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Theoretical and Experimental Study of Steam Condensation Induced Water Hammer Phenomena

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Abstract – *We investigate steam condensation induced water hammer (waha) phenomena and present experimental and theoretical results. The experiments were performed in the PMK-2 facility, which is a full-pressure thermohydraulic model of the nuclear power plant of VVER-440/312 type and located in the Atomic Energy Research Institute Budapest, Hungary. The present experimental setup is capable to measure water hammer phenomena in a wide range of steam pressure, cold water temperate and floating mass rate at a high level of accuracy. On the theoretical side waha is studied and analyzed with the WAHA3 model based on two-phase flow six first-order partial differential equations that present one dimensional, surface averaged mass, momentum and energy balances. A second order accurate high-resolution shock-capturing numerical scheme was applied with different kind of limiters in the numerical calculations. The applied two-fluid model shows some similarities to Relap5 which is widely used in the nuclear industry to simulate nuclear power plant accidents. Experimentally measured and theoretically calculated waha pressure peaks are in good agreement, however simulations always show additional pressure peaks. As a new feature in this study we present calculations without additional unphysical reflections caused by boundary conditions.*

I. INTRODUCTION

Safety of nuclear reactors is a fundamental issue. Nuclear and thermo-hydraulic processes in the active zone of modern reactors are well known and well-controlled, explosions are out of question. However, violent unwanted thermo-hydraulic transients in the primer loop may cause serious derangement or pipe breakage. Such an unplanned transient is the steam condensation induced water hammer. In thermal loops of atomic reactors or in other pipelines where water steam and cold water can mix, quick and dangerous transients can occur causing explosions which mean high financial expenses or even cost human lives.

In the following we will introduce the PMK-2 facility which is an integral experimental device and capable to produce waha effects.[1]

On the other side we present the WAHA3[2] model we use, which is a complex physical model suitable to simulate various quick transients in single and two-phase flows.

In the last two decades the nuclear industry developed a few complex two-phase flow-codes like Relap5[3], Trac[4] or Cathare[5] which are feasible to solve safety analysis of nuclear reactors and model complicated two-phase flow transients.

The model, WAHA3[6] is very similar to Relap5. This means that the conservation equations and all the applied correlations are essentially the same[6]. The main difference between the above mentioned models and our WAHA3 code is basically the applied numerical scheme; other commercial codes have a ratio of spatial and time resolution $\Delta x / \Delta t$ which describes usual flow velocities. This code, however is capable of capturing shock waves and describe pressure waves which may propagate quicker than the local speed of sound. To our knowledge there is no special model and computer code for water hammer simulation in the field of nuclear thermal-hydraulics.

WAHA3 model can successfully reproduce the experimental data of different one- or two-phase flow problems such as ideal gas Riemann problem, critical flow of ideal gas in convergent-divergent nozzle, column separation or cavitation induced water hammer or even rapid depressurization of hot liquid from horizontal pipes.[2]

The main new message of the following study is to show how to eliminate the effects of unwanted and und unphysical pressure peaks which are reflected from wall boundary.

II. EXPERIMENTAL SETUP AND THEORY

The PMK-2 facility is located at the KFKI Atomic Energy Research Institute (AEKI) Budapest, Hungary[1]. It is a full-pressure scaled down thermohydraulic model of the primary and partly the secondary circuit of the nuclear power plant of VVER-440/213 type (VVER is a Hungarian abbreviation of the water-water energetic reactor). It was primarily designed for the investigation of off-normal transient processes of small-break loss of coolant accidents.

Between 1985 and 2007 there were 55 different experiments performed on the apparatus. The group of transients are as follows 7.4 % cold leg breaks(15 tests), cold leg breaks of different sizes(10 tests), hot leg breaks and primary to secondary leaks(10 tests); tests for natural circulation characteristics and disturbances(10 tests); plant transients and accidents (10 tests). Results of experiments were used to validate thermohydraulical system codes as ATHLET, CATHARE and REALP5 for VVER applications.

