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RELAP5 Capability to Predict Pressure Wave Propagation Phenomena in Single- and Two-Phase Flow Conditions

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Abstract

Correct evaluation of the hydrodynamic loads induced by large and rapid pressure waves propagating with the speed of sound along the reactor piping systems and Reactor Pressure Vessel (RPV) is an important and difficult issue in nuclear power plant safety. The pressure shock transients and resulting hydrodynamic loads on the pipes and RPV structures are commonly calculated with one-dimensional thermo-hydraulic system codes such as RELAP5, TRACE, DRAKO and ROLAST. In Sweden, the most widely used computer code for this purpose is RELAP5. This code needs, therefore, to be assessed for its capability to predict pressure wave behavior. The conducted assessment involves simulations of single- and two-phase shock-tube problems and two-phase blowdown as well as water hammer experiments. The performed numerical experiments clearly show that RELAP5, with the proper time step and spatial mesh size, is capable of predicting the complex dynamics of single- and two-phase pressure wave phenomena with good to reasonable accuracy.

Keywords: Pressure waves, Shock-tube, Two-phase flow, Water hammer, RELAP5

1. Introduction

The capabilities of the existing best estimate nuclear codes, such as RELAP5 [1] and TRACE [2], to correctly predict rapid pressure wave propagation phenomena as well as their response on piping systems were recently subjected to an extensive assessment. The new computer code WAHA [3] was developed in order to improve some weaknesses exhibited by RELAP5 and TRACE in simulating the two-phase flow water hammer phenomena.

There are several expected and postulated transients that can lead to rapid and large pressure changes propagating along the hydraulic nuclear systems at the speed of sound. The cause of such transient may be intentional or accidental rapid valve closure, i.e. the fast closure of the main steam isolation valves or the turbine valves. Such transients may also be caused by a shutdown of the main feedwater pumps. In addition to the loads on the vessel internal structures, the pressure shock waves entering the reactor vessel from the main steam lines may, in BWR reactors, cause collapse of the vapor bubbles. That could result in a surge of positive reactivity in the core and in turn in a rapid increase of reactor power.

Other pressure waves are caused by pipe ruptures in the reactor pressure systems. The expansion wave that propagates towards the reactor pressure vessel after a loss of coolant accident may result in destructive loads on the vessel internals.

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The pressure waves also appear in other components of the nuclear systems, such as pipes, valves and pumps, as a consequence of water and cavitation hammers. The large pressure surges caused by fluid momentum changes and a collapse of vapor bubbles at the entering liquid front may induce significant loads on the components of piping systems.

The evaluation of pressure shock transients and induced pressure loads on structures and components of the reactor hydraulic systems is an important issue of nuclear safety at the construction, operation, upgrade and life extension stages of the reactor [4, 5].

Depending on the complexity of the reactor system a variety of computer codes, such as DRAKO [6], ROLAST, RELAP5, or TRACE, is used by the nuclear industry and regulatory authorities for the simulation of pressure shock transients and evaluation of the resulting dynamic pressure and fluid forces on the solid structures. The time-dependent results are then supplied to the structural analysis codes for the stress analysis.

The two-phase flow is modeled in the RELAP5 computer code using six equations, namely mass, momentum and energy balances for vapor and liquid. The system of the six first-order partial differential equations is derived from the cross-section averaged Navier-Stokes equations [7]. Diffusion terms with second-order derivatives are replaced by flow-regimerelated empirical correlations. The type of the flow regime is determined by the flow parameters, generally void fraction and mass flux, and the geometry.

The first-order-accurate numerical scheme commonly used in RELAP5 for fast transient calculations is based on a semi-implicit finite difference method with staggered grid and donor-cell discretization of the convective terms. The applied numerical scheme is efficient and robust, and avoids some problems associated with the ill-posedness of the basic two-phase flow equation system in RELAP5 [8].

The large numerical diffusion, which is a consequence of the first-order spatial and temporal discretization, introduces in some cases a significant numerical error into the solutions, e.g. stretching discontinuity waves on coarse grids. On the other hand, the numerical diffusion is the main mechanism suppressing the ill-posedness of the basic two-phase flow model, and ensuring stability of the numerical scheme used in RELAP5. For instance, a significant reduction of the diffusion causes numerical oscillations behind the shock wave in the RELAP5 solution.

Several assessment studies have been performed in the past decade to demonstrate the suitability of the RELAP5 code to calculate the propagation of pressure waves in piping systems, for example [9–12]. These studies have shown that RELAP5 may be successfully used for transients with the characteristic time scale determined by the fluid velocity, but should be used with extreme caution for transients with acoustic waves [13]. Recent investigations of the of the RELAP5 numerical scheme, however, have demonstrated the capability of the code to predict acoustic waves with almost second-order accuracy if sufficiently small time steps are used [14].

The purpose of this work is to assess the capability of the RELAP5 computer code to simulate single and two-phase acoustic wave propagation with the use of default computational options and fine temporal and spatial discretizations.

The RELAP5 code is assessed against known single and two-phase moving discontinuity benchmarks [15, 16] experiments with depressurization of a vertical pipe under a temperature gradient [17], and experiments with water and cavitation hammers [18].

2. Single-Phase Shock-Tube Benchmarks

The one-dimensional ideal gas shock-tube problem is helpful when evaluating various finite difference techniques [3]. The steep propagating shock fronts are among the most difficult phenomena to replicate with a uniformly spaced finite difference mesh. This applies to both single as well as two-phase cases. Many highly specialized finite differencing techniques (high order spatial differencing, non uniform and adaptive gridding or direct application of the Rankine- Hugoniot jump conditions) have been proposed for the purpose of modeling shocks and related phenomena. RELAP5 has not been developed as a specialized "shock-tube" code and does not include these numerical techniques.

2.1. Ideal Gas Shock-Tube Problem

In order to asses the computational dispersion errors caused by the first-order highly diffusive upwind

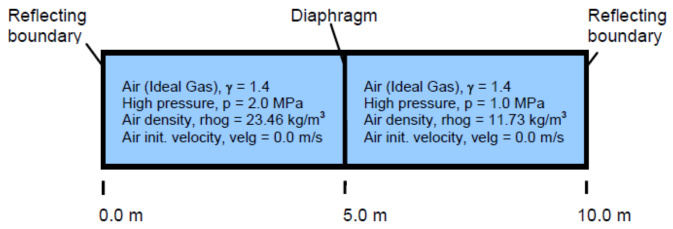

Figure 1: Schematic of air shock tube

difference scheme and the artificial viscosity terms in the difference equations, the RELAP5 results of the ideal gas single-phase shock-tube simulation are compared to an exact solution of the problem.

Discussed here is a simulation of the classic shock-tube problem (sometimes called Sod's problem). A diaphragm located at the midpoint of a 10 m long shock tube, with an inner diameter of 0.0762 m, separates higher pressure (2.0 MPa) air from lower pressure (1.0 MPa) air. The pipe is adiabatic and the air on both sides of the diaphragm initially has the same temperature (297 K). The initial conditions used for the simulation are shown in Fig. 1.

A sudden rupture of the diaphragm creates a shock wave traveling into the lower pressure air region, and a rarefaction wave traveling into the higher pressure air region. This problem is a classical Riemann problem where an exact solution can be derived as long as the generated waves do not interact with the boundaries at either end of the tube [15].

The comparison of RELAP5 results with the exact solution is shown in Figures 2 to 4. In order to trace the acoustic wave propagation with almost secondorder accuracy [14], both RELAP5 calculations have been performed with time steps of about 0.1 times the acoustic Courant Number ($\Delta t \leq 0.1 \cdot \Delta x/c$). Both RELAP5 simulations are accurate representations of the exact solution, although the simulation with 200 nodes is clearly slightly more accurate.

The contact discontinuity and the shock and rarefaction waves are slightly smeared because of the numerical diffusion. These effects are reduced in the higher resolution calculation with 200 nodes. The use in the RELAP5 calculations of this very small time step, however, results in greater numerical oscillations behind the shock wave.

