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Modelling of Cold Water Hammer with WAHA Code

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ABSTRACT

The Cold Water Hammer experiment described in the present paper is a simple facility where overpressure accelerates a column of liquid water into the steam bubble at the closed vertical end of the pipe. Severe water hammer with high pressure peak occurs when the vapor bubble condenses and the liquid column hits the closed end of the pipe. Experimental data of Forschungszentrum Rossendorf are being used to test the newly developed computer code WAHA and the computer code RELAP5. Results show that a small amount of non-condensable air in the steam bubble significantly affects the magnitude of the calculated pressure peak, while the wall friction and condensation rate only slightly affect the simulated phenomena.

1 INTRODUCTION

Due to its potential for damage of pipes, water hammer has been a subject of study since the middle of the nineteenth century. During these studies several specific mechanisms have been identified, which can lead to severe water hammer [2]. In accordance with water hammer classification presented in [2], the Cold Water Hammer experiment performed by Forschungszentrum Rossendorf [1] is initiated by the so-called "Water Cannon" mechanism: sub-cooled water with condensing steam in a vertical pipe. The Cold water hammer experiment is interesting and instructive because it covers a wide spectrum of particularities. One of them is "cold" steam present at the closed end of the vertical pipe at room temperature and corresponding saturation pressure of approximately 2500 Pa.

The WAHALoads research project of the 5th EU program has been initiated in Fall 2000, will end on April 1st 2004, and combines eleven contractors. The "Jožef Stefan" Institute leads a group of three contractors that aims to develop the WAHA computer code for simulation of water-hammer transients in piping systems. Other three contractors are performing different water hammer experiments, each of them dealing with different water hammer mechanism. Other partners are involved in verification and testing of the existing computer codes and WAHA code. The project aims at the elaboration of improved and innovative tools and methods for maintaining and improving the safety of existing reactor installations. The global objective is to predict the loads on equipment and support structures, which are caused by water hammers and shock waves.

2 TWO-PHASE FLOW MODEL OF WAHA CODE

The mathematical model of the WAHA code is a one-dimensional six-equation two-fluid model similar to the models of RELAP, TRAC or CATHARE computer codes. The basic equations are mass, momentum and energy balances for vapor and liquid, without terms for wall-to-fluid heat transfer [3]. The pipe elasticity is taken into account in the equations. The numerical scheme of the WAHA code is based on the Godunov method and allows second-order accurate capturing of the steep waves during transients [4].

2.1 Two-fluid model

The elasticity modulus may have a significant influence on the propagation of pressure waves in pipes [5,6]. Especially in the pipes with small wall-thickness, it significantly reduces the speed of sound in fluid. With elasticity taken into account, the six-equation two-fluid model of the WAHA code can be written into the following form:

The continuity equations for liquid and vapor (gas) phase are:

$$\frac{\partial(1-\alpha)\rho_f}{\partial t}+(1-\alpha)\rho_f K\frac{\partial p}{\partial t}+\frac{\partial(1-\alpha)\rho_f v_f}{\partial x}+(1-\alpha)\rho_f v_f K\frac{\partial p}{\partial x}= -\Gamma_g-(1-\alpha)\rho_f v_f\frac{1}{A(x)}\frac{dA(x)}{dx}, \quad (1)$$

$$\frac{\partial\alpha\rho_g}{\partial t}+\alpha\rho_g K\frac{\partial p}{\partial t}+\frac{\partial\alpha\rho_g v_g}{\partial x}+\alpha\rho_g v_g K\frac{\partial p}{\partial x}=\Gamma_g-\alpha\rho_g v_g\frac{1}{A(x)}\frac{dA(x)}{dx}, \quad (2)$$

where terms with K represent the contribution of the pipe elasticity (see [5] for details), and the terms with pipe cross-section $A(x)$ allow description of the pipes with variable cross-section.

