function of acceleration:

$$\tau_{wu} = A\frac{\mathrm{d}U}{\mathrm{d}t} \tag{3}$$

where the coefficient A may be a function of the fluid properties, the local geometries, the local mean velocity, and whether the system in question is experiencing acceleration or deceleration. More complex analytical efforts include higher order derivatives of the velocity:

$$\tau_{wu} = f\left(A_1\frac{\mathrm{d}U}{\mathrm{d}t}, A_2\frac{\mathrm{d}^2U}{\mathrm{d}t^2}, A_3\frac{\mathrm{d}^3U}{\mathrm{d}t^3}, \ldots\right) \tag{4}$$

which have resulted in a variety of weighting methods. Practical applications, and experimental correlations typically concentrate on the more simple relationship in equation 3. A recent effort has led to some confusion as to the correct values of the coefficient A however [13], resulting in a wide range of suggested values for both accelerated and decelerated flows.

Attempts are currently underway to implement an unsteady friction term of the form of equation 3 in CATHENA.

9. SUMMARY AND CONCLUSIONS

The series of CATHENA modelled water hammer cases presented here tends to indicate that larger discrepancies in the inter-peak timing can be expected with larger generated bulk flows in the water hammer. A parametric study preformed using CATHENA tends to indicate that the inter-peak timing is relatively insensitive to the bubble diameter, the vapour generation rate and the apparent density. Modifying flow resistance factors tends to have a significant influence however.

An examination of the available literature on the subject tends to agree with this assessment, and also suggests that additional wall friction due to the acceleration of the fluid under water hammer conditions, particularly in the long thin pipes under investigation here might be the additional factor that is needed to make the agreement between the CATHENA results and the experimental results better. Efforts are currently underway to implement an unsteady flow model for wall friction in CATHENA.

10. ACKNOWLEDGEMENTS

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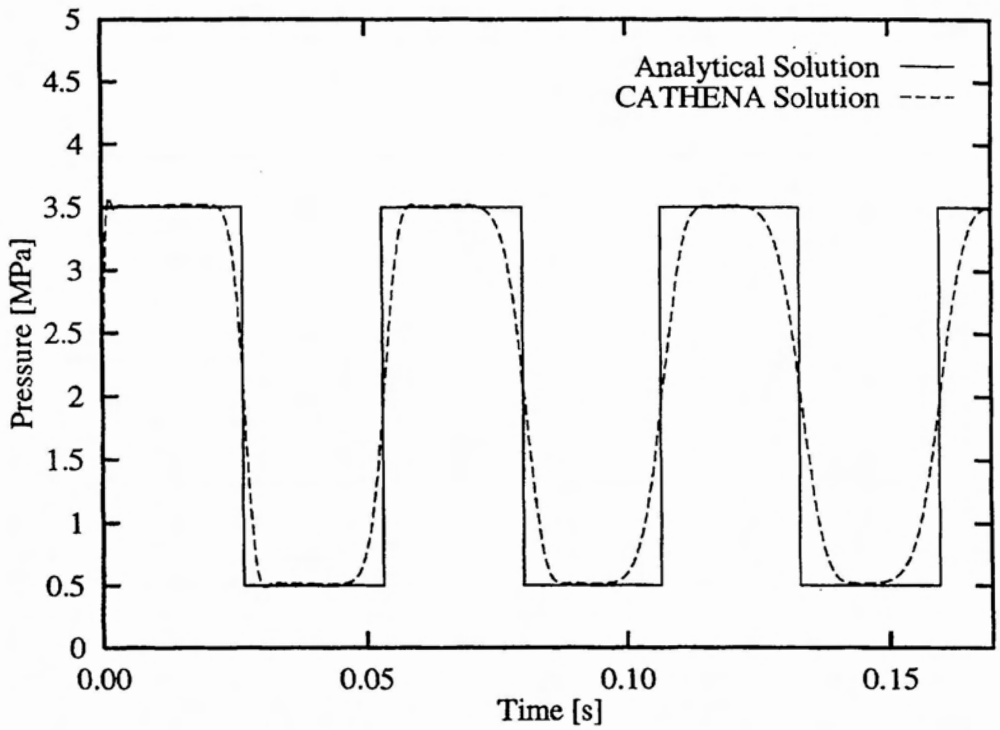