Considering the scaling ratio interval and the financial possibilities of the country, a 19 rod core model with 2.5 m heated length was selected which gives a power ratio of 1:2070 (39.312:19 ~ 2070) and, therefore, the overall volume scaling ratio is also 1:2070. The operating pressure of the PMK-2 is 12.3 MPa and the core thermal power is 664 kW. The heat loss for the PMK-2 facility is about 3.6 percent of the nominal heat power. Due to the importance of gravitational forces in both single- and two-phase flow the elevation ratio is 1:1. Other important similarity properties like the Richardson, Stanton, Froude and the Nusselt numbers are 1:1 as well. There are 10 integral type facilities for PWR's (Pressurized Water Reactors) and VVER's in the world like the American LOFT, the ROSA-IV in Japan, the PACTEL facility in Finland or the Hungarian PMK-2. VVERs are slightly different from PWRs of the usual design and have a number of special features, viz: 6-loop primary circuit, horizontal steam generators, loop seal in hot and cold legs, safety injection tank set-point pressure higher than secondary pressure. Figure 1 shows the PMK-2 facility from bird's eye view.

The steam pressure on the steam generator side is 4.6 MPa. The WAHA experimental setup is connected into the steam line of PMK-2 and located on the top of the integral facility. The photo of the experimental tube is presented on Fig 2. The experimental setup is basically a horizontal pipe section of 3 m length and 73 mm internal pipe diameter initially filled with vapor that is supplied from the dome of the steam generator of the PMK-2. The other side of the test device is connected to the condenser unit of PMK-2 which substitutes turbine of the real power plant. Both ends of the WAHA tube are further equipped with inertia blocks of 200 kg each serving a 90 deg bend in the same time. The test section can be isolated by two valves; one is located in the connection with the head of the stem generator, and the other in the connecting line towards the condenser. For the flooding, a cold water tank with a volume of 75 l is installed and pressurized with air.

Fig 1. The PMK-2 Experimental Facility

Fig 2. The Water hammer experimental device

The waha experimental test section is well equipped with advanced two-phase flow instrumentation (wire mesh sensor, needle probes, fast pressure transducers and strain gauges). (Three needle probes can be seen in Fig. 2 standing on the WAHA test tube.) The mentioned instruments allow observations and studies about the dynamics of liquid and steam flow and liquid slug formation which is responsible for water hammer. The most advanced measuring instruments is the wire mesh sensor that consists of two grids of 12x12 parallel electrode rods placed into the flow in a short distance behind each other. The output information of the mesh sensor is the 2 dimensional cross section distribution of the void fraction with time resolution of 1000 Hz. A large set of data for 35 experimental runs performed with different initial conditions (pressure, liquid temperature, subcooling and intake flooding water flow rate). Two very interesting conclusions were made after the experiments. The first is that the steam condensation induced waha has a highly stochastic nature this was confirmed with two consecutive experiments performed with equal initial conditions. In the first experiment a 100 bar pressure peak was formed and in the later experiment a 210 bar peak was measured. The second conclusion is that the amplitude of the first pressure peak showed a tendency to decrease with growing initial system pressure. In the following we will analyses the experiment labeled with E05.

The time history of a performed experiment is the following. Initially the pipe is filled with saturated steam. The transient begins when the subcooled water starts to flow into the pipe with a constant mass flow rate. At the first time of the transient the flow is purely stratified. As the flow continues and the inter surface is increased a well defined water level forms. A Kelvin-Helmholtz instability occurs, which interrupts the stratification. Finally a cold water slug is formed capturing a steam bubble. A strong water hammer sounds when the whole bubble is condensed.

There are large number of different two-phase flow models with different levels of complexity [7,8] which are all based on gas dynamics and shock-wave theory. In the following we present the one dimensional six-equation equal-pressure two-fluid model.