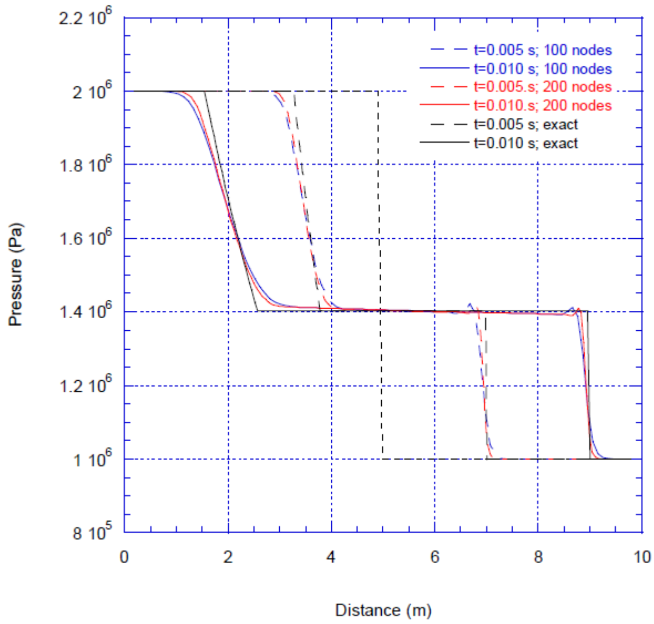

Figure 2: Air shock-tube—Riemann problem. Pressure profile, comparison of RELAP5 with exact solution

2.2. *Single-Phase Vapor Shock-Tube Problem*

The shock-tube problem presented next is an initial pressure and temperature jump in single-phase water vapor conditions. The problem consists of a onedimensional 2 m long shock tube with a diaphragm located at the midpoint which separates vapor at two different states. The initial vapor conditions used already in [3] are defined in Fig. 5. At time $t = 0\,s$, the diaphragm ruptures and the flow inside the tube starts evolving.

Figs. 6 through 8 show a comparison of RELAP5 results with an analytical solution of the problem with steam treated as a perfect gas. For pressures and temperatures determined by the shock tube initial conditions, however, water vapor is not a perfect gas. The initial vapor densities and speeds of sound have therefore been estimated using steam tables, while the rest of the thermo-hydraulic parameters were calculated using hydrodynamic equations for a perfect gas.

The results calculated with RELAP5 are in good agreement with the solutions obtained using analytical considerations.

The RELAP5 simulations were performed with a fine 200 nodes spatial discretization and two time steps $\Delta t = 0.10 \cdot CL$ and $\Delta t = 0.01 \cdot CL$, where CL

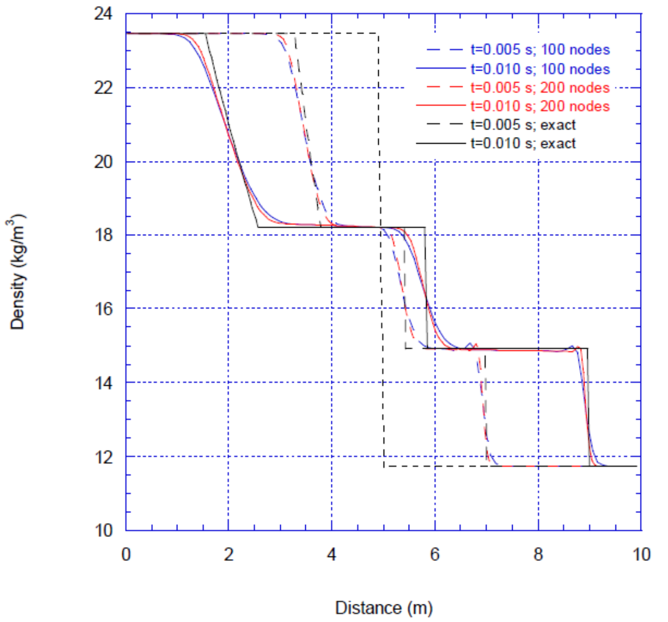

Figure 3: Air shock-tube—Riemann problem. Density profile, comparison of RELAP5 with exact solution

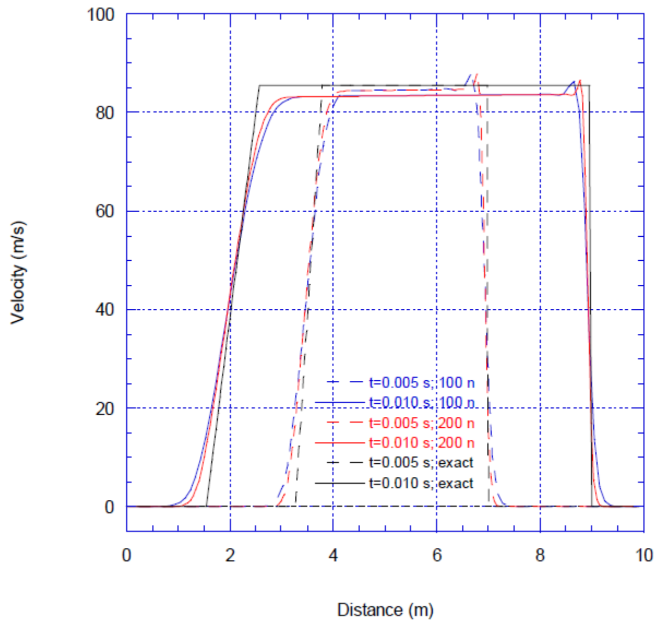

Figure 4: Air shock-tube—Riemann problem. Velocity profile, comparison of RELAP5 with exact solution

denotes the acoustic Courant limit. For such small time steps the RELAP5 code calculates the shock and rarefaction waves with very high, almost second-order accuracy [14]. The resolution of the shock and rarefaction waves is improved as the time step decreases. The decrease of the time step does not affect the middle change of the steam density at the contact discontinuity. On the other hand, there is a lack of numerical diffusion at very small time steps, causing increased numerical oscillations near the shock front.

The RELAP5 code is used mainly for simulations of reactor coolant systems during postulated transients. For those simulations such, very small time steps are usually used only for some critical moments. There is a special time-step control technique implemented in the code. It halves the time step, until the minimum time step equals 10^{-7} s, when numerical difficulties arise.

Solutions of higher accuracy become important and necessary in calculations of values and frequencies of hydrodynamic loads caused by pressure waves or water hammers in separate piping systems [6].

2.3. *Single-Phase Liquid Shock-Tube Problem*

In this problem, a shock tube with a length of 10 m filled with pure single phase water is modeled. The

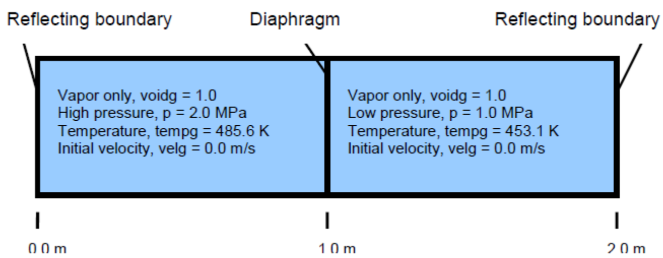

Figure 5: Schematic of single-phase vapor shock tube

simulation starts at time 0.0 s when the diaphragm which separates two halves with significantly different states is ruptured. The initial conditions are defined in Fig. 9.

The figures below (Fig. 10 and 11) show the RELAP5 results compared with the results obtained with the DRAKO computer code [5]. The DRAKO code has been specially developed for the analysis of pressure wave propagation in complex piping systems. This code is still commonly used in the nuclear industry for calculation of hydrodynamic loads on nuclear power plant piping systems, especially loads induced by water and steam hammers. The calculations with DRAKO were performed using the method of characteristics and the second-order McCormack finite different numerical scheme. Both RELAP5 and DRAKO simulations were performed

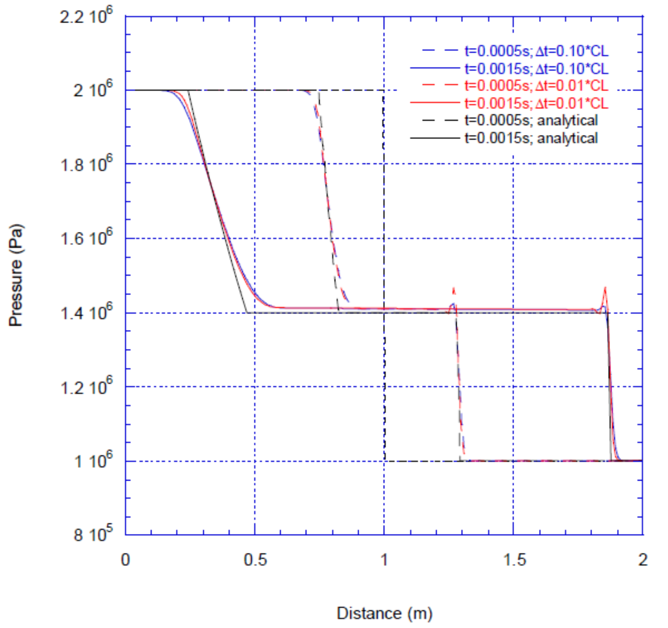

Figure 6: Water vapor shock tube. Pressure profile, comparison of RELAP5 with analytical solution

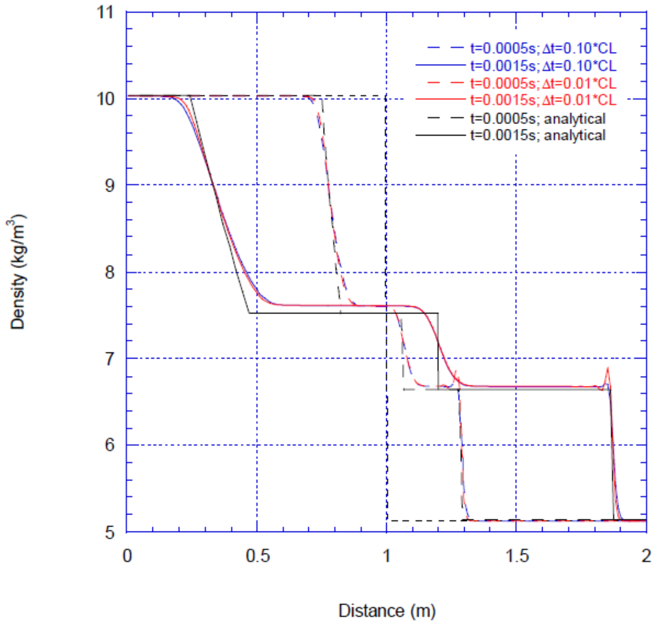

Figure 7: Water vapor shock tube. Vapor density profile, comparison of RELAP5 with analytical solution

with 180 nodes spatial discretization and the same time step $\Delta t = 1.0 \cdot CL$.

