Two-Phase Flow Water Hammer Transients: Towards the WAHA Code

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ABSTRACT

In view of developing and validating a new code aimed at predicting fast transient two-phase flows in NPPs, extensive experimental data sets are being collected by means of three test facilities in the WAHALoads project. The paper reports on the benchmark exercises which show the need for a specific code using advanced numerical methods, on the experiments which have been carried out, and on the main characteristics of the code itself.

1 INTRODUCTION

In NPPs water hammer phenomena can occur in case of an inflow of sub-cooled water into pipes or other equipment filled with steam or a steam-water mixture. They may also happen due to fast valve closing or opening or following pipe ruptures with single-phase or two-phase flow. In the latter case, pressure waves in a two-phase medium must be expected. In all cases, dynamic stresses are induced in the walls of the pressure-retaining equipment. Moreover, the change of momentum of the fluid and the displacements of the components generate dynamic loads on the support structures of the components.

In the WAHALoads project currently running in the 5th Framework Programme of the European Union, the following objectives are pursued:
- Perform benchmark exercises to compare existing codes and the new WAHA code with standard cases and existing data sets;
- Develop new models applicable to fast transients, to predict wall friction as well as thermodynamic non-equilibrium and mechanical non-equilibrium between the phases;
- Develop new methods to calculate the loads induced on the supports of the pipe components;
- Establish an original experimental data base by using three test facilities: CWTF at FZR Dresden, PPP at UMSICHT and PMK2 at AEKI. These data cover a wide range of geometries and thermodynamic conditions, and include void fraction, pressures, temperatures and flow rates;
- Develop a new code (WAHA) based on the two-fluid model and using a second order accurate numerical method;
- Validate the code against the experimental data.

The first versions of WAHA are presently available, as well as several sets of new original data.

The paper presents the results of the benchmark exercises, which fully justify the development of the new code. It also describes the experiments which have been performed.
and are being used to validate the WAHA code, as well as some of the new models which have been developed to simulate the large non-equilibriums which are encountered in rapid transient two-phase flows.

2 THE BENCHMARK EXERCISES

Eight organisations took part in the benchmark exercise, involving two types of codes [1]:

- general purpose system codes, including a six (or seven) equation two-phase flow model, with 1st order space and time integration, staggered mesh, and a library of fluid interface models based on flow regime maps;
- specialized fast transient codes, including the two-phase homogeneous equilibrium model; they are of the 2nd order in space and time.

Figure 1: Definition of benchmark exercise BM1: fast closure of a valve.

Figure 2: BM1.1b - hot liquid case; comparison of pressure evolutions calculated by different codes.

Three exercises were proposed (BM 1 to 3). In BM1, a frictionless flow is instantaneously interrupted by the closure of a valve (fig.1). Two cases were considered: either the water was cold or near saturation. It appears that general purpose system codes that are not specifically designed for fast transients are effectively not capable of capturing secondary wave due to vapour cavity collapse (fig.2). Special purpose codes for fast dynamic transients can capture condensation shock, but amplitude seems underestimated.
BM2 is the Edwards pipe experiment [2]. The rarefaction wave propagation is well predicted by all codes. However, one of the codes presented a problem with its flashing model. All codes predict higher pressure during first phase, and predict some kind of a “void” wave travelling to closed end, whereas experiment shows approximately constant pressure during first 0.2 sec. The time when pressure starts to drop depends of course on the model for critical flow at the break.

Finally, BM3 uses pre-existing data from the Pilot Plant Pipework (PPP) loop located at Oberhausen; this loop is described in section 3 below. This exercise dealt with the prediction of the pressure, velocity and void fraction just after closure of a quick closing valve, in a pipe cross section located downstream of this valve. Only one code was used. The timing of the pressure pulses appeared to be well predicted; however the stability of the solution was dependent on initial void fraction and initial dissolved air fraction.

3 THE NEW DATA

At Forschung Zentrum Rossendorf, the CWHTF (Cold Water Hammer Test Facility) consists of a pressure vessel, a pipe line with two straight sections (one horizontally and one vertically oriented), two 90° bends (curvature radius 306 mm) and a fast opening valve (fig. 3). The total length of the pipe line is about 3 meters, the outer pipe diameter is about 219 mm and the wall thickness 6 mm. The vertical pipe region is terminated by a lid flange which acts as a bouncing plate.

