Applying RELAP5 Code To Water Hammer Analysis Of The Point Lepreau HPECC Piping System

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Abstract

Described in this paper is the rationale for applying the RELAP5 code to water hammer analysis of the Point Lepreau HPECC piping system where incondensable gas pockets are entrapped. The preliminary water hammer consequences derived from the developed RELAP5 model are analyzed in comparison with those of real measurements and other codes.

1. Background

The Safety Operating Envelope (SOE) process at Point Lepreau has identified the potential for accumulation of gas in the ECC pipework, to either cause or magnify the effects of water hammer should the ECC system be called to act in a LOCA. However, a limited number of tools exist for water hammer analysis, especially the analysis involving entrapped gas volumes which, under the influence of high pressure gradients, will be free to move. This non-equilibrium behavior is extremely complex to fully model. Initial investigations suggest that RELAP5 may be an analysis code that can fully capture all of the pressure transients involved.

The RELAP series of codes have been validated and applied in safety analysis activities in many countries including those where CANDU-type reactor systems exist. What is presented here will focus on the topics relevant to the applications of RELAP5 in water hammer analysis: code capabilities and practices for water hammer analysis, features suitable for water hammer analysis, application to water hammer analysis of the HPECC System, preliminary water hammer analysis, and results as input to stress analysis codes for water hammer analysis.

2. Rationale of selecting RELAP5 for water hammer analysis

The RELAP5 code was developed principally to calculate fluid behavioral characteristics during operational and LOCA transients. The results describing fluid behavioral characteristics also provide the basis for calculating structural loading (including water or steam hammer) because the transient hydrodynamic pressures are key results [1]. Furthermore, RELAP5 can calculate acoustic wave propagation (pressure signal transmission) in pipelines and various system components [1].

RELAP5 code has been used for structural analysis (including water and steam hammer) for many years. Some of those applications are:

- Water hammer analysis on the Braidwood Unit 1 Nuclear Power Plant residual heat removal piping [1].
- Pressure wave propagation simulation for instantaneous pipe breaks of the Advanced Verification Neutron Source Reactor (ANSR) designed by the Oak Ridge National Laboratory (ORNL) [2, 3].
- Analysis of water hammer phenomenon in RBMK cooling circuit [4]. RBMK is Russian acronym for 'channeled large power reactor'.
- Analysis of potential water hammer of the main circulation circuit at the Ignalina Nuclear Power Plant [5].
- Benchmarked against the water hammer test performed in UMSICHT facility in Germany and justification of the application in Lithuanian nuclear power plants [6].
- Analysis of transient load of safety depressurization system in Ulchin Nuclear Power Plant units 3&4, cause by sudden transition of fluid phase (water hammer phenomenon) [7].
- Calculation of forces (caused by water hammer) on reactor containment fan cooler piping [8].
- Investigation of limiting transients including condensation-induced water hammer of high pressure steam piping system [9].

These applications indicate that there has been extensive work performed around the world on development and validation of RELAP series codes in water hammer analysis. Furthermore, these applications of the RELAP5 code for water hammer analysis provide very valuable referential experience for the HPECC system water hammer analysis, especially on selection of time step and nodalization schemes which are considered important issues for system simulation and modeling.

The necessary features, which should be considered in water hammer analysis of the thermal-hydraulics codes are:

1) Stable Computation Under High Acceleration

For water hammer analysis of the HPECC system in CANDU nuclear power stations, analysis codes must have stable computation under high acceleration. Entrapped air pockets will be accelerated very quickly by rapid air injection from the high pressure valves. RELAP5/MOD3 has been adapted to simulate bulk water acceleration (100 times of $g=9.8m/s^2$) caused by rapid air injection [10].

2) Flexible Time Step Control

Solution time step control is very important for water hammer analysis of piping systems. There are four options related to time step control for water hammer calculations in RELAP5.

(a) An option to scale back the Courant limit to 75% of its calculated value so that the RELAP5 time step will always be less than or equal to 75% of the Courant limit. For water hammer, it is very important to make the ratio of current time step to current Courant time step less than 1.0. When the ratio is equal to or larger than 1.0, the pressure wave will attenuate rapidly.
(b) An option to allow the code to run at the Courant limit with a multiplication factor. These limits can be used in the mass error check for the time step control.
(c) An option to provide complex time step control based on the change in void fraction and is designed to limit the time step when the void fraction in any cell is decreasing rapidly such as during a period of entrapped air pocket compression in HPECC piping system.
(d) An option to provide time step control based on a change in pressure within a hydrodynamic volume. This time control generally causes the code to run more reliably and to track pressure wave and oscillations more accurately.