FIGURE 1: Water Hammer Created by an Instantaneous Valve Closure

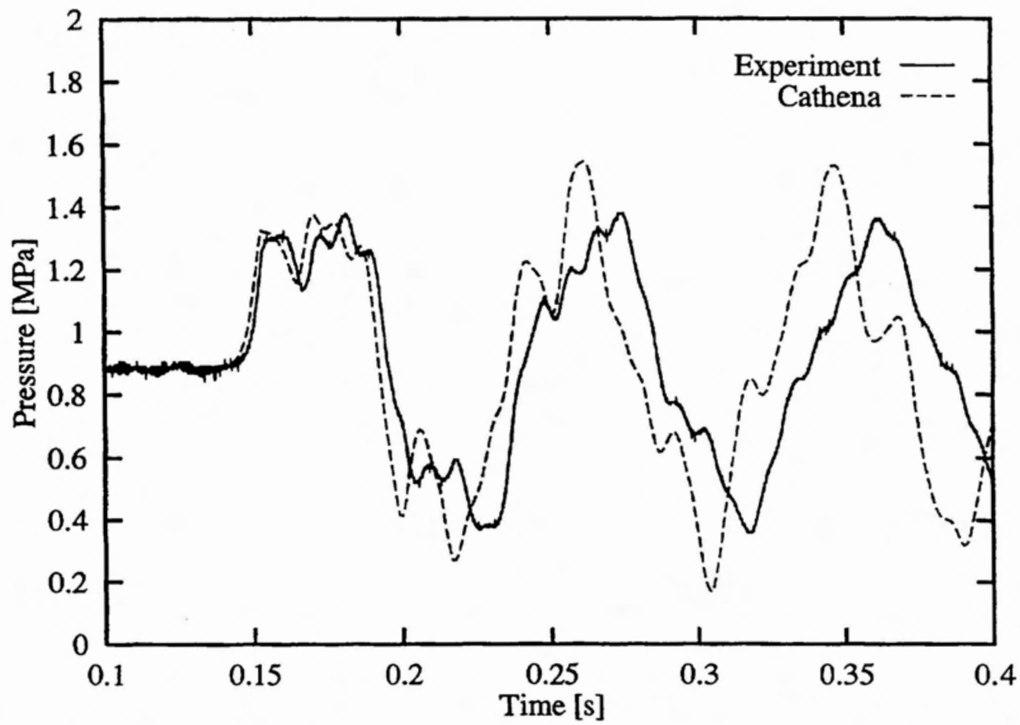

FIGURE 2: Seven Sisters Single Phase Valve Slam Water Hammer and Corresponding CATHENA simulation

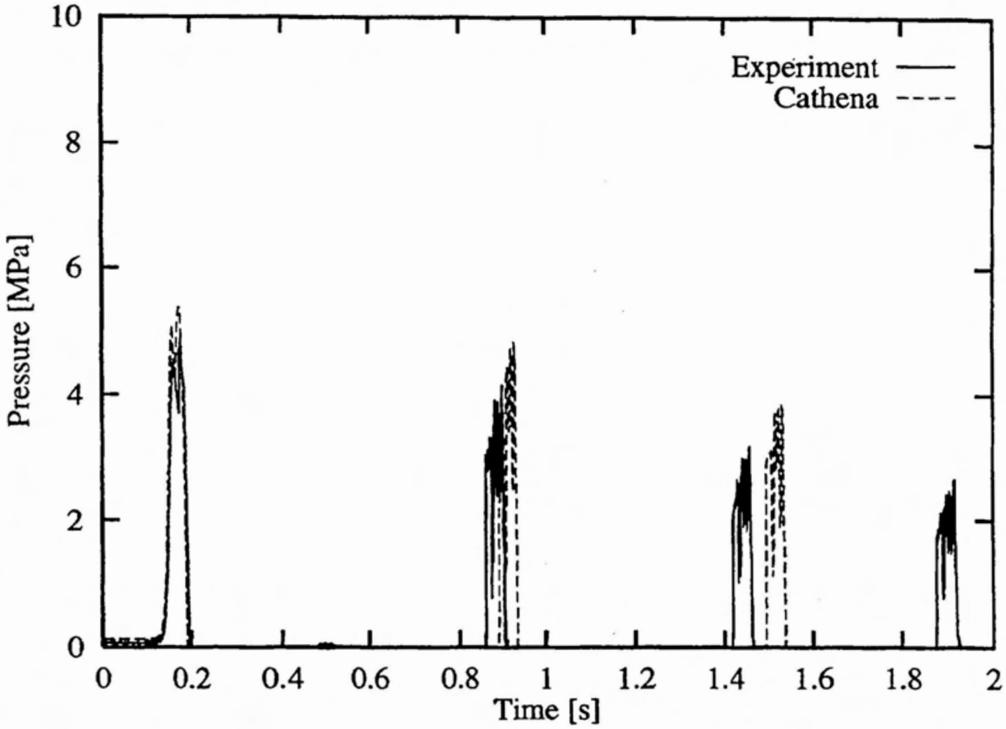

FIGURE 3: Seven Sisters Valve Slam Water Hammer (Small Void Generated) and Corresponding CATHENA Simulation