Figure 3 : Description of the Cold Water Hammer Test Facility (CWHTF) at FZ-Rossendorf.

The water hammer is generated by the accelerated water bouncing against the lid flange. The water level in the vertical part of the pipeline is adjusted in a certain distance from the lid flange. This free volume above this level is evacuated (p << 1 bar) through a hole in the bouncing plate.

During the air evacuation, the fast acting valve is closed. After its fast opening, the fluid is accelerated until bouncing against the upper lid of vertical pipeline. At that time a water hammer is induced. The pressure in the tank may be increased by pressurized air (up to 6 bars) to increase the amplitude of the pressure waves generated (up to 200 bars). The generated pressure wave travels back through the bend, causing a strong structural response of the pipe system. The pipe line is instrumented with a number of sensors between the lid flange and the valve: dynamic pressures, strains, void fractions [3] and acceleration are measured. An example of results is given in Fig. 4, where the initial height was 0.300 m, and the evacuation pressure 29 mbar. The three signals shown in the figure are the pressure at the
bend, and the axial and tangential strain at the bend intrados. These tests have demonstrated how fixing the pipe at the bouncing plate or leaving it free to move affects dramatically the strain at the bend.

A finite elements model capable of describing the fluid-structure interaction during a water hammer has been developed by FZR and is being used to simulate the CWHTF data.

Figure 4: Example of results from CWHTF: signal MP7-P-0 is the pressure at the bend; MP6-D-0T is the tangential strain, and MP6-D-0A is the axial strain.

Figure 5: Configuration of scenario 1A at PPP (Pilot Plant Pipework) facility at Fraunhofer UMSICHT (Oberhausen, Germany).

In the PPP facility of UMSICHT, experiments are conducted using the dynamic behaviour of closing and opening valves [4]. The test rig includes two 230 m pipes with high and low levels (difference in height: 10 m) and inner diameters of 54 mm and 108 mm respectively. There are several flanges along the pipe to be able to realise other pipework...
geometry and to insert pieces of glass pipe to make the flow visible. The interconnection of pressure vessel (maximum pressure: 40 bar), storage tank (Vol.: 3.5 m³), heat exchanger, compressor and pumps enable runs with different temperatures or pressures up to 140 bar. The liquid pressure and the wave velocity are monitored with pressure transducers. Steam/air and fluid distribution in the cross sectional area of the pipe is measured by wire-mesh sensors equipped with micro-thermocouples. Within the plant, measuring data are transferred via optical fibre transmission and saved in a transient recording station with professional software. The sampling time of all measurement systems described above varies between 1 and 10 kHz. For validation of FSI codes the force on pipe supports (FP1, 2 & 3), the displacement and frequency response are fastly monitored as well.

In scenario 1A (fig. 5 with the bridge), cavitation is produced by the quick closure of the valve; Initial temperature varies from 20°C to 180°C, and the initial pressure is above saturation. An example of pressure history downstream the valve is shown in fig. 6. Different pressure pulses due to the collapse of the bubbles created downstream the valve may be clearly observed.

![Pressure history just downstream the valve](image)

Figure 6 : Example of result of PPP experiments (scenario 1A), cavitation produced by the quick closure of a valve.

The PMK-2-WHE (steam line water hammer equipment) is installed into the secondary circuit of the PMK-2 facility, at AEKI-KfKI (Budapest) between the steam dome of the steam generator and the condenser. The test section is a horizontal tube with a length of 2897 mm and an inner diameter of Ø 73.7 mm. In both two ends there are relatively big masses, 100 kg each, for damping hydraulic forces other than water hammer forces displacement. The nominal initial conditions as in the PMK secondary side are as follows: steam side pressure of 4.6 MPa and temperature of about 260 °C (fig. 7). To induce the water hammer phenomenon, subcooled water is injected to the test section, containing saturated steam, from the tank by N₂ gas pressure. To measure the pressure peaks produced by the water hammer, fast response pressure sensors are installed as well as a wire-mesh sensor. It is observed that water hammer do not necessarily take place when the injected flow rate is high. The test results indicate that the origin of the phenomenon depends on various parameters. An example is shown in fig. 8.
THE NEW CODE AND ITS VALIDATION

The main features of the WAHA code (version 1) under validation process are as follows [5]. The code is based on a one-dimensional six-equation two-fluid model for two-phase flow of water. It uses its own steam tables. It distinguishes two flow regimes: dispersed and horizontally stratified. Hyperbolicity of the set of equations is ensured by a virtual mass term and an interfacial pressure in the momentum equations.