There is practically no difference between the results of RELAP5 and DRAKO with method of characteristics. Both the shock and rarefaction waves have almost identical slopes. Unlike the first-order upwind scheme used in RELAP5, the McCormack scheme does not introduce diffusion errors into the numerical solution but instead introduce significant dispersion errors near steep gradients. Thus, the numerical diffusion errors introduced by the RELAP5's first-order accurate numerical scheme are negligible for the case of single-phase liquid shock waves.

3. Two-Phase Shock-Tube Benchmarks

The most interesting issue, however, is to investigate the performance of RELAP5 regarding calculations of the pressure wave propagation in twophase flow conditions. There are several variations of the two-phase shock tube problem first proposed by Toumi [16] to test numerical schemes for hyperbolic equations. Fig. 12 defines the initial conditions for the two-phase shock tube problem used, among other, in [3].

The diaphragm which separates the left and the right halves of the 100 m long horizontal tube is removed at time 0.0 s.

There is no exact analytical solution of this problem. The RELAP5 results are, therefore, compared with the results published in [3], obtained by using the WAHA computer code. The RELAP5 calculations were performed with 200 node spatial grid and a time step of $\Delta t = 0.10 \cdot CL$. Figs. 13 to 16 present a comparison of the main variables at time $t = 0.0081\ s$. One can see that there are no significant differences between the RELAP5 and WAHA results.

However, both sets of results do not display the expected differences between the phasic velocities and phasic temperatures. The initial conditions defined in Fig. 12 assume that, on both sides of the tube, the phasic velocities and phasic temperatures are equal to one another. Moreover, the two-phase flow models used in both codes imply almost immediate and significant inter-phase mass, momentum and energy transfer. All this causes the phasic velocities and temperatures to be nearly identical, and the RELAP5 and WAHA solutions are similar to the solution of the problem with a homogeneous equilibrium model.

Figs. 18 through 22 shows pressure, phasic velocities, phasic temperatures and vapor volume frac-

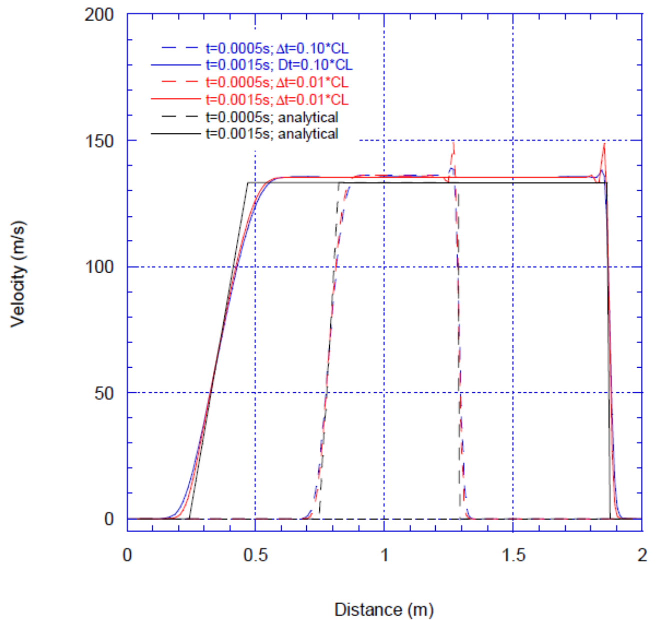

Figure 8: Water vapor shock tube. Vapor velocity profiles, comparison of RELAP5 with analytical solution

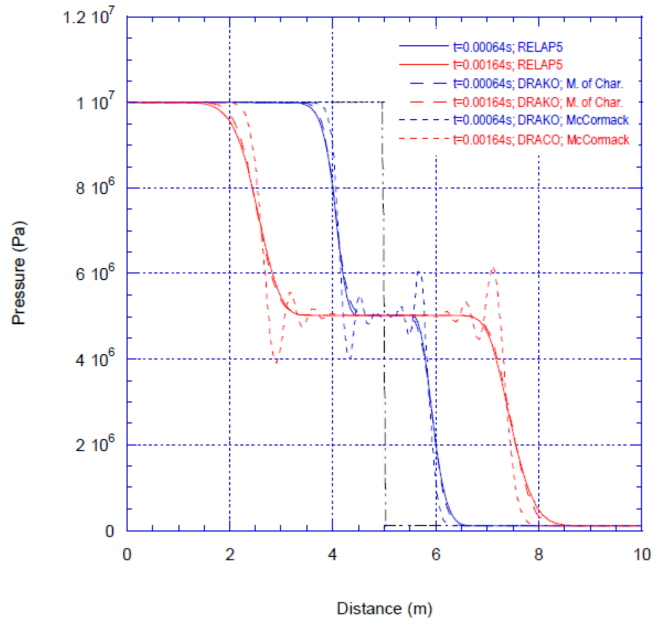

Figure 10: Liquid shock tube. Pressure profiles at different times, comparison of RELAP5 with DRAKO

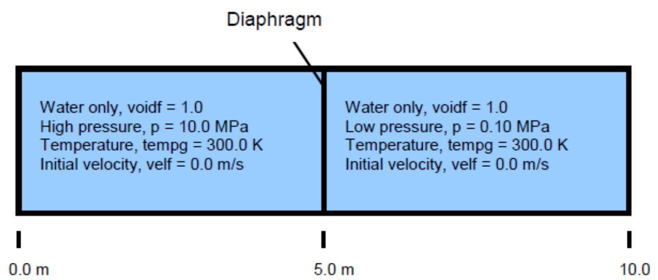

Figure 9: Schematic of single-phase liquid shock tube

tions calculated with RELAP5 for the other twophase shock tube problem [13]. In this case the initial conditions for the liquid and gas phases on both sides of the tube, as defined in Fig. 17, are quite different.

Fig. 19 shows slight but visible differences in phasic velocities, whereas Figs. 20 to 21 show completely different phasic temperatures. Figs. 12 and 15 show not only the motion of discontinuities between the shock and rarefaction waves traveling in opposite directions, but also a change of the thermodynamic variables in the regions before the shock and rarefaction waves. This is because the interphase exchange source terms in the RELAP5 twophase flow model tend to achieve thermal equilibrium between phases in the tube immediately.

4. Blowdown under Temperature Gradient

The pressure wave behavior during a rapid depressurization of an unequally heated vertical pipe has been investigated both experimentally and computationally in [17]. The transient can be expected during the LOCA in water cooled nuclear reactor.

The RELAP5 nodalization scheme used for the simulation of the blowdown test is shown in Fig. 23. The model contains a water filled vertical pipe with a length of 3.2 m and a 0.0533 m inner diameter. The pipe is divided into 99 axial nodes, each 0.0323 m in length. The initial conditions of the pipe are a pressure of 0.855 MPa at the top of the pipe and a linear temperature distribution in the pipe with 283.7 K at the pipe bottom, and 437.9 K at the top. The break with 0.015 m in diameter at the pipe top is modeled by using a valve junction and a time dependent volume representing the constant atmospheric boundary conditions. The break is simulated with a delay time of 0.0055 s to match the experiment conditions.