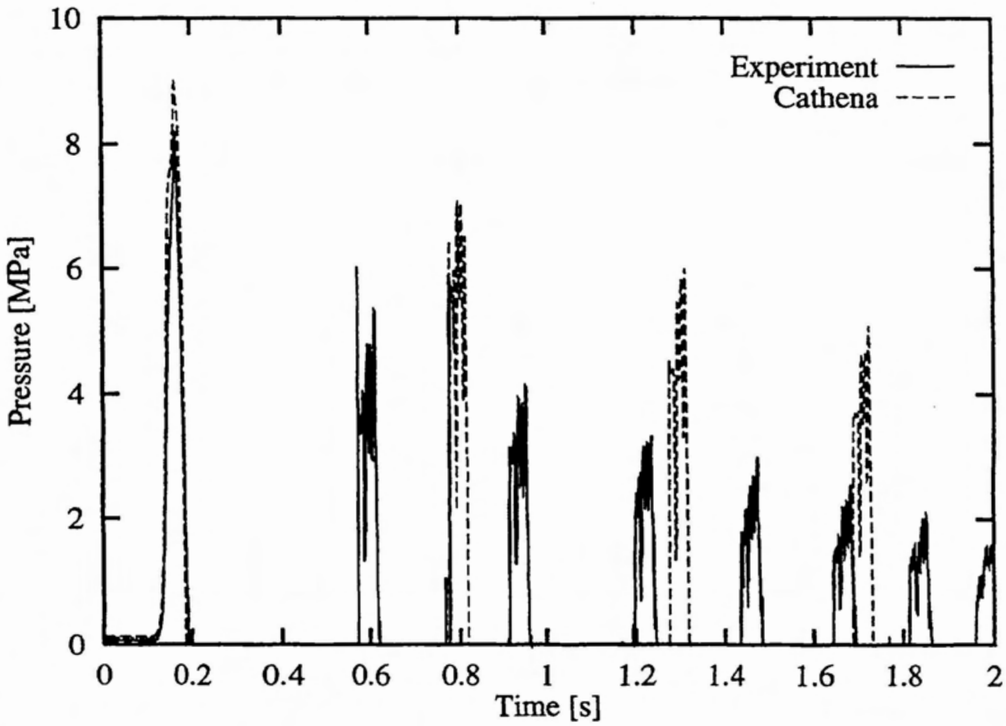

FIGURE 4: Seven Sisters Valve Slam Water Hammer (Large Void Generated) and Corresponding CATHENA Simulation

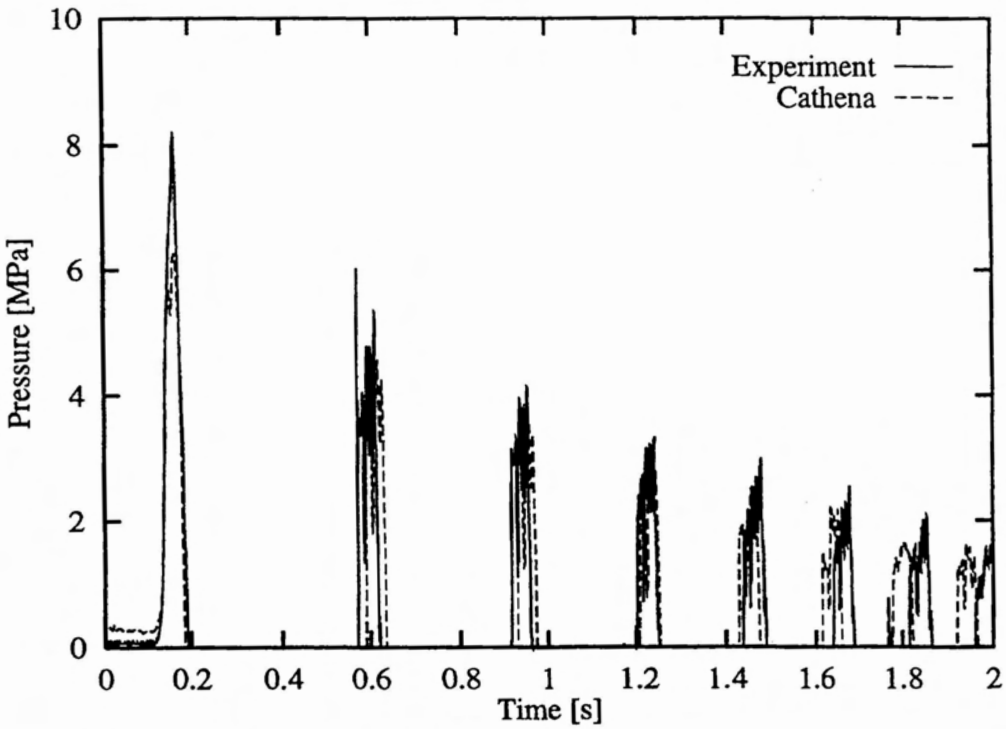

FIGURE 5: Seven Sisters Valve Slam Water Hammer (Large Void Generated) and Corresponding CATHENA Simulation with Adjusted Velocity-dependent Hydraulic Resistance