The density, momentum and energy balance equations for both phases are the following:

$$\frac{\partial A(1-\alpha)\rho_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f(v_f-w)}{\partial x}=-A\Gamma_g \tag{1}$$

$$\frac{\partial A\alpha\rho_g}{\partial t}+\frac{\partial A\alpha\rho_g(v_g-w)}{\partial x}=A\Gamma_g \tag{2}$$

$$\begin{aligned}\frac{\partial A(1-\alpha)\rho_f v_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f v_f(v_f-w)}{\partial x}+A(1-\alpha)\frac{\partial p}{\partial x}-A\cdot CVM\\ -Ap_i\frac{\partial \alpha}{\partial x}=AC_i|v_r|v_r-A\Gamma_g v_i+A(1-\alpha)\rho_f cos\theta-AF_{f,wall}\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial A\alpha\rho_g v_g}{\partial t}+\frac{\partial A\alpha\rho_g v_g(v_f-w)}{\partial x}+A\alpha\frac{\partial p}{\partial x}+A\cdot CVM+Ap_i\frac{\partial \alpha}{\partial x}=\\ -AC_i|v_r|v_r+A\Gamma_g v_i+A\alpha\rho_g cos\theta-AF_{g,wall}\end{aligned} \tag{4}$$

$$\begin{aligned}\frac{\partial A(1-\alpha)\rho_f e_f}{\partial t}+\frac{\partial A(1-\alpha)\rho_f e_f(v_f-w)}{\partial x}+p\frac{\partial A(1-\alpha)}{\partial t}+\frac{\partial A(1-\alpha)p(v_f-w)}{\partial x}\\ =AQ_{if}-A\Gamma_g(h_f+v_f^2/2)+A(1-\alpha)\rho_f v_f g cos\theta\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{\partial A\alpha\rho_g e_g}{\partial t}+\frac{\partial A\alpha\rho_g e_g(v_f-w)}{\partial x}+p\frac{\partial A\alpha}{\partial t}+\frac{\partial A\alpha p(v_f-w)}{\partial x}\\ =AQ_{ig}+A\Gamma_g(h_g+v_g^2/2)+A\alpha\rho_g v_g g cos\theta.\end{aligned} \tag{6}$$

Index f refers to the liquid phase and index g to the gas phase. Nomenclature and variables are described at the end of the manuscript. Left hand side of the equations contains the terms with temporal and spatial derivatives.

Hyperbolicity of the equation system is ensured with the virtual mass term CVM and with he interfacial term (terms with p_i). Terms on the right hand side are terms describing the inter-phase heat, mass (terms with Γ_g vapor generation rate) volumetric heat fluxes Q_{ij}, momentum transfer (terms with C_i), wall friction $F_{g,wall}$, and gravity terms. Modeling of the inter-phase heat, mass and momentum exchange in two-phase models relies on correlations which are usually flow-regime dependent.

The system code RELAP5 has a very sophisticated flow regime map with a high level of complexity. WAHA3 however has the most simple flow map with dispersed and horizontally stratified regimes only, because the uncertainty of steady-state correlations in fast transients are very high.

A detailed analysis of the source terms can be found in Tiselj et al. [2,6]

Two additional equation of states (eos) are needed to close the system of equations

$$\rho_k=\left(\frac{\partial\rho_k}{\partial p}\right)_{u_k}dp+\left(\frac{\partial\rho_k}{\partial u_k}\right)_p du_k. \tag{7}$$

Partial derivatives in Eq. 7 are expressed using pressure and specific internal energy as an input. The table of water and steam properties was calculated with a software from UCL. [9]

The system of Eqs. (1-6) represents the conservation laws and can be formulated in the following vectorial form

$$\mathbf{A}\frac{\partial\mathbf{\Psi}}{\partial t}+\mathbf{B}\frac{\partial\mathbf{\Psi}}{\partial x}=\mathbf{S} \tag{8}$$

where $\mathbf{\Psi}$ represents the non-conservative variables

$$\mathbf{\Psi}(p,\alpha,v_f,v_g,u_f,u_g)$$

A, B are matrices and **S** is the source vector of non-differential terms. These three terms can be obtained from Eq. (1-6), with some algebraic manipulation.