Immediately after the pipe rupture, pressure suddenly drops to the saturation pressure in a small region close to the break. Some liquid flashes to steam and a two-phase region with low vapor void fraction forms at the top of the pipe. The rarefaction wave moving back and forth in the pipe is slowed

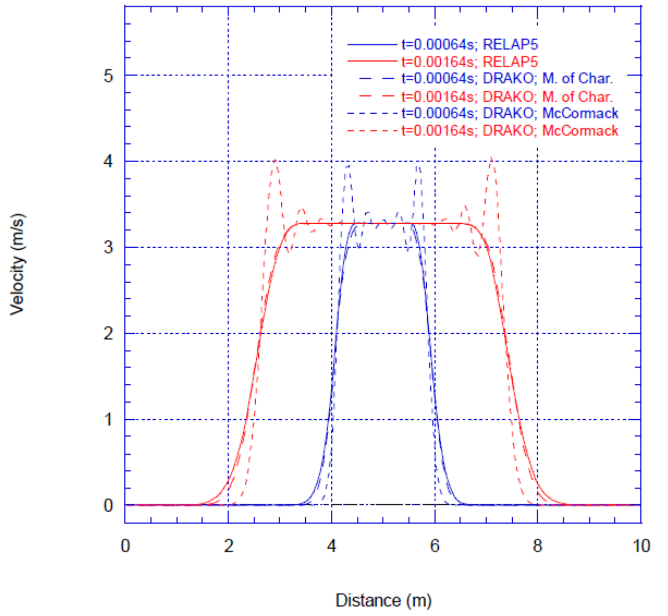

Figure 11: Liquid shock tube. Velocity profiles at different times, comparison of RELAP5 with DRAKO

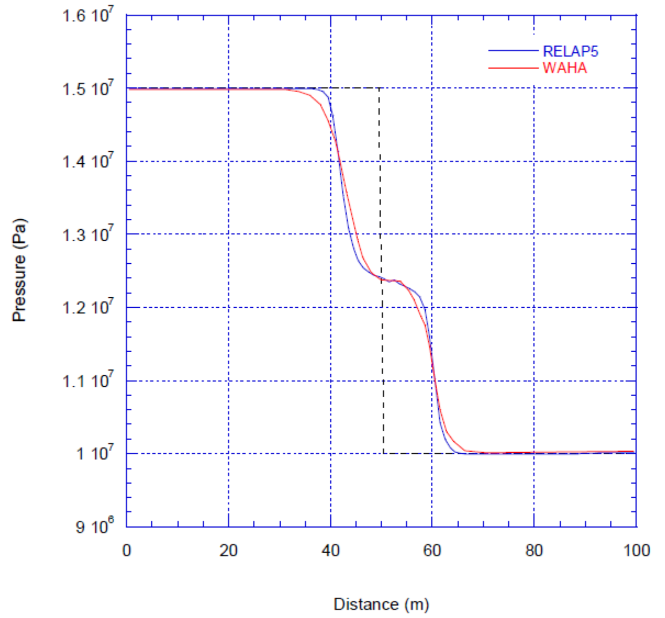

Figure 13: Two-phase shock tube. Pressure profile at time 0.0081 s, comparison of RELAP5 with WAHA

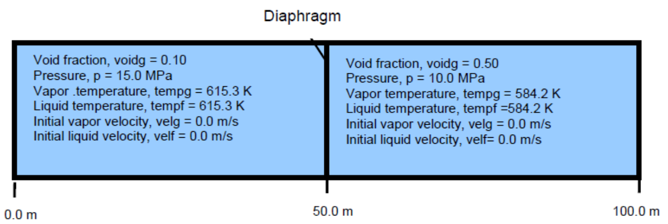

Figure 12: Two-phase shock tube problem initial conditions [3]

down and partially reflected by the discontinuity in the speed of sound at the interface between the single and two-phase regions.

In contrast to the calculations published in [11], the blowdown calculations presented here were performed with the use of the Henry-Fauske critical flow model (the default model in RELAP5). For subcooled conditions RELAP5, with the Henry-Fauske model, usually overestimates the break flow. The discharge coefficient of 0.78 was used to adjust the model to the orifice geometry used in the experiments and to reduce the break flow.

Fig. 24 to 26 show a comparison of pressure calculated with RELAP5 against data measured at three different positions PT3, PT4 and PT5 located 0.444 m, 1.20 m and 2.20 m, respectively, from the top of the pipe.

The RELAP5 results are in reasonable agreement with the measured data. Apart from the initial pressure drop following the tube break, which is significantly overestimated despite the discharge coefficient reduction, RELAP5 predicts the propagation velocities and amplitudes of the rarefaction waves traveling back and forth in the tube with good accuracy. Further decrease of the discharge coefficient in the RELAP5 default critical flow model does not reduce the overestimation of the initial pressure drop, but instead causes a significant damping of the amplitude of the reflected rarefaction wave. It seems that this large difference between the measured and calculated initial pressure drop is a result of some inaccuracies in the experiment, namely with possible break flow obstructions by the burst paper disk resulting in a smaller break area [11].

5. Water Hammer Experiments

The cold water hammer might occur when a travelling mass inventory in the pipeline bounces and diverts due to the close of a valve or as a result of a blow with a dead-end (wall). During such an event pressure increases in the system. The value of pressure peaks due to the water hammer might become a few orders higher than the nominal pressure of

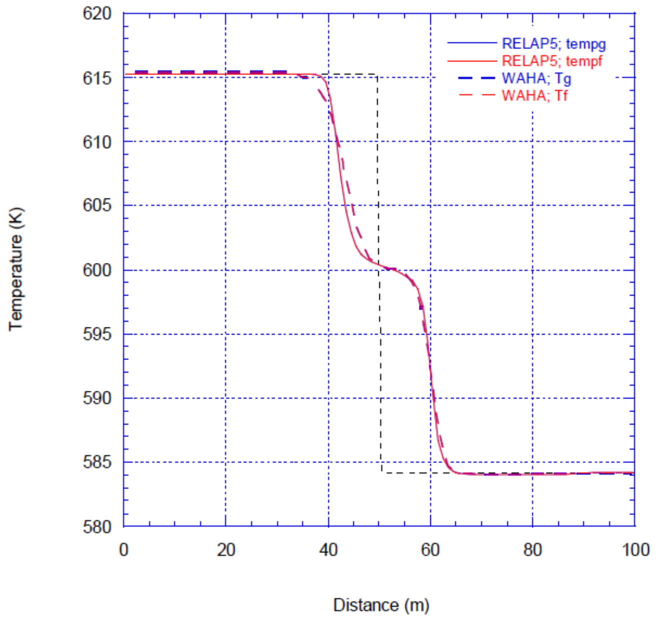

Figure 14: Two-phase shock tube. Temperature profiles at time 0.0081 s, comparison of RELAP5 with WAHA

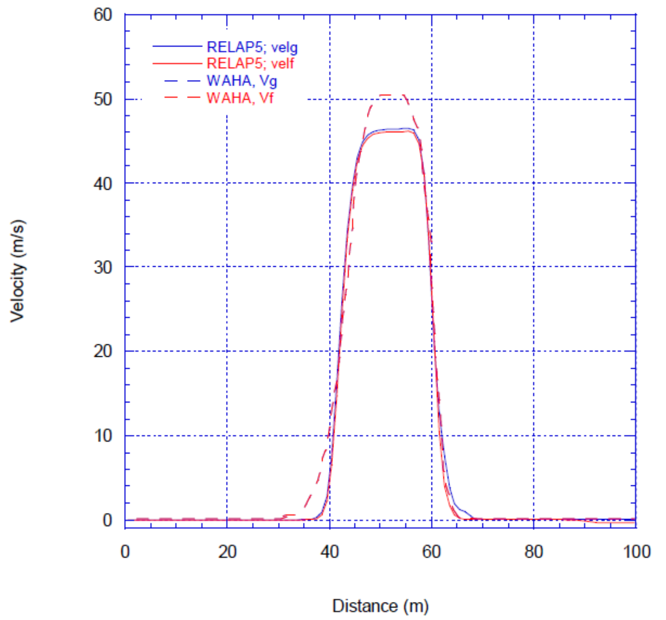

Figure 15: Two-phase shock tube. Velocity profiles at time 0.0081 s, comparison of RELAP5 with WAHA

the considered system. This potentially creates, undoubtedly, a risk of damage of the pipeline.

The thermal-hydraulics codes predict a cold water hammer with varied precision. In certain cases the first pressure peak is satisfactory predicted [18] and sometimes it tends to be under-predicted [19]. Thus the improvement of the codes' efficiency in predicting the cold water hammer would be desirable. The qualitative and quantitative judgment of the peaks comprehends peak amplitude (e.g. in MPa), numbers of peaks within a certain time interval and additionally, for instance, the shape of peaks. The most important, from the point of view of the installation' safety, are codes' water hammer computed results regarding the first pressure peaks, since these peaks have always the highest amplitude. Extreme values are taken into account in determining safety margins e.g. in stress analysis of the nuclear equipment.

5.1. CWHTF Experiment

The following section presents results from the validation of the thermal-hydraulics code RELAP5 against the Cold Water Hammer Test Facility (CWHTF) experiment of the FZ-Rossendorf institute. The main objective of the study was to examine the thermalhydraulics code accuracy and precision in predicting the cold water hammer, i.e. pressure peak values and wave amplitudes. The CWHTF experimental facility (Fig. 27) consisted of a 700-liter pressure vessel, which was filled with water (temperature was constant for all experiments (20°C) and pressure did vary from 0.1 to 0.5 MPa); a pipeline, which consisted of two pipes separated by a fast opening valve; a fast opening valve (the opening time did vary from 0.021 sec to ∼ 1 sec). A series of tests were performed. The tests did vary with respect to evacuation height, evacuation pressure, valve opening time, evacuation pressure, type of fixation of the bouncing plate and the gas pressure inside the vessel. The arrangement (overall dimensions) of the vessel and pipeline component (Table 1) remained the same for all tests.