WAHA contains correlations for mass, momentum and heat transfer between phases, and wall friction. Correlations are flow regime dependent. Relaxation source terms describe inter-phase exchanges of mass, momentum and energy. The code can describe departure from thermal equilibrium for both the vapour and the liquid phase. However, in dispersed
flows, vapour is always close to equilibrium, and therefore a very high heat transfer coefficient is used for the vapour. The mass flux at the interface is evaluated by the equation:

\[ \Gamma_g = \frac{\alpha \rho_g - (\alpha \rho_g)_{\text{Saturation}}}{\theta} \]

where \(\theta\) is the relaxation time of the mass transfer from the bulk of the liquid to the interface, \(\alpha\) the void fraction and \(\rho_g\) the vapour density. The evaluation of a new model for wall friction in transients is under study [6].

The pipe elasticity and variable pipe cross-section can be modelled. In the current version of WAHA: two pipes can be connected with an abrupt-area change model, as well as a tank (constant pressure boundary condition), or a pump (constant velocity B.C.). The study of a 1D averaged model which would be suitable for a pipe undergoing arbitrary motions is under progress [7].

Most important, the explicit numerical scheme is based on operator splitting: characteristic upwind discretisation of convective and non-relaxation source terms is used in one sub step, while stiff relaxation source terms (inter-phase exchange terms) are treated in the second sub step. Numerical diffusion can be suppressed with second-order accurate treatment of the convective terms. Comparisons made in the case of BM 1 (BM 1.2b means pipe section between the valve and the downstream reservoir, after valve closure, initially hot water flow), the Homogeneous Relaxation Model (HRM) brings little change to the pressure signal compared to the Homogeneous Equilibrium model (HEM) (Fig.9a), but the void fraction evolution is more affected (Fig. 9b).

![Figure 9](image_url)

**Figure 9**: a.- Pressure evolution predicted by WAHA code with HEM and HRM models; b.- idem for the void fraction (HEM = biggest signal).

5 **CONCLUSIONS**

The first phase of the WAHALoads project has consisted in a benchmark exercise aimed at verifying the abilities of various existing codes to predict very fast transients such as those resulting from the fast closure or opening of a valve inserted in a pipe. It has been shown that only codes based on second order accurate numerical schemes can simulate the fast pressure waves.

For more extensive verifications and for adjustments of the codes high quality experimental data are needed. In two-phase transient flows they should be based at least on pressure, temperature and void fraction measurements. Since such experimental data were not currently available, it was decided to equip three existing test facilities with fast response instrumentation, including the wire-mesh sensor for the measurement of void fraction distribution in the pipe cross-section.
The three test facilities operated with water cover a wide range of pressures (from atmospheric pressure to 5 MPa), of temperatures (from room temperature to 260°C) and of geometries with diameters ranging from 50 to 200 mm. In these experiments the stresses in the pipe wall and the forces on the pipe supports are also measured. The new experimental data base is now being used for further verification of the codes.

The observed deficiencies of the existing codes both from the numerical point of view as well as from the modelling point of view, suggested that some efforts should be put on the development of a new code. The new code, called WAHA, under development, is based on a 6-equation two-fluid model in an elastic pipe with second order accurate numerical scheme. It allows simulations of fast transients of ideal gas – liquid water mixtures, or vapour – liquid water mixtures. The geometry consists of a set of pipes with smooth varying cross-sections, or abrupt area changes. At the boundaries closed ends and constant pressure tanks are considered. The model is made more and more realistic by including relaxation models for the simulation of the thermal and mechanical non-equilibriums encountered in fast transients.

After validation thanks to the new experimental data, the WAHA code should become a useful tool for prediction of loads on piping structure due to water hammers and other transient phenomena which occur sometimes during incidental conditions in Nuclear Power Plants.

REFERENCES