3) Flexible Nodalization Method

Compared with other codes, RELAP5 code has flexibility to model the piping systems in which an independent control volume (cell or node) is needed for every elbow, tee and straight pipe section for load calculation of water hammer. Each control volume inside the piping system model can have its own variable parameters including flow area, hydraulic diameter, flow length, vertical angle used in the interphase drag calculation, elevation, form loss coefficient and modeling option selection. This is very useful to model a piping system for the purpose of water hammer analysis where detailed pressure wave distributions are usually desired.

It has been found that the behaviors of valves have a strong effect on the results of water hammer analysis, especially the check valves. RELAP5 can model these valves quite accurately. RELAP5 related theory manual and user's manual [1] present details of the valve models.

4) Effective Water Packing Mitigation Scheme

Water packing is the numerical analog of the physical water hammer (pressure spike) phenomenon. These fictitious pressure spikes are sometimes calculated when steam (or non-condensable gas) is disappearing, and water is about to fill a control volume. The situation is often referred to as water packing.

In thermalhydraulic analysis codes such as RELAP5 and CATHENA, the water packing scheme is necessary. The water packing scheme that has been installed to mitigate pressure spikes in RELAP5 closely follows the method used in the TRAC code, a reactor core thermalhydraulic analysis code widely used in nuclear engineering for safety assessment.

The water packing mitigation scheme installed in RELAP5 code ensures that a legitimate water hammer situation would not be eliminated.

3. Applying RELAP5 to water hammer analysis of the HPECC system

3.1 RELAP5 model of HPECC system

A complete RELAP5 model of the HPECC system at Point Lepreau has been developed and many cases related to water hammer analysis with/without entrapped air pockets have been performed by ANSL. These simulation results have shown that the entrapped air pockets can cause severe water hammer inside the piping system during HPECC injection.

The RELAP5 model consists of the HPECC piping system from the HPECC gas tank, 3432-TK2, to the reactor headers and ECC system tanks, valves, rupture discs, pumps, resistance orifices and the water tank heater circuit. The total number of control volumes is 609 and number of junctions is 621. The model can provide detailed pressure wave distributions along the piping system for all tees, elbows and pipe sections with different lengths. This model is applicable to HPECC systems similar to the one in PLGS and could be applied to others by modification.

3.2 Analysis cases and model verification/validation

The preliminary cases that have been analyzed at this point include the following cases:

(1) 20% Reactor Inlet Header (RIH) Break,
(2) 100% Reactor Outlet Header (ROH) Break,
(3) 100% Pump Suction Pipe (PSP) Break,
(4) PLGS Test 1994 of water tank pressurization,
(5) Water tank pressurization with different initial conditions, and
(6) Analyses of entrapped air with different volumes and locations.

Cases (1) to (5) are used to verify/validate the developed RELAP5 model of the Point Lepreau HPECC piping system.

The HPECC injection phase of cases (1), (2) and (3) are also analyzed in relevant AECL reports in which the HPECC system is modeled by the FIREBIRD code. The calculation results for the RELAP5 model agree well with the FIREBIRD analysis. The results of the pressurization are available from the RELAP5 calculation.

In case (4), the HPECC pressurization of the water tanks, 3432-TK1 and TK3, is simulated by the RELAP5 model and the simulation results are in agreement with the test data of PLGS measured in 1994.

The simulation results from case (1) to (4) are used to benchmark the RELAP5 model of the Point Lepreau HPECC system for the injection calculation and pressurization process simulation for the water tanks. HPECC injection calculation and tank pressurization simulations are relevant to water hammer analysis of the HPECC piping system.

In total, 12 transients, which were recommended for water hammer analysis from the analysis of the test data, are simulated using RELAP5 model of the HPECC system in case (5). RELAP5 predictions are consistent with calculated physical limits. The RELAP5 model also shows excellent solution stability and consistency of results under varieties of calculation conditions, including initial gas tank pressure and valve opening time. Such solution stability and result consistencies are key characteristics of a simulation model for water hammer analysis.