In this case the system eigenvalues which represent wave propagation velocities are given by the determinant det(**B**- λ **A**). An improved characteristic upwind discretization method is used to solve the hyperbolic equation system (Eq. 8). The problem is solved with the combination of the first-and second-order accurate discretization scheme by the so-called flux limiters to avoid numerical dissipation and unwanted oscillations which appear in the vicinity of the non-smooth solutions. Exhaustive details about the numerical scheme can be found in LeVeque(1992).[10]

III. RESULTS AND DISCUSSION

Figure 3 presents the geometrical model with the initial and boundary conditions of the experimental setup. The temperature of the saturated steam is T = 470 K with an initial pressure of p = 14.5 bar and the temperature of the cold water is T_w = 295 K with a flow velocity of v = 0.242 m/s. The horizontal length of the pipe is 3 meter with a diameter of 7.3 cm. For a satisfactory convergence in the calculations we used 60 nodal volume elements for the horizontal pipeline. Second order numerical scheme was used with the MINMOD flux limiter.[2,6]

The Courant number which measures the relative wave propagation speeds of the exact solution and the numerical solution was set to CFL = 0.6 during the calculation.

It is possible to take into account the pipe elasticity in the model, if the Young's modulus is taken as 10^{10} N/m^2 (which is usual for steel) than the waha pressure peak is changed with less than 10 percent. This is a negligible effect among other uncertainties as we will see.

It is worth to mention that all kinds of correlations (heat, mass, impulse transfer) in both (dispersed and horizontally stratified) flow regimes have to be used during the simulation to get reasonable pressure peaks.

There is a 1 meter long vertical pipe connected to the left end of the horizontal pipe. A pump was fixed to the free end of this pipe as the cold water injector. In the numerical simulation the pump represents a constant pressure boundary condition. The right side of the horizontal pipe ends up in an elbow pipe connected to a steam tank.

In the mathematical model a tank always represents a constant pressure boundary condition. Beginning of the calculation the left side vertical pipe is fully filled with water, the transient begins when the subcooled water starts to flow into the pipe with a constant mass flow rate. The flow is purely stratified in the first time of the transient. However, as the flow continues and the inter surface is increased a well defined water level, which means about 40 percent water void fraction. A Kelvin-Helmholtz instability occurs, which interrupts the stratification. Finally a cold water slug is formed which captures a steam bubble. A thunder like strong water hammer sounds when the whole bubble is condensed. The measured widths of the pressure peaks are about 2ms which is approximately one tenth of a human eye glance. It is worth to mention that our numerical simulations are capable to achieve such time resolution and the calculated pressure peak widths are in good agreement with measurements.

After the condensation of the steam bubble quick pressure waves start to propagate in the water towards the cold water injection pump, which acts like a closed pipe end causing total reflection. This reflected wave propagates to the right till it reaches the water-steam phase discontinuity which lies approximately in the middle of the horizontal pipe. According to the high pressure wave propagation velocity in water and the short distance these kind of reflections happen in some milliseconds after the main water hammer event. The two-phase flow equations (Eq. 1-6) contains no direct viscosity terms (the Euler and not the Navier-Stokes equations are solved) however on the right hand side of the energy equations there are water-and-wall friction terms which causes damping. If the length of the water filled vertical pipe is enhanced the amplitude of the reflected waves can be suppressed. Former steam condensation induced water hammer simulations[2,6] did not realized this role of the left side vertical feed-pipe and caused large number of unwanted pressure peaks.

If the length of the water-filled feed-pipe is changed from 1m to 25 cm than a long train of decaying pressure peaks will appear in the calculations. Figure 4 shows such pressure peaks.

Careful analysis of the vapor fraction around 4.8 sec showed no periodic boiling and condensation which means that the pressure peaks cannot come from cavitation.