The momentum balance equations for both phases are:

$$\frac{\partial A(1-\alpha)\rho_f v_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f v_f^2}{\partial x}+A(1-\alpha)\frac{\partial p}{\partial x}-A*CVM-Ap_i\frac{\partial\alpha}{\partial x}= AC_i|v_r|v_r-A\Gamma_g v_i+A(1-\alpha)\rho_f g\cos\theta-AF_{f,wall}, \quad (3)$$

$$\frac{\partial A\alpha\rho_g v_g}{\partial t}+\frac{\partial A\alpha\rho_g v_g^2}{\partial x}+A\alpha\frac{\partial p}{\partial x}+A*CVM+Ap_i\frac{\partial\alpha}{\partial x}= -AC_i|v_r|v_r+A\Gamma_g v_i+A\alpha\rho_g g\cos\theta-AF_{g,wall}, \quad (4)$$

The internal energy balance equations for both phases with terms for pipe elasticity are:

$$(1-\alpha)\rho_f\frac{\partial u_f}{\partial t}+(1-\alpha)\rho_f v_f\frac{\partial u_f}{\partial x}-p\frac{\partial\alpha}{\partial t}+p(1-\alpha)K\frac{\partial p}{\partial t}+p\frac{\partial(1-\alpha)v_f}{\partial x}+p(1-\alpha)v_f K\frac{\partial p}{\partial x}= Q_{if}-\Gamma_g(u_f^*-u_f)+v_f F_{f,wall}-(1-\alpha)v_f p\frac{1}{A(x)}\frac{dA(x)}{dx}, \quad (5)$$

$$\alpha\rho_g\frac{\partial u_g}{\partial t}+\alpha\rho_g v_g\frac{\partial u_g}{\partial x}+p\frac{\partial\alpha}{\partial t}+p\alpha K\frac{\partial p}{\partial t}+p\frac{\partial\alpha v_g}{\partial x}+p\alpha v_g K\frac{\partial p}{\partial x}= Q_{ig}+\Gamma_g(u_g^*-u_g)+v_g F_{g,wall}-\alpha v_g p\frac{1}{A(x)}\frac{dA(x)}{dx}, \quad (6)$$

where the specific total energy of liquid or gas is a sum of specific internal energy and specific kinetic energy:

$$e = u + v^2 / 2\,, \tag{7}$$

Differential terms in Eqs. (1)-(6) are collected on the left-hand side of the equations and the non-differential terms are collected on the right.

2.2 Additional closure relations of the two-fluid model

1). Two additional equations of state for each phase are needed. The equation of state for phase *k*, where *k* is *f* for fluid and *g* for gas, is:

$$d\rho_k = \left(\frac{\partial \rho_k}{\partial p}\right)_{u_k} dp + \left(\frac{\partial \rho_k}{\partial u_k}\right)_p du_k \quad . \tag{8}$$

Derivatives on the right hand side of Eq. (8) are determined by the water property subroutines developed for the WAHA code using pressure and temperature or specific internal energy as input. Water properties are pre-tabulated and saved at approximately 400 pressures and 400 temperatures.

2). The virtual mass term *CVM* in Eqs. (3) and (4) is used to obtain hyperbolicity of the system:

$$CVM = (1-S)C_{vm}\,\alpha\,(1-\alpha)\,\rho_m\left(\frac{\partial v_g}{\partial t} + v_f\frac{\partial v_g}{\partial x} - \frac{\partial v_f}{\partial t} - v_g\frac{\partial v_f}{\partial x}\right). \tag{9}$$

3). The interfacial pressure term exists only in horizontally stratified flow:

$$p_i = S\alpha(1-\alpha)(\rho_f - \rho_g)gD\,, \tag{10}$$

where *S* represents the stratification factor ($S = 0$ for dispersed flow, $S = 1$ for horizontally stratified flow, $0 < S < 1$ for transitional flow (see [3] for details).

4). The WAHA code distinguishes two flow regimes: dispersed and horizontally stratified with transition area between both regimes. Dispersed flow is further divided into bubbly flow ($\alpha < 0.5$), droplet flow ($\alpha > 0.95$) and transitional bubbly-to-droplet flow. Source terms are flow regime dependent and their detailed form is given in the WAHA manual [3]. Terms that do not include derivatives (source terms) are terms with inter-phase drag (C_i), terms with inter-phase exchange of mass and energy (Γ_g, Q_{ig}, Q_{if}), terms due to the variable pipe cross-section ($A(x,t)$), terms with wall friction ($F_{f,wall}$, $F_{g,wall}$), and term with volumetric forces ($g\cos\theta$).

3 COLD WATER HAMMER TEST FACILITY

3.1 Geometry and experiments

The test facility (Fig. 1) consists of a pressure vessel, a pipe line with horizontal and vertical straight sections, two 90° elbows and a fast acting valve in the horizontal section. The pipeline in the WAHA code is modeled with 66 volumes with total length of the pipeline 3.3 m, where the length of one computational volume is $\Delta x = 0.05$ m.