Through the simulations and analyses performed in the above five cases, it has been validated that the RELAP5 basic HPECC model is accurate. Hence, the RELAP5 code is capable of modeling the HPECC system for safety assessments.

3.3 Water hammer analysis with entrapped air pocket

The calculations and analysis results of case (6) have demonstrated that entrapped air has a strong effect on pressure waves inside the HPECC piping system. Some results are shown in Figures 2 to 4. Figure 1 shows the location of the entrapped air volume, which is downstream the high pressure water tanks and at the connection to the H_2O Zero Air Gap Tank. During ECC injection for a 100% ROH break, pressure wave attenuation inside the piping system between the connection downstream at the water tanks and the connection upstream at the high pressure injection valves is presented in Figure 2. Pressure transient upstream of the high pressure injection valves is shown in Figure 3 and the corresponding pressure ratio in Figure 4. When the entrapped air volume is larger, the pressure transients inside the piping system become more severe.

The entrapped air volume in the current analyses ranges from very small to large and it is assumed to be at different locations. The calculation results demonstrate that when the air is entrapped into the piping system at different locations, its effects on pressure waves are different. For example, compared with the results of just one air pocket described in Figure 1, the pressure waves become more severe when two separated air pockets are located at the same straight piping, node 1 of component C729 and node 2 of C720, or node 8 of C729 and node 2 of C720. If the entrapped air is divided into three pockets located at node 5 of C729, node 1 of C729 and node 2 of C720, its effects on pressure wave are stronger than that of two locations. When two separated air pockets are located at the same straight piping, i.e. node 5 of C729 and node 8 of C729 (not shown in the figure), it seems to have the strongest effects on the pressure waves. In these analyses, the total air volume for each situation is assumed to be the same.

For the purpose of comparison, a CATHENA model with the same nodalization scheme and simulation conditions as RELAP5 model has been developed. When the entrapped air pocket has a small volume, the calculation results of both RELAP5 and CATHENA model agree well. However, when the entrapped air volume becomes larger, the CATHENA results begin