A single test was initiated when the valve was opened. At the time the water inventory in the system started to move and after a certain time period the evacuation height was filled with water. The pressure wave would hit the bouncing plate and scatter from it. Then it would travel from the bouncing plate, through the vertical pipe, horizontal pipe (with the fast opening valve), a short vertical section of the pipe and finally would reach the vessel. Here again, it would bounce from the water reservoir in the vessel (a pressure wave reflects from the solid

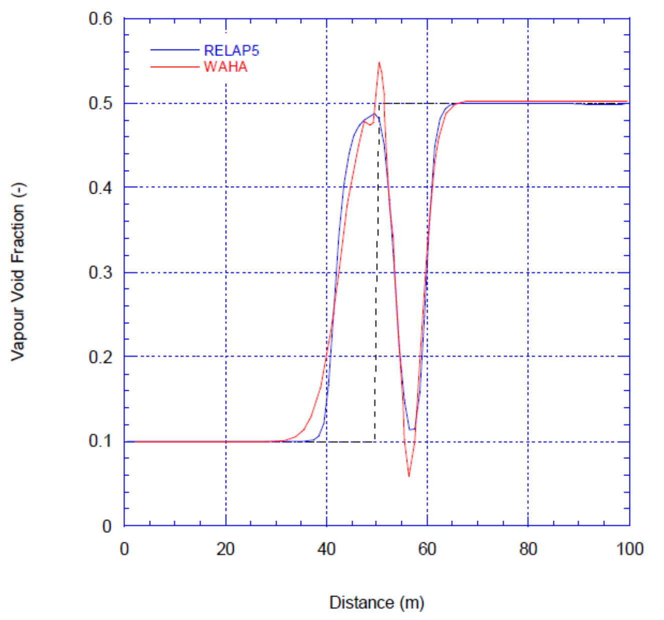

Figure 16: Two-phase shock tube. Vapor fraction profile at time 0.0081 s, comparison of RELAP5 with WAHA

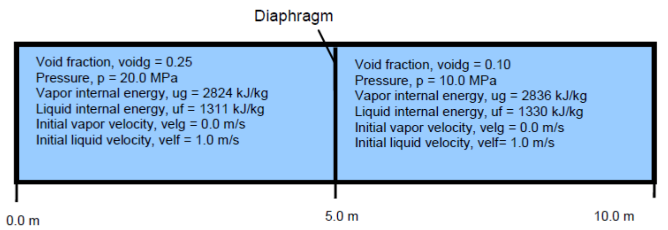

Figure 17: Two-phase shock tube problem initial conditions [13]

boundary and, like here, from the pressure boundary) [9, 18, 20]. And over again, the generated pressure wave would accelerate towards the bouncing plate. The bouncing wave procedure would repeat several times.

The computational model consisted of the following components that are listed in order of the appearance on Fig. 28:

- pipe component modeling the vessel; it consisted of 10 cells in which two at peripheries had smaller hydraulics diameters (areas) than the others in order to take into account the vessel's shape;
- pipe component modeling a horizontal part of the pipeline downstream the vessel; consisted of five cells;

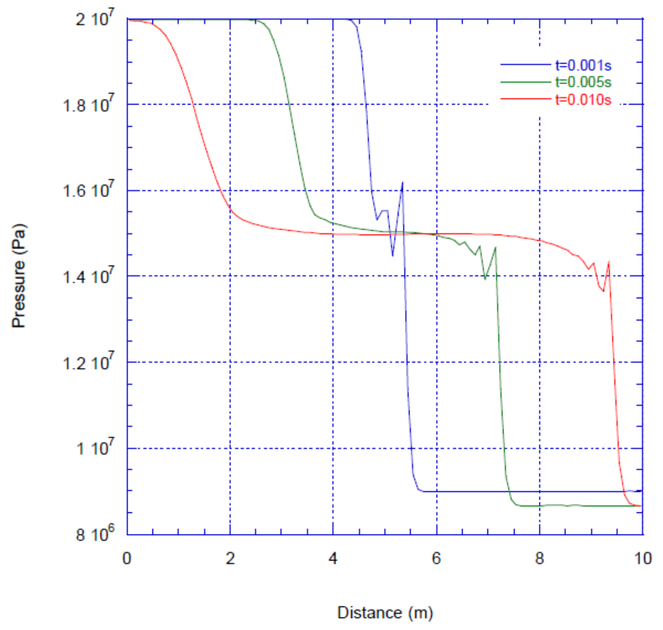

Figure 18: Two-phase shock tube. RELAP5 calculated pressure profiles at different times

- pipe component modeling the vertical part of the pipeline downstream the vessel; consisted of five cells;
- valve component modeling the fast opening valve;
- pipe component modeling a horizontal part of the pipeline downstream the valve; consisted of 10 cells;
- pipe component modeling a vertical part of the pipe downstream the valve; consisted of 14 cells; the last cells at the top were denoted to model the evacuation height;
- three junction components between neighboring model components;

The influence of pipe bends on the calculation was acquired by adjusting pressure loss coefficients at certain junctions in the model ($K = 0.225$; resistance coefficients for smooth- 90° bends). Time-step was determined in order to fulfill the Courant criterion.

Fig. 29 through 32 show the comparison between the computational results and the measured data. The evacuation pressure p_1 (mbar) for tests 150601, 150601a and 150601b [18] was 29, 40 and 50, respectively. The other test arrangements were for

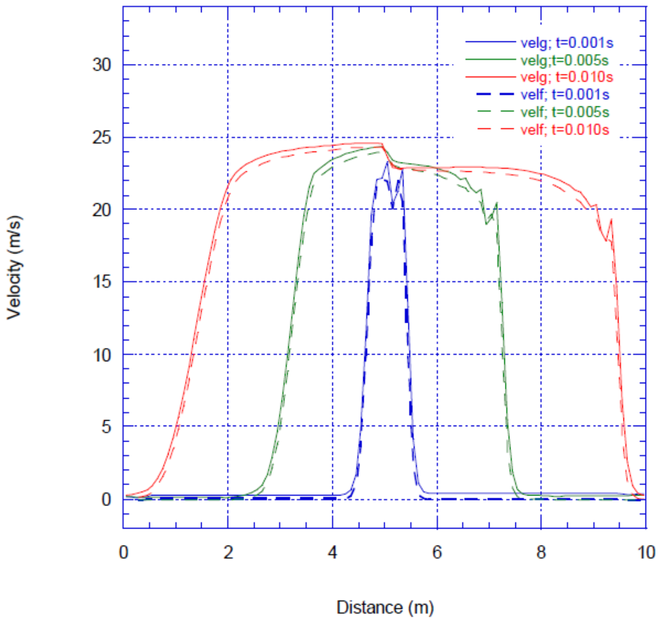

Figure 19: Two-phase shock tube. RELAP5 calculated profiles of phasic velocities at different times

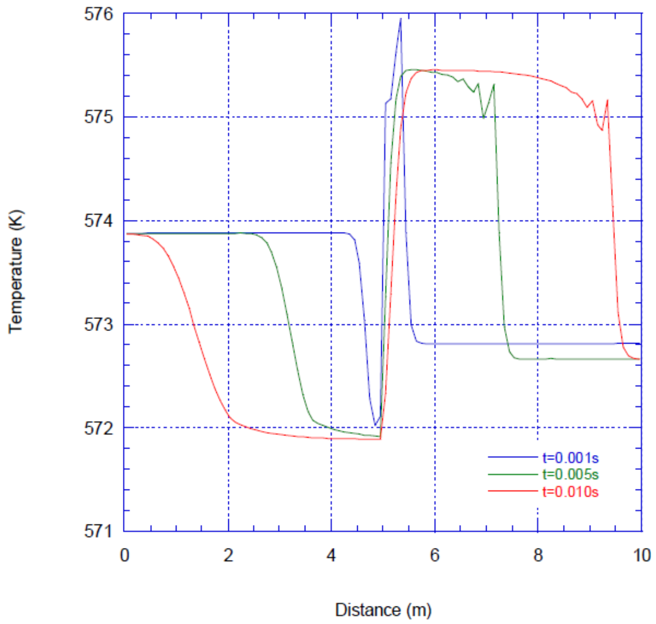

Figure 20: Two-phase shock tube. RELAP5 calculated liquid phase temperature profiles at different times

these experiments identical: evacuation height (H1-H2) 0.15 m, valve opening time 0.021 sec, vessel gas pressure p_3 = 0.1 MPa. Regarding test nr. 190601 [18] the experimental facility set-up was as follows: evacuation height 0.3 m, valve opening time 0.021 sec, evacuation pressure 29 mbar and vessel gas pressure p_3 = 0.1 MPa.