At the beginning, the valve is open and the pipeline is filled with water at room temperature. The top section of the vertical part of the pipeline contains air (α = 1.0). The valve is then set to closed position and holds initial pressure in the vessel and in the first part of the pipeline. The air from the evacuation area is then being evacuated by the vacuum pump. The pressure is reduced close to the saturation pressure at the given fluid temperature. The transient starts when the fast acting valve is opened again. The pressure difference between the tank and the closed end, and condensation of steam in evacuation area, accelerates water in the pipe, and the water hammer appears when the water column is abruptly stopped by the closed end of the pipe. The process can then repeat but with a weaker intensity of pressure peak due to the dissipation processes. The height of the pressure peak is proportional to the velocity of water at the moment of reaching the closed end. A higher initial pressure in the tank and/or larger evacuation area L_E increase the acceleration and consequently the velocity of water column and hence the pressure peak.

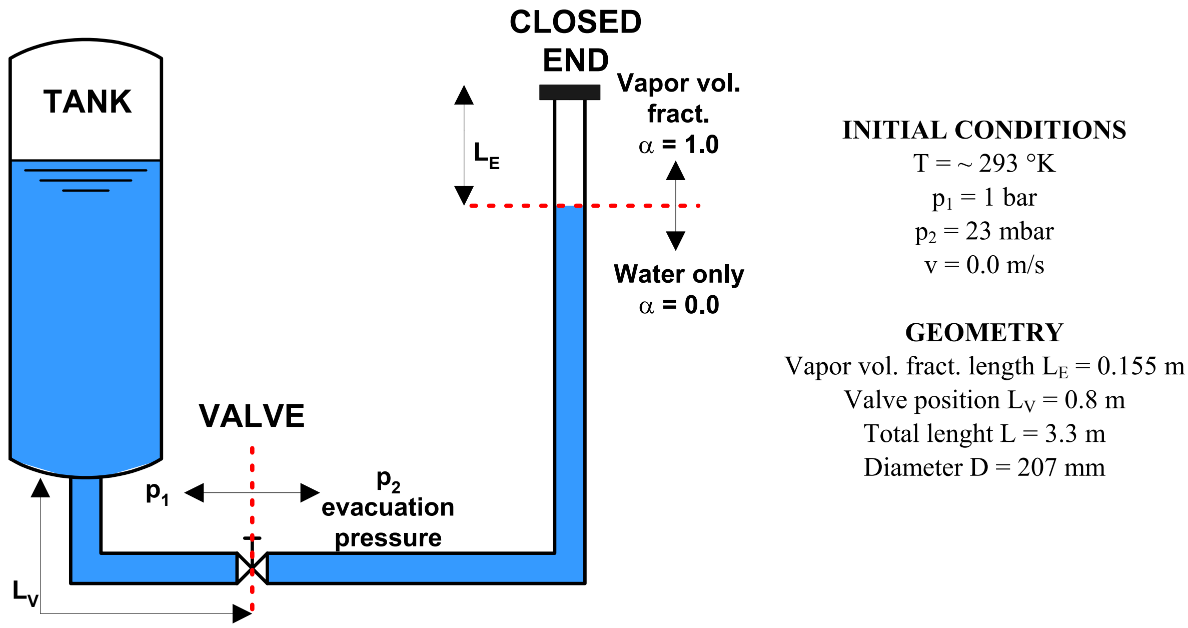

Figure (1): Geometry of Cold Water Hammer Test Facility and initial conditions

3.2 Results

Over 20 experiments with different initial pressures and evacuation area lengths were performed and documented on the experimental facility. For the purpose of this paper the case with tank pressure p_1 = 1 bar, evacuation pressure p_2 = 23 mbar and initial evacuation length L_E = 0.155 m has been chosen (for details see [2]). Simulations of this experiment were performed with WAHA and RELAP5 codes. Pure steam was assumed in the gas bubble near the closed end of the pipe. In both cases, the tank was modelled as a constant pressure boundary condition.

Fig. (2) shows that both, the WAHA code and the RELAP5 code over predict the first pressure peak for some 70% and the pressure peak occurs earlier than it is in experiment. WAHA (basic) code uses inter-phase heat, mass, and momentum exchange for dispersed flow, while RELAP5 simulation was performed with HEM - homogenous equilibrium options (instantaneous relaxation of heat, mass and momentum transfer). The simulation with built-in RELAP5 correlations completely missed the measured pressure time-history. To successfully simulate the cold water hammer experiment with RELAP5 we thus used HEM options, and besides, it was necessary to reduce the allowed minimum time step to 10^{-18} which points to the numerical difficulties of the RELAP5 code.