We emphasize that we do not eliminate reflected waves with mathematical or physical means. We just force them to propagate and decay. It is possible and very simple to include absorbing (non-reflecting) boundaries into our model, however such conditions are questionable. It is practically impossible in our experiment to measure the ratios among incoming, reflected and absorbed wave amplitudes. Such experiments could be useful and would help us to develop realistic boundary conditions in numerical models.

Figure 5 presents our calculated pressure peak according to the geometry of Figure 3 and compares it with the measured data. Calculation and measurement were performed in the horizontal pipe at 40 cm from the left elbow. Experimental and theoretical pressure peaks are in good agreement. The time shift between the peaks has very little interest and it can be neglected because in engineering problems the existence and the absolute magnitude of the pressure peak have the crucial importance.

A key issue in such investigation is the question of numerical uncertainties. Our experience shows that pressure peaks are sensitive to the choice of the applied limiter (e.g. MINMOD or Superbee). The original WAHA3 model includes 3 different flux limiters, we tried additional ten cases. All the results are different; the major deviation is about 50 percent at the maximal peak pressure values. This means that steam condensation induced water hammer is a highly non-linear physical phenomena with hard numerical consequences and have to be handled with great care.

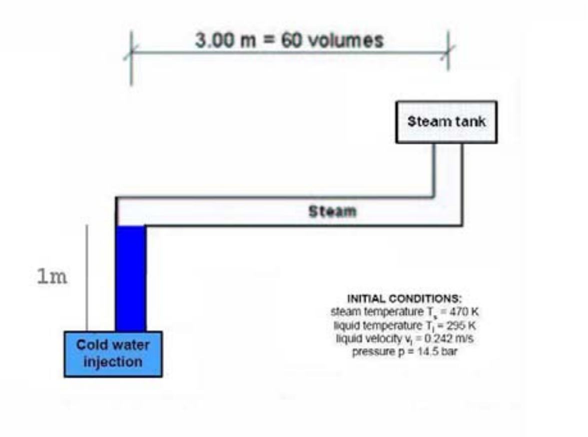

Fig. 3. The geometrical model with the initial conditions of the WAHA experiment

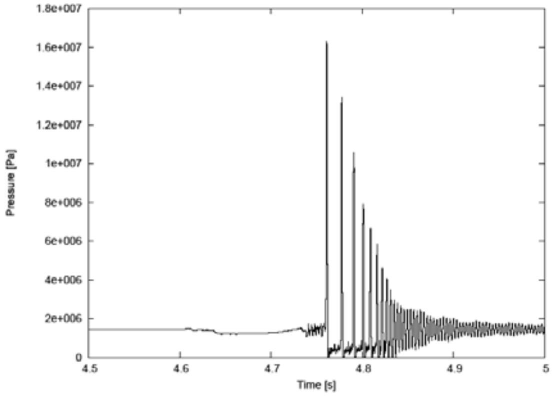

Fig 4. Unphysical pressure peaks from boundary reflections in calculations

Further and even larger uncertainties may come from the applied correlations, the condensation model and from the equation of state. The two-phase steam table, which is basically the numerical equation of state(eos) is taken from ordinary thermodynamics which is based on thermal equilibrium. However, during a quick transient like WAHA the fluid is not in equilibrium. How to develop eos for non-equilibrium systems is probably the largest unsolved dilemma of high-speed high-temperature hydrodynamics.

Our final statement is that recent numerical models and analysis can forecast if a waha event happens in a flow system with great surety, but the absolute value of the overpressure peak needs further peculiar investigation.

IV. CONCLUSIONS

We presented the Hungarian PMK-2 experimental facility which is a full pressure scaled down model of the primary and partly the secondary loop of the national Nuclear Power Plant equipped with the VVER-440/312 type.