Regarding Fig. 29 (Test 150601), the first pressure peak of the experimental data appears a dozen of milliseconds earlier than a pressure peak computed by the code. The experimental pressure peak magnitude (3.25 MPa) is smaller from that of the computed value (3.63 MPa). In Fig. 30 (Test 150601a) the measured pressure peak appears earlier than the computed peak as well and its value (2.90 MPa) is higher from the computed value (2.50 MPa). In Fig. 31 (Test 150601b) a similar phenomenon takes place as in Figure 30: the code under-estimated the magnitude of the peak (measured value 2.70 MPa; computed value 2.25 MPa) which occurs ~0.02 sec earlier than the peak in the test. In Fig. 32 (Test 190601) the code over-estimate the peak magnitude (5.50 MPa compared to 4.40 MPa experimental) which appears at the nearly same time as the computed peak.

In order to assess the accuracy and performance of the code in modeling cases where the cold water hammer occurs, the relative error for every test was calculated and L_1 norm was calculated for the whole CWHTF experiment, since for this experiment we did possess data about the experimental matrix. L_1 norm is a convenient way to quantify an error concerning measurement and computed data:

$$L_{1,rel} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{c_1 - e_1}{e_1}\right| \tag{1}$$

where, $L_{1,rel}$—the L_1 relative error norm, N—a number of data pints, c—calculated data, e—measurement data.

L_1 norm for the CWHTF experiment is 0.166 and the standard deviation of the L_1 norm is 0.112. These values are regarding only the value of the first pressure peak and do not reflect the influence of the timing of the peak.

5.2. *PPP—test rig*

The objectives of the Pilot Plant Pipework (PPP) test rig tests of the Fraunhofer-Institut für Umwelt-, Sicherheits- und Energitechnik (UMSICHT) was to determine the air valves capability in protecting a pipeline system against cavitational hammers induced by a fast closing valve. The experimental set-

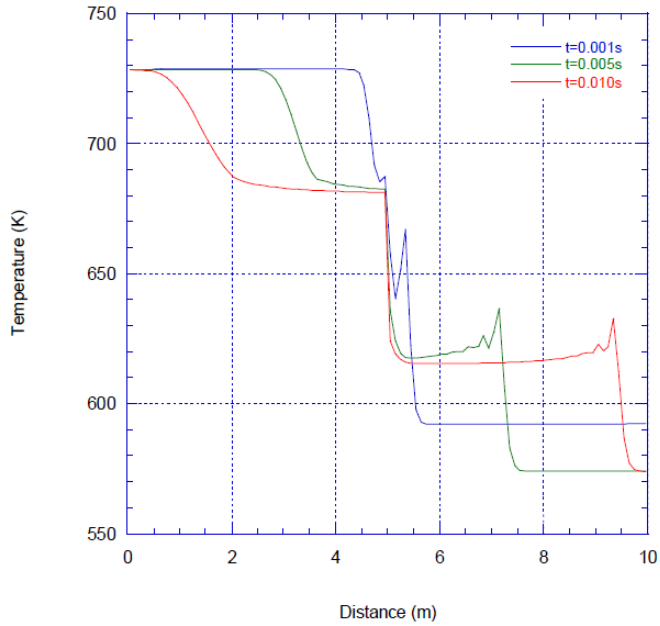

Figure 21: Two-phase shock tube. RELAP5 calculated vapor phase temperature profiles at different times

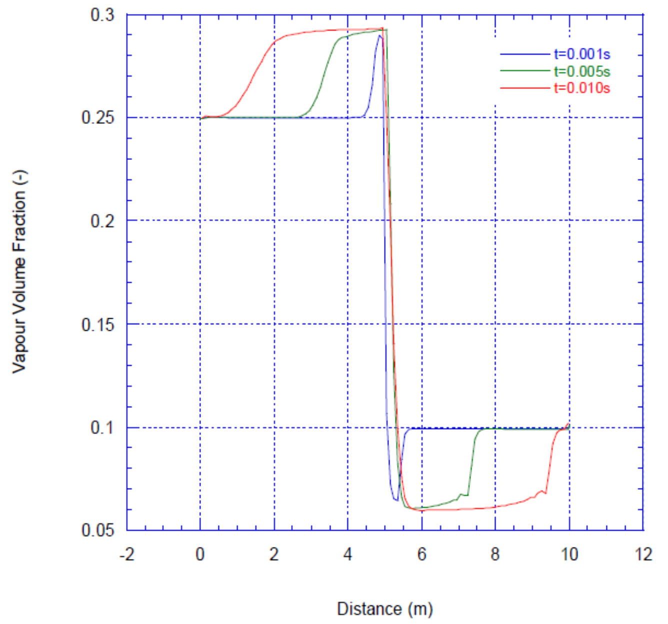

Figure 22: Two-phase shock tube. RELAP5 calculated vapor volume fraction profiles at different times

up of the PPP test rig (Figure 33) consisted of 160 m-long pipeline with an internal diameter of 0.11 m and two bridges (vertical and vertical/horizontal); fast closing valve situated 8.7 m from a pump with a closing time of 0.07 sec; pressure tank B2.

Test no. 329 was initiated (closure of the fast closure valve) when the boundary and initial conditions in the system (pipeline) were achieved: pressure p = 1.018 MPa, temperature T = 419.6 K and initial fluid velocity of v = 3.975 m/s. The closing valve was fully open at 0.1 sec within a time of 0.03 sec. At the time a rarefraction pressure wave was generated that traveled from the closure valve, passing through first horizontal bridge, a turning point, vertical/horizontal bridge up to pressure tank B2. The wave would therefore reflect from the water reservoir in the tank B2 (water boundary condition) and would change its direction towards the fast closing valve. When the backflow would reach the closed valve the water hammer would occur. The flow would oscillate between the valve and tank B2.

The computational model consisted of pipe components, valve, time-dependent volume and timedependent junction. Boundary conditions were constituted by the time-dependent volume and pipe component modeling pressure tank B2. Pressure loss coefficients for 90-degree bends were adjusted to k_{90} = 0.19and for 45-degree bends to k_{45} = 0.12. Timestep was set-up with taking into consideration Courant criterion ($\Delta t = 0.1 \cdot CL$ where CL is the Courant limit).

Calculated results were compared with the measured results (Fig. 34) and depict a pressure magnitude at the position of the closed valve (position P03). Concerning the first pressure peak, the time that the rarewave needs to cover two times distance between the fast closing valve and the pressure vessel B2 for the computational model is shorter than in the test by about 0.1 sec (similar to the results presented in [21]). The experimental data may possibly be prone to systematic error. Regarding the amplitude of the first pressure peak it is 3.2 MPa (1.6 sec) for computed data compared to around 5.0 MPa (1.7 sec) from the PPP test rig test. The second pressure peak magnitudes are 2.4 MPa (2.8 sec) and 2.6 MPa (2.9 sec) for computation and experiment, respectively. Consecutive pressure peaks become significantly of much smaller amplitude (around 2.0 MPa and 1.4 MPa) than the first two; computed values exceed those of the test. Regarding the UMSICHT test facility the computed peak magnitude is significantly under-predicted. The fluid structure interac-

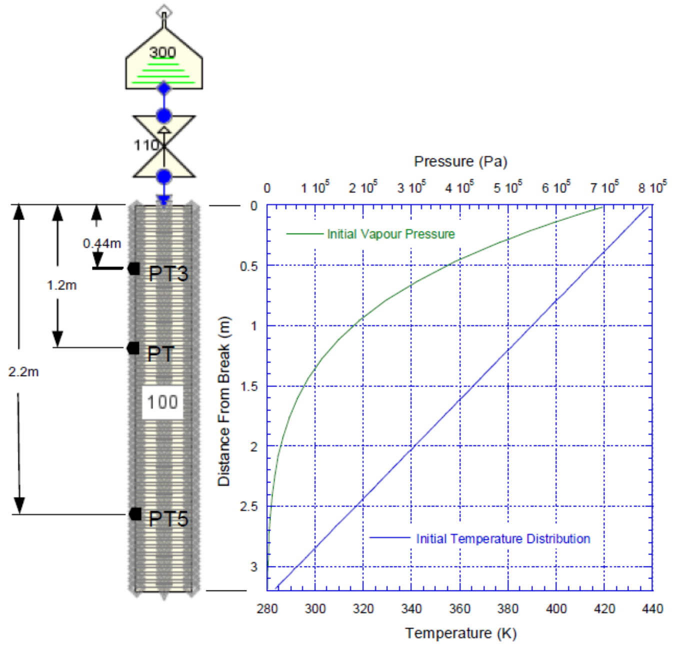

Figure 23: Pressurized pipe nodalization scheme with temperature and vapor pressure initial distributions