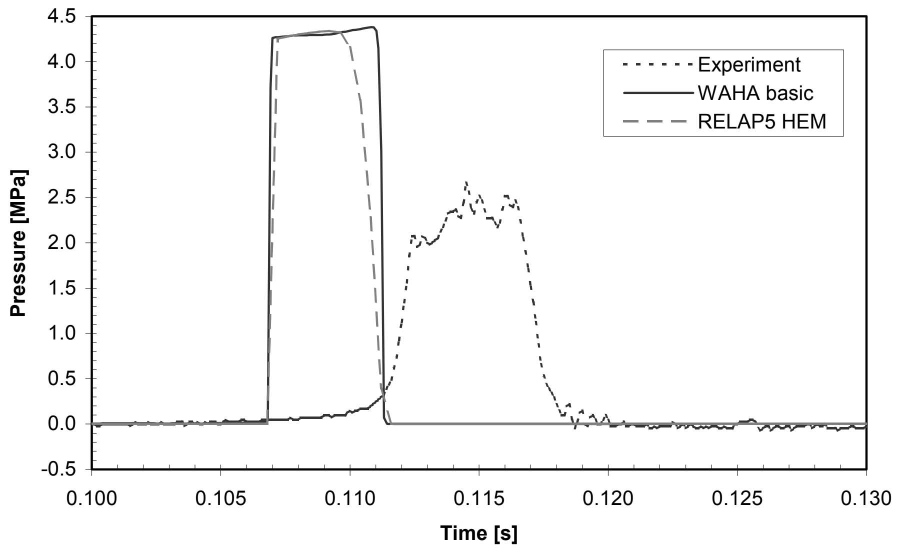

Figure 2: Pressure time-history near closed end with basic settings in WAHA compared with experimental results and RELAP5.

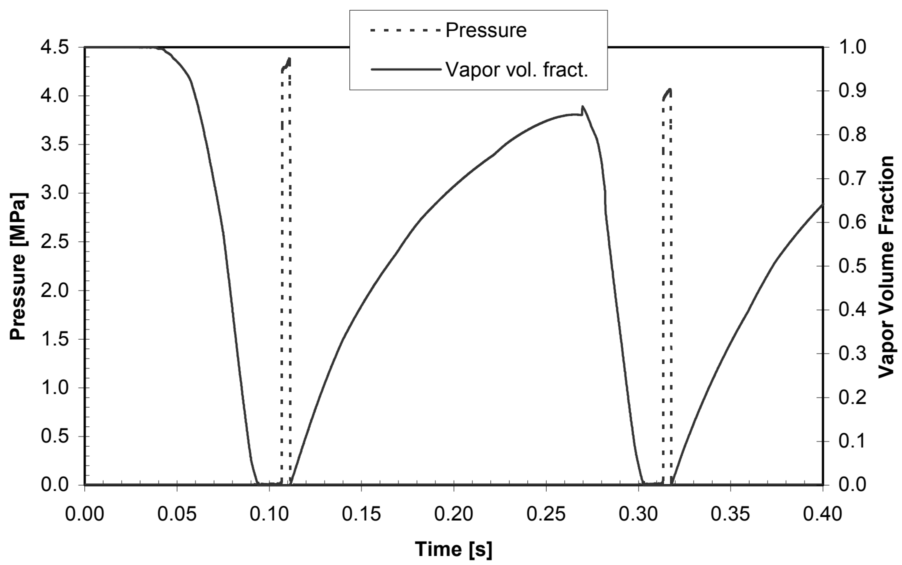

Figure 3: Vapor volume fraction and pressure time-history near closed end (WAHA).

The complete pressure history from the opening of the valve at time $t = 0$ s at the point near the closed end and the history of the vapor volume fraction at the same point are shown in Fig. 3. The WAHA prediction is shown in Fig. 3, as vapor volume fraction was not measured in the experiment. It can be clearly seen that the pressure peak is formed each time when vapor in the evacuation area is condensed and the water column reaches the closed end. During the pressure peak, the water velocity changes direction, the pressure drops to the saturation level again and vapor is generated during the flashing process until reflection from the tank (t = 0.27 s). This is a periodic phenomenon and the number of periods and the frequency of pressure peaks strongly depend on damping, i.e. friction loses.