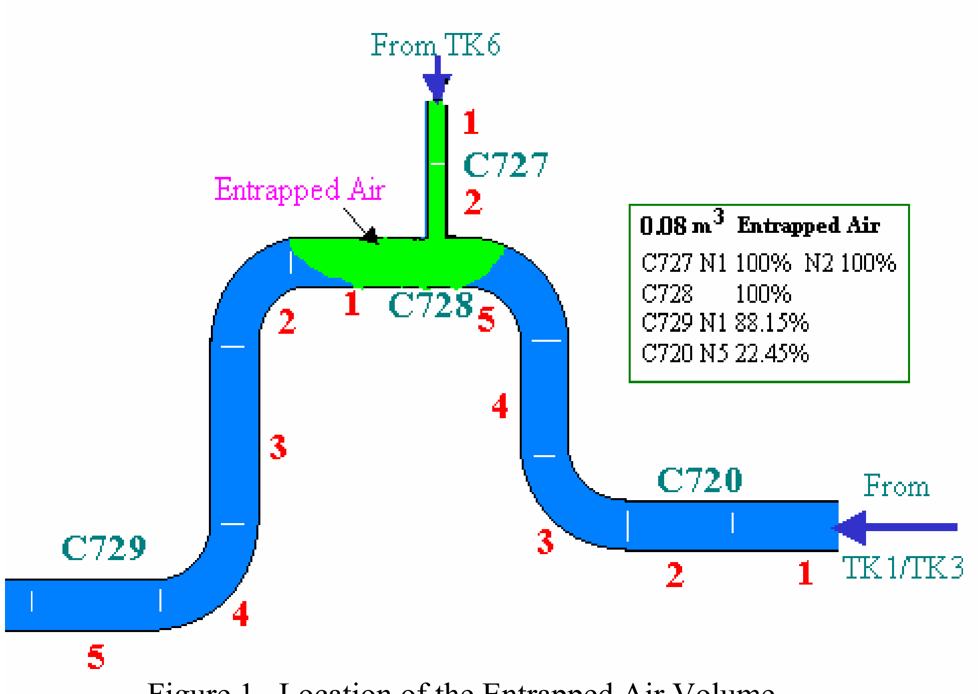

Figure 1 Location of the Entrapped Air Volume

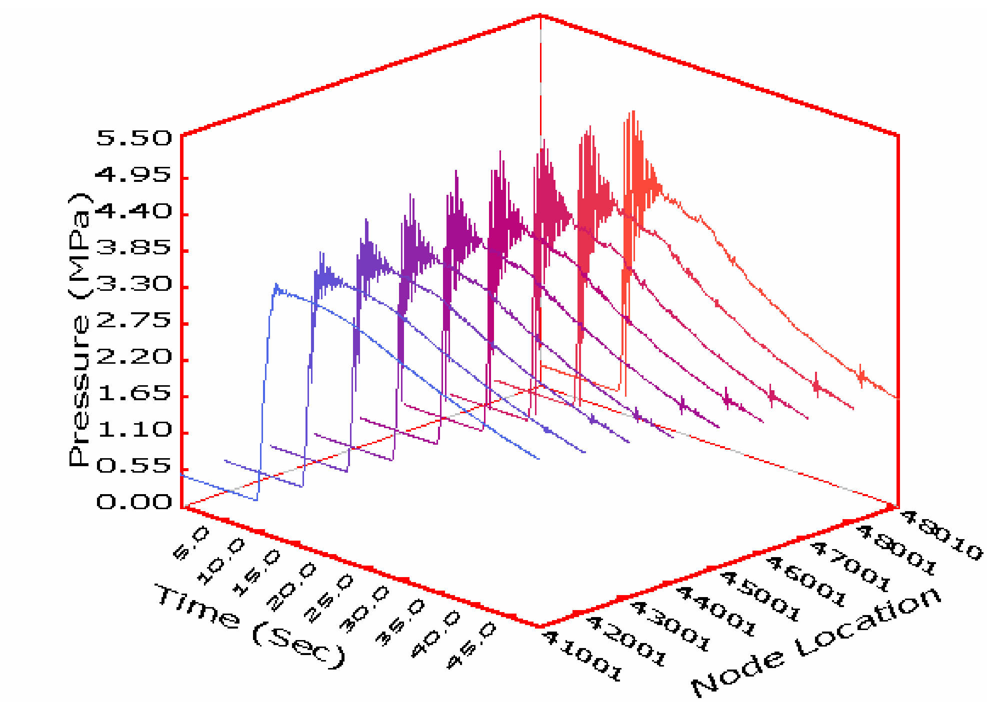

Figure 2 Pressure wave attenuation inside the piping system downstream water tanks during ECC for 100% ROH break event