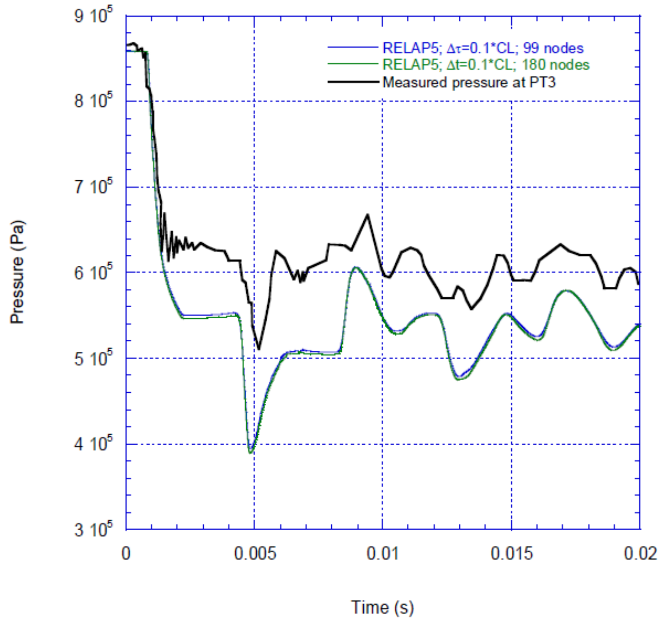

Figure 24: Pressure comparison at position PT3

tions were not taken into account since the code does not have this feature.

6. Conclusions

The RELAP5 code is capable of calculating, with satisfactory accuracy, the pressure wave phenomena in both the single-phase and two-phase flow conditions expected in the nuclear reactor cooling systems.

For the analyzed single-phase shock-tube benchmarks, the results obtained with RELAP5 agree very well with analytical solutions or results computed with other codes approved in the nuclear industry to determine loads caused by pressure waves.

The RELAP5 results regarding both two-phase shock-tube problems analyzed are also very reasonable and in line with expectations. Due to the assumption of instantaneous heat, mass and momentum transfer between liquid and vapor, the discontinuities of phasic velocities and phasic temperatures are very close together.

Simulation of the blowdown with temperature gradient experiment matches the experimental results qualitatively. The initial pressure drop caused by the rapid tube depressurization is significantly overestimated, but the reflections of the rarefaction wave off of the solid tube bottom as well as of the sound speed discontinuities were predicted reasonably well.

The RELAP5 simulations of the CWHTF and PPP water hammer experiments show a good to satisfactory agreement between measured and calculated results. The timing and amplitude of the first pressure peak predicted by RELAP5 are in good agreement with the measured data for all the CWHTF tests. Convergence between the calculations and measurements for the PPP tests is much lower due to too much damping of the waves by friction on the pipe walls.

In all considered benchmarks a fine discretization in time is more important than discretization in space. In order to trace acoustic waves with almost second order accuracy the use of time step $0.01 \cdot CL \leq \Delta t \leq 0.10 \cdot CL$ is recommended. Further reducing the time step usually leads to numerical oscillations near the steep pressure gradients.

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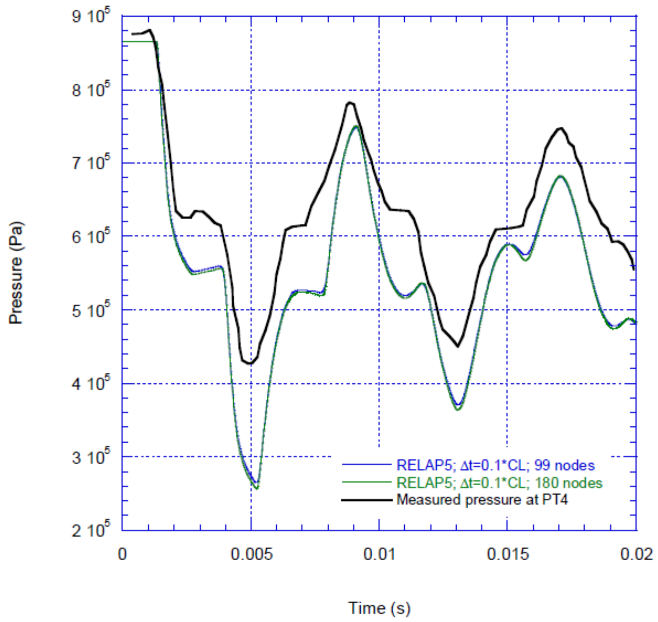

Figure 25: Pressure comparison at position PT4

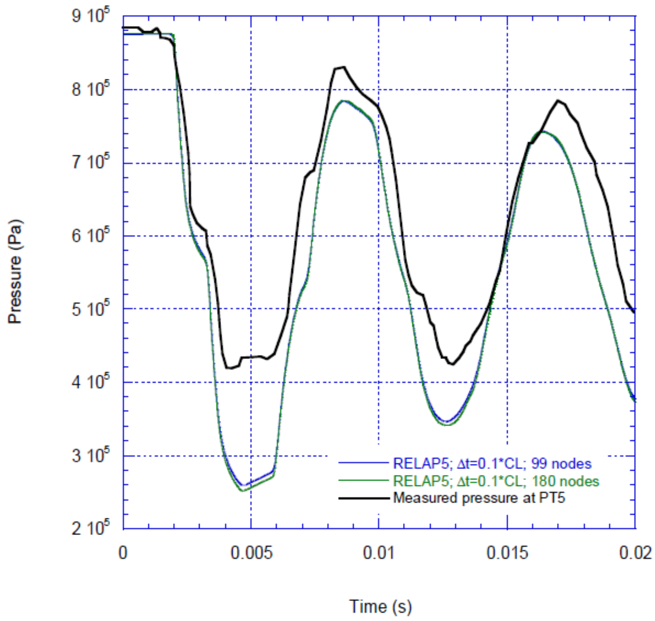

Figure 26: Pressure comparison at position PT5

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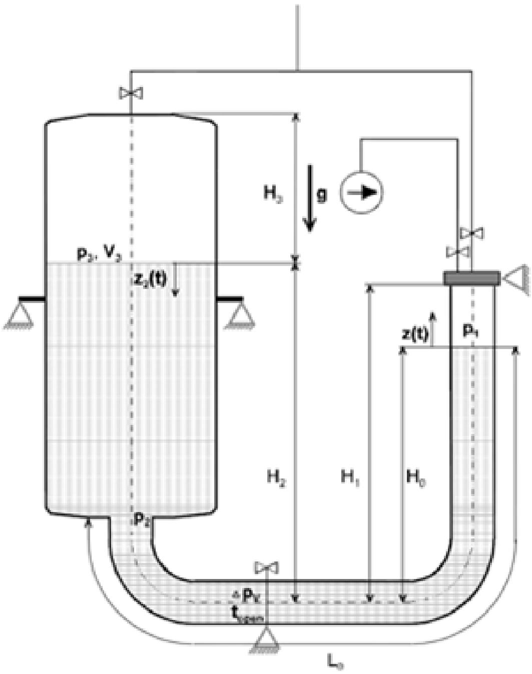

Figure 27: Schematic diagram of the CWHTF experimental facility

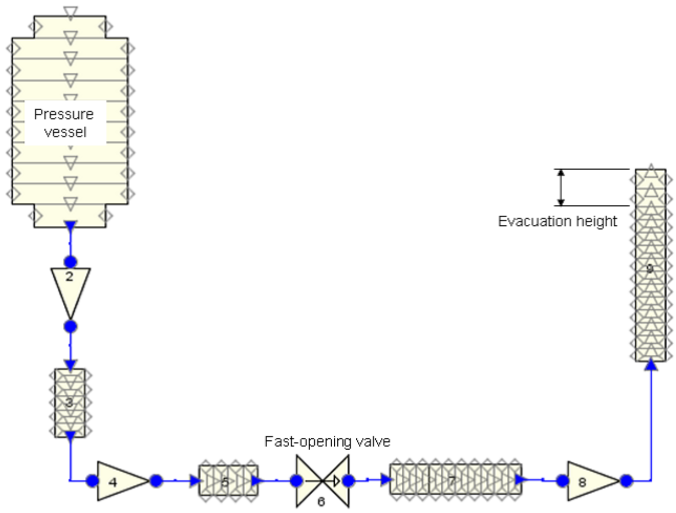

Figure 28: Nodalization of the CWHTF experimental facility

Table 1: Detailed description of the pipeline and the vessel properties in the CWHTF experiment [1]

Parameter	Pipeline	Vessel
Outer diameter, mm	219	800
Wall thickness, mm	6.0	6.0
Curvature radius of the bend, mm	306	-
Total pipe length L_0, m	3.285	-
Internal volume, dm^3	124	700
Design pressure, MPa	6.0	1.0
Pressure of plastification, MPa	9.0	-
Pressure of break, MPa	22.6	-
Temperature of water inventory in the facility, °C	20	