Friction losses were thought to be an important parameter, especially for the prediction and damping of further pressure peaks. Fig. 4 shows simulations performed with 2 and 10 times larger friction coefficient in the WAHA code, which one can consider as an additional friction due to the valve, which was not modeled in WAHA (and RELAP5), where a smooth pipe was assumed. However, the first pressure peak remains practically unchanged.

Dynamic friction was also analyzed. This phenomenon is important when pressure jump is present in the water. More about the modeling of the dynamic friction can be found in [7]. The numerical experiments showed that changes of coefficient of dynamic friction do not have any significant impact on simulation (all results presented in Figs. 2-6 are calculated without dynamical friction). A possible reason is that the pipeline is relatively short and dynamic friction like longitudinal wall friction can be neglected. Nevertheless, this area is open for future work on determination of exact friction coefficients in future version of WAHA.

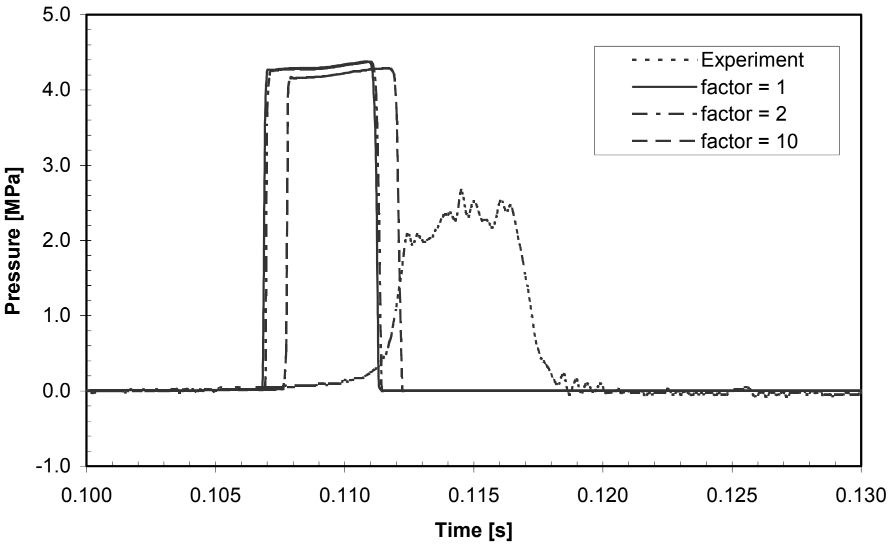

Figure 4: Influence of coefficient of local losses (WAHA).

Another tested factor that might be important is condensation rate of the steam in the bubble. Vapor volume fraction is present only in a vertical section of pipeline, where the WAHA code uses inter-phase heat, mass, and momentum exchange for dispersed flow, which is not very accurate in this case. However, Fig. 5 shows that the condensation rate of the steam does not influence the phenomena significantly; better timing, but the pressure peak is still overestimated. Simulation with basic WAHA correlations in Fig. 5 are compared with simulation performed with WAHA Homogeneous-Equilibrium Model (HEM) option, where infinitely fast condensation rate is assumed.