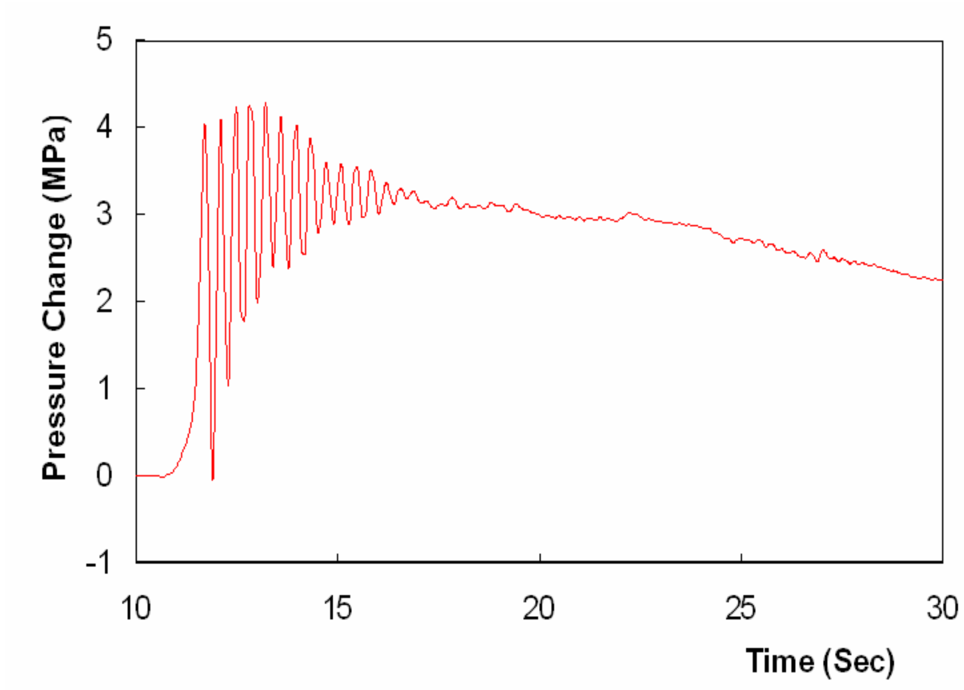

Figure 3 Pressure transient upstream of high pressure injection valves

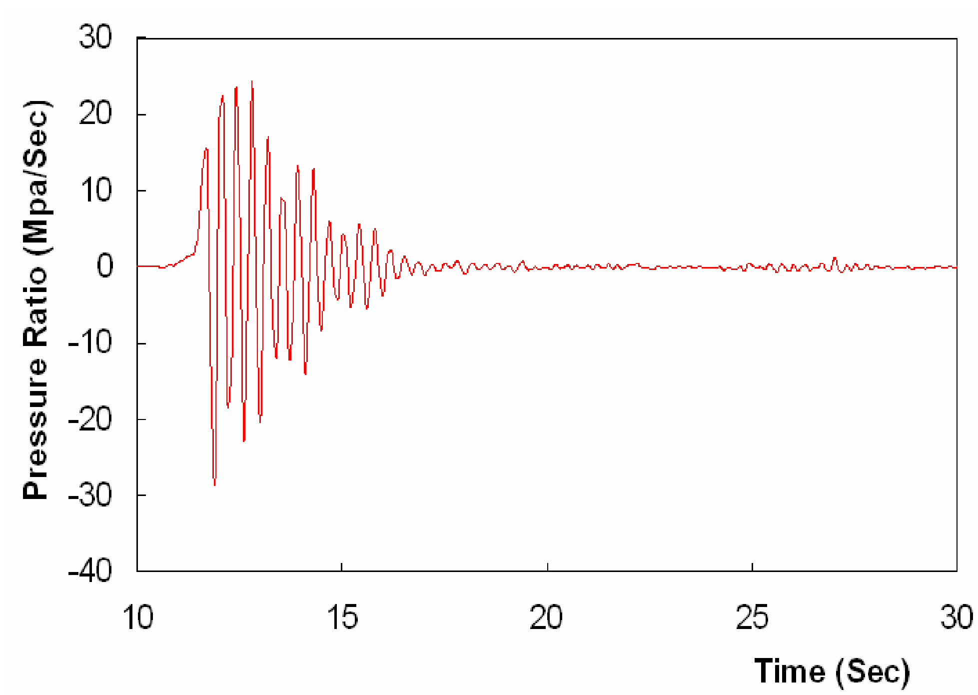

Figure 4 Pressure ratio corresponding to the pressure transient upstream of high pressure injection valves

to deviate from those of the RELAP5 model and to enter divergent pressure transients. The RELAP5 model always has excellent simulation performance, and can provide reasonable and reliable results no matter what the entrapped air volumes and locations are. Moreover, the RELAP5 predictions are similar to those of the PTRAN code [11]. This supports the current RELAP5 model.

4. RELAP5 results as input to stress analysis codes for water hammer analysis

As demonstrated in Reference [12], all force-time history input data required by stress analysis codes or structural codes can be extracted and converted from the RELAP5 outputs. Moreover, a data post-processing code WHA has been developed by ANSL to extract and convert RELAP5 output results, through which complete pressure (including pressure gradient and pressure rate, etc) time histories along the pipelines from the gas tank to reactor headers of the HPECC system can be generated. The detailed method or procedure for data transformation depends on the specific requirements (for example, data format) of the stress calculation codes.

5. Conclusions

Based on the extensive use of this code worldwide and the validation simulations presented here, it is concluded that RELAP5 is an excellent code for water hammer analysis with entrapped air pockets inside the CANDU HPECC piping system. The code incorporates the important features required for this type of analysis and has demonstrated satisfactory stability and accuracy for a wide range of simulation conditions. The preliminary RELAP5 results show that there may exist severe water hammer phenomena inside the CANDU HPECC piping system during the first ten seconds of high pressure injection when air pockets are entrapped. Based on these results, further investigation on water hammer of CANDU HPECC systems with entrapped air pockets is merited, especially the effects of entrapped air pocket sizes and locations on the pressure transients. And further input data model development is required for the stress analysis codes for which RELAP5 is an input.

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