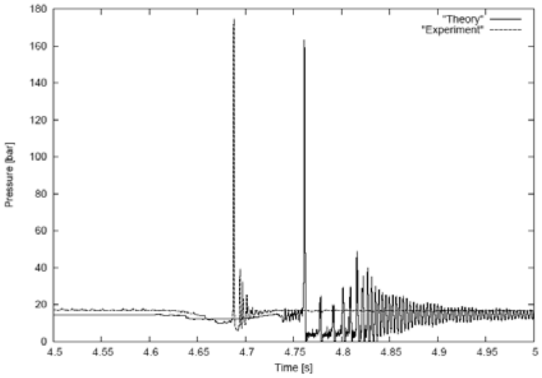

Fig 5. Time history of the pressure peaks at 40 cm from the left end of the horizontal pipe.

With the help of a one dimensional two-phase flow model we investigated the steam condensation induced water hammer phenomena. With a detailed analysis of the pressure wave propagation and the dynamics of the vapor void fraction along the pipeline the "steam bubble collapse" mechanism is identified which is responsible for the steam condensation induced water hammer in horizontal pipes.

Steam bubble collapse induced water hammer events happen if the following six conditions meet: [11]

1) the pipe must be almost horizontal (max. pipe inclination must be less than 5 degree)
2) the subcooling must be greater than 20 C°

3) the L/D (length-to-diameter ratio of the tube) must be greater than 24
4) the velocity must be low enough so that the pipe does not run full, i.e. the Froude number must be less than one
5) there should be a void nearby
6) the pressure must be height enough so that significant damage occurs, that is the pressure should be above 10 atmospheres.

Construction of a new WAHA experimental facility is in progress in the Hungarian PMK-2 integral experimental device right now. The geometry is basically the same as mentioned above but a much larger horizontal pipe will be raised with 5 meter lengths and 25 cm in diameters. First experiments gave water hammer events with 60-80 bar peak pressures, which are much smaller than in previous experiments. On the other side, theoretical analysis show that appearance of 350 bar overpressure peaks are not impossible. We explain such huge discrepancies with the fact that waha events are very sensitive to initial flooding water velocity. The new experimental system has another peculiarity, two or even three independent waha events happen one after another separated by 10 seconds or more. A careful investigation of the dynamics of the void fraction along the tube during the flooding clearly shows that in a longer tube(now 5 meters long former was only 3) there is enough room for two steam bubble formation. Unfortunately, the second steam bubble is "only formed" and shows a "nervous" shiver motion but cannot vehemently condense in our simulations. We think that the condensation model included in WAHA3 should be improved to overcome this problem.

Further theoretical investigations are in progress to illuminate all details.

In contrast to large system codes like REALP5 or Trac we have the source code of WAHA3 which is transparent and flexible to apply it to other two-phase flow systems.

Recently, we modify the model and create a realistic two-phase liquid-steam table for mercury. We try to simulate pressure waves and cavitation effects in the planned European Spallation Source (ESS)[12].

As a long term interest we also plane to investigate other liquid metal (e.g. bismuth-lead eutectic) systems[13] or liquid helium which can be interesting as a cooling media for new type of nuclear reactors. Liquid metal systems can operate on low (some bar) pressure and have much larger heat conductivity than water which can radically enhance thermal efficiency.

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NOMENCLATURE

A pipe cross section (m^2)
C_i internal friction coefficient (kg/m^4)
CVM virtual mass term (N/m^3)
e_i specific total energy [$e = u + v^2/2$] (J/kg)
$F_{g,wall}$ wall friction per unit volume (N/m^3)
g gravitational acceleration (m/s^2)
h_i specific enthalpy [$h = u + p/\rho$] (J/kg)
p pressure (Pa)
p_i interfacial pressure $p_i = p\alpha(1-\alpha)$ (Pa)
Q_{ij} interf.-liq./gas heat transf. per vol. rate (W/m^3)
t time (s)
u_i specific internal energy (J/kg)
v_i velocity (m/s)
v_r relative velocity ($v_r = v_g - v_f$) (m/s)
w pipe velocity in flow direction (m/s)
x spatial coordinate (m)
Γ_g vapor generation rate (kg/m^3)
α vapor void fraction
ρ_i density (kg/m^3)
ϑ pipe inclination

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