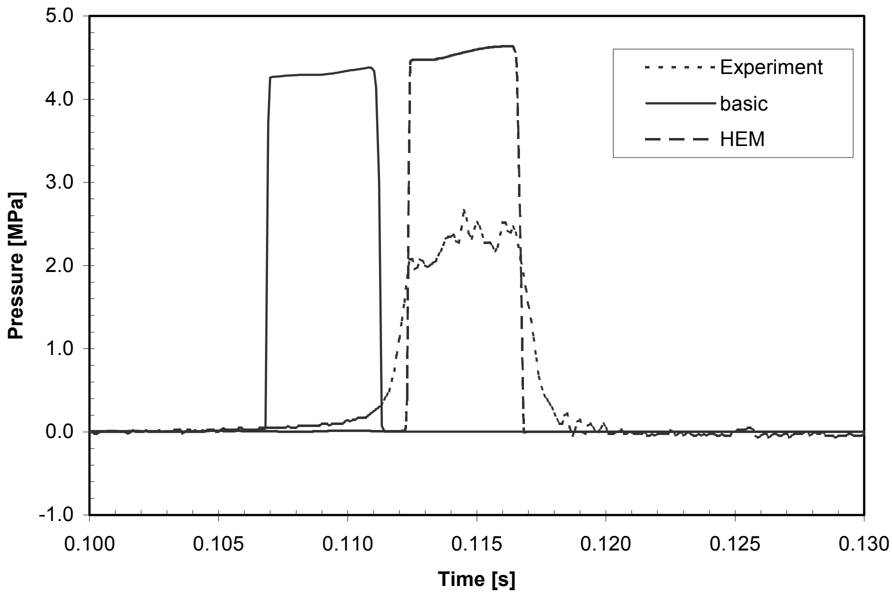

Figure 5: Influence of condensation rate (WAHA).

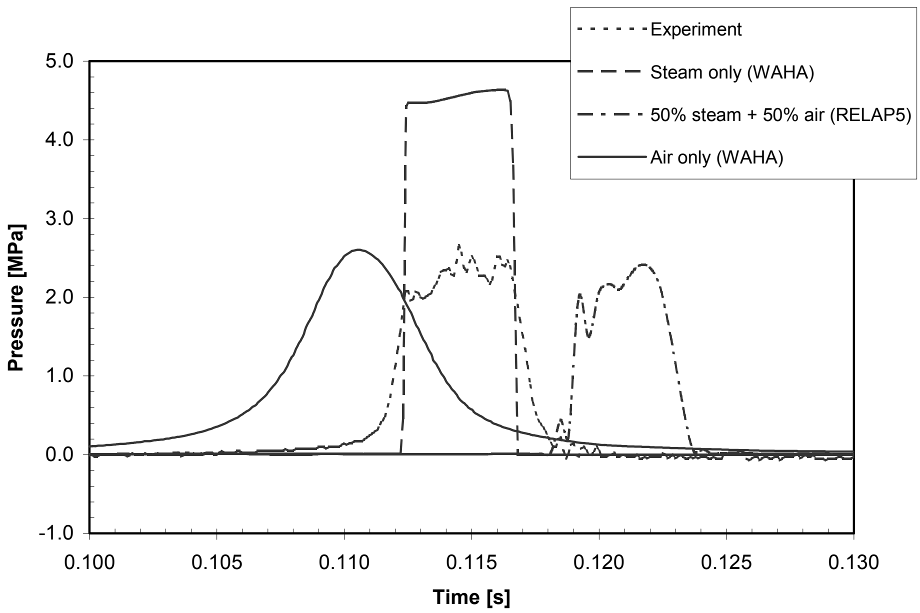

Figure 6: Influence of air in the gas bubble (HEM).

The fourth factor that was tested was the presence of the air in the steam bubble. The WAHA code cannot treat steam and ideal gas simultaneously; but can calculate two cases of two-fluid flow: liquid water-vapor or liquid water-ideal gas. The fourth curve in Fig. 6 was obtained with WAHA simulation which treated the gas bubble as a pure ideal gas (air). The slope of the pressure varies smoothly and not as rapidly as in pure vapor cases. The first pressure peak obtained with the WAHA pure air model, looks like the water column is being bounced by a spring. From the measurement in Fig. 6 we assume that the vacuum pump did not (could not) evacuate all the air from the bubble. The fourth curve on Fig. 6 (WAHA, pure air) shows, that the obtained first pressure peak is very similar to the measured one. The RELAP5 allows simulation with the mixture of steam and air. Fig. 6 confirms our conclusions about the impact of the air in the vapor bubble. The RELAP5 simulation was performed with

50% of air quality in the gas bubble, using the homogeneous equilibrium model. The problem of the comparison with the experiment is that the initial air contents in the experimental bubble is not known.

4 CONCLUSIONS

This work aims to show the capabilities of the two-fluid six-equation mathematical and numerical model of the recently developed computer code WAHA, which was intended for simulations of fast transients in NPPs. This code was successfully used in numerous cases, one of them being Cold Water Hammer simulation. This case reflects our recent work on WAHA code where the basic frame of the code was constructed. At present we are focused on the development of correct correlations and coefficients in closure equations.

Experimental facilities for simulation of fast transients often contain non-negligible amounts of non-condensable gases. This paper confirms that air (50% of initial void) can drastically affect the behavior inside the pipeline. It would be therefore important to include the modeling of non-condensable gases into the WAHA code. However, on the other hand, the water systems in nuclear power plants are deaerated and such an option is less important for nuclear installations.

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