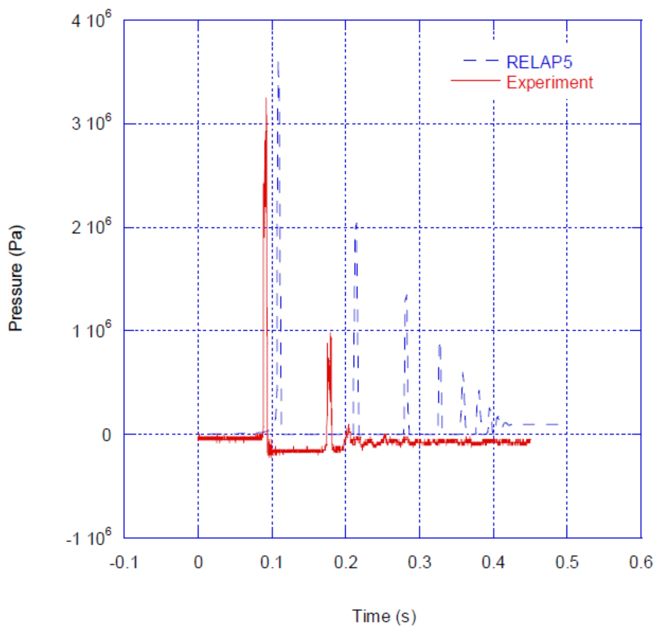

Figure 29: The CWHTF test facility: test 150601

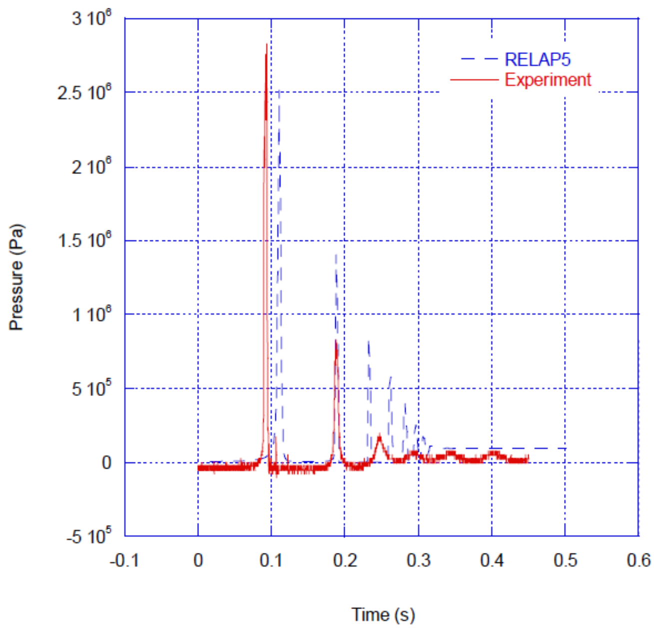

Figure 30: The CWHTF test facility: test 150601a

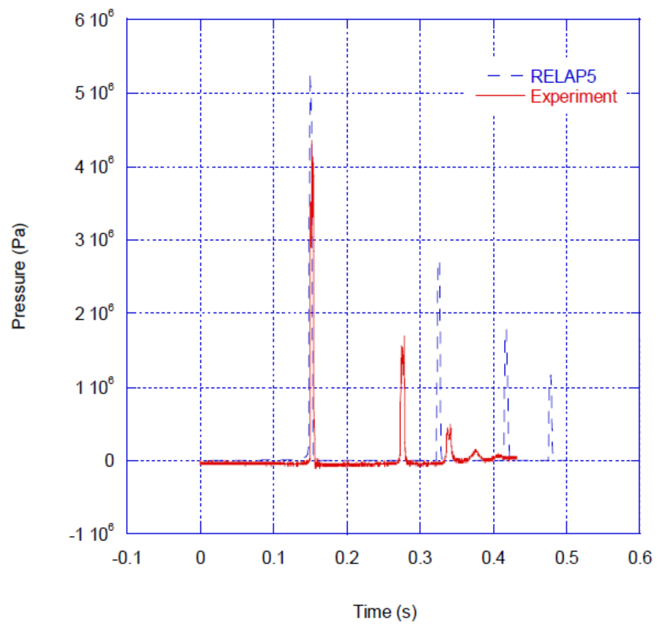

Figure 32: The CWHTF test facility: test 190601

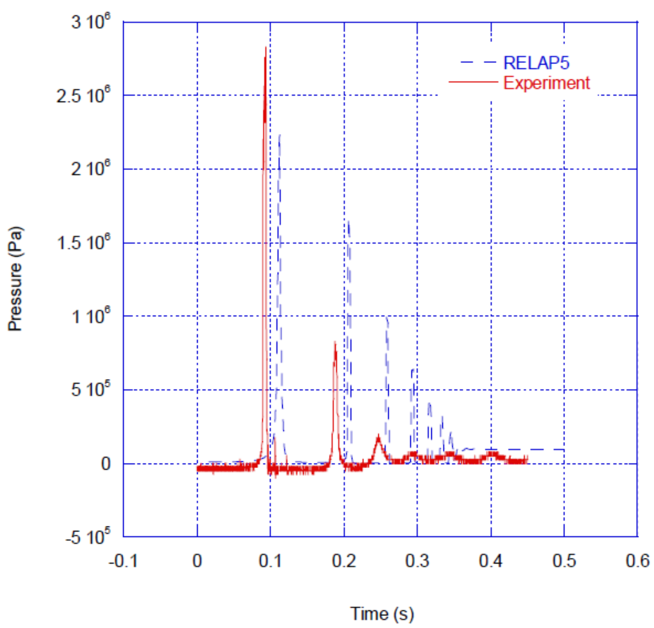

Figure 31: The CWHTF test facility: test 150601b

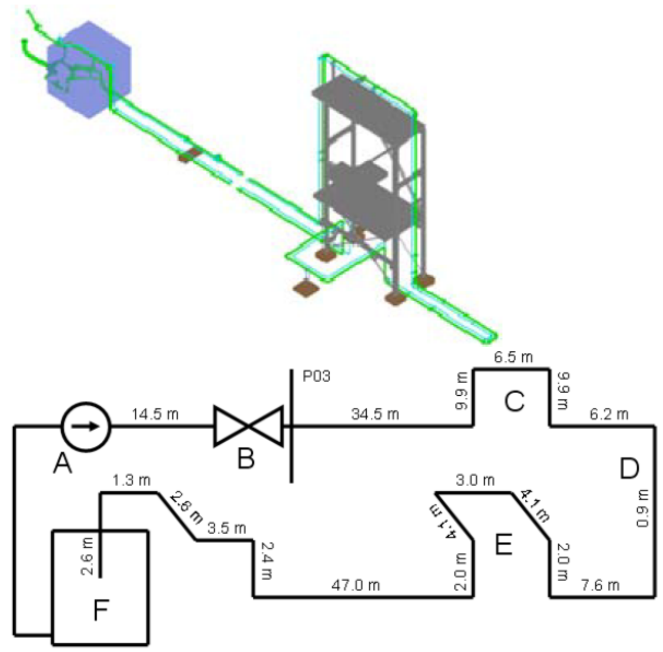

Figure 33: The experimental set-up of the PPP test ring [8]: A: Pump; B: Fast closing valve; C: Vertical bridge; D: Turning point; E: Vertical and horizontal bridge; F: Pressure tank B2

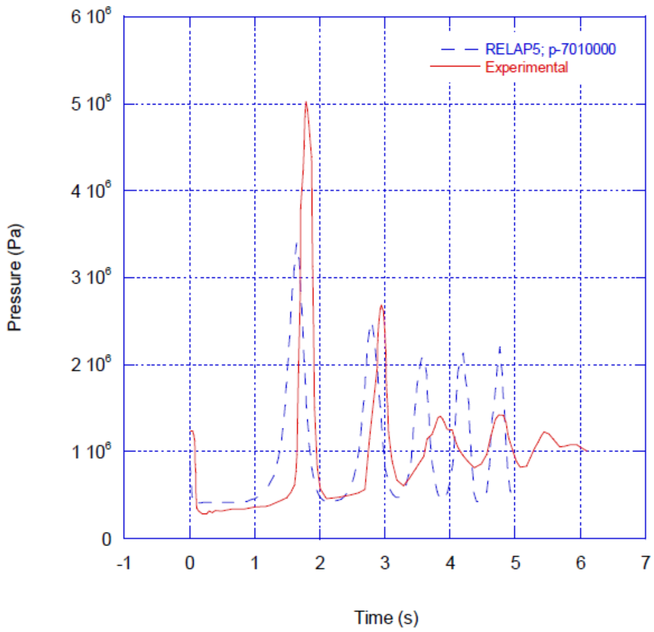

Figure 34: The UMSICHT test facility: pressure at P03