Theoretical study of steam condensation induced water hammer phenomena in horizontal pipelines

I. F. Barna, M. A. Pocsai, A. Guba and A. R. Imre

Steam condensation induced water hammer (CIWH) phenomena are investigated and new theoretical results are presented. We use 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. This model was validated with different CIWH experiments which were performed in the PMK-2 facility, which is a full-pressure thermohydraulic model of the nuclear power plant of VVER-440/312 type in the Energy Research Center of the Hungarian Academy of Sciences and in the Rosa facility of the Japan Atomic Energy Agency. In our present study we show the first part of a planned large database which will give us the upper and lower flooding mass flow rates for various pipe geometries where CIWH can happen. Such a reliable database would be a great help for future reactor constructions and scheming.

1 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 primary circuit may cause serious deformation or pipe breakage. Such an unplanned transient is the Condensation Induced Water Hammer (CIWH). In thermal loops of nuclear reactors or in other pipelines where water steam and cold water can mix, quick and dangerous transients can happen causing pressure surges which mean high financial expenses or even cost human lives.

In the following we will present the WAHA3 computer code developed by Tiselj [1], which is a complex physical model suitable to simulate various quick transients in single and two-phase flows, such as ideal gas Riemann problem, critical flow of ideal gas in convergent-divergent nozzle, rapid depressurization of hot liquid from horizontal pipes and column separation water hammer or even CIWH.

In the last two decades the nuclear industry developed a few complex two-phase flow codes like RELAP5 [2], TRAC [3] or CATHARE [4] which are feasible to solve safety analysis of nuclear reactors and model complicated two-phase flow transients.

The code WAHA3 [1] shows some similarities with RELAP5. This means that the conservation equations are the same but the applied correlations are to some extent different [1]. There are only three flow-regimes included in the model, which are dispersive, stratified and slug flows. In the RELAP5 code there are additional regimes, like, churn and bubbly flows are included as well. The main difference between the above mentioned models and 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 (some m/s). WAHA3, however, is capable of capturing shock waves and describe pressure waves – even multiple ones [5, 6] – which may propagate quicker than the local speed of sound (approx. 1000 m/s). As a second point WAHA3 has a quick condensation model which is not available for RELAP5 and CATHARE.

2 Numerical scheme

There is a 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:

\[
\frac{\partial A(1-\alpha)\rho_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l(v_l - w)}{\partial x} = -A\Gamma_g
\]  
(1)

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

\[
\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w)}{\partial x} + A(1-\alpha)\rho_l g \cos \theta = A\Gamma_v
\]  
(3)

\[
\frac{\partial A\alpha\rho_g v_g}{\partial t} + \frac{\partial A\alpha\rho_g v_g(v_g - w)}{\partial x} + A\alpha\rho_g g \cos \theta = A\Gamma_v
\]  
(4)

\[
\frac{\partial A(1-\alpha)\rho_l v_l^2}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w)}{\partial x} + B\frac{\partial A(1-\alpha)}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l g \cos \theta}{\partial x} = A\Gamma_u
\]  
(5)

\[
\frac{\partial A\alpha\rho_g v_g^2}{\partial t} + \frac{\partial A\alpha\rho_g v_g(v_g - w)}{\partial x} + A\alpha\rho_g v_g g \cos \theta = A\Gamma_u
\]  
(6)

Subscript \( l \) refers to the liquid phase and \( g \) for the gas phase, respectively. Nomenclature and variables are explained at the end of the paper. 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 the interfacial term (terms with \( \rho_l \)). Terms on the right hand side are describing the inter-phase heat, mass (terms with \( \Gamma_g \) vapor generation rate) volumetric heat fluxes \( Q_v \), momentum transfer (terms with \( C_l \)), wall friction \( F_g \), 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. The uncertainties of steady-state correlations in fast transients employed in the conservation Eqs. (1)–(6) are very high. A detailed analysis of the source terms can be found in Tisfj et al. [1].

Two additional equation of states (EOS) are needed to close the system of Eqs. (1)–(6). Here the subscript \( k \) can have two values \( l \) for the liquid phase, and \( g \) the for gas phase

\[
\rho_k = \left( \frac{\partial \rho_k}{\partial p} \right)_k dp + \left( \frac{\partial \rho_k}{\partial u_k} \right)_p du_k
\]  
(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 developed by Seynaeve [9].

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

\[
A \frac{\partial \Psi}{\partial t} + B \frac{\partial \Psi}{\partial x} = S
\]  
(8)

where \( \Psi \) represents a vector of the non-conservative variables \( \Psi = (p, \alpha, v_l, v_g, u_l, u_g) \), \( A, B \) are \( 6 \times 6 \) matrices and \( S \) is the source vector of non-differential terms. These three terms can be obtained from Eqs. (1)–(6) with some algebraic manipulation.

In this case the system eigenvalues which represent wave propagation velocities are given by the determinant \( \det(A - \beta B) \). 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 the work of LeVeque [10].

### 3 Results and discussion

In our present study we investigated pipelines with three different diameters (\( D = 10, 20 \) and \( 50 \) cm) with three different pipe aspect ratios (\( L/D = 25, 50 \) and \( 75 \)) and with three different pressures (\( p = 10, 20 \) and \( 40 \) bar). These are physically relevant geometries with pressures values which are interesting in various nuclear facilities. Table 1 presents these system parameters with the minimum and the maximum mass flow rates between CIWH events happen.

**Table 1. Minimum and maximum mass flow rates for the investigated systems**

| System parameters | Minimal flow rate (kg/s) | Maximal flow rate (kg/s) |
|-------------------|--------------------------|--------------------------|
| **D = 10 cm**     |                          |                          |
| \( p = 10 \) bar  | 0.12                     | 7.64                     |
| \( p = 20 \) bar  | 0.12                     | 4.60                     |
| \( p = 40 \) bar  | 0.195                    | 4.60                     |
| \( L/D = 50 \)    |                          |                          |
| \( p = 10 \) bar  | 0.23                     | 7.64                     |
| \( p = 20 \) bar  | 0.19                     | 5.46                     |
| \( p = 40 \) bar  | 0.23                     | 4.52                     |
| \( L/D = 75 \)    |                          |                          |
| \( p = 10 \) bar  | 0.39                     | 3.90                     |
| \( p = 20 \) bar  | 0.27                     | 4.21                     |
| \( p = 40 \) bar  | 0.23                     | 4.29                     |
| **D = 20 cm**     |                          |                          |
| \( p = 10 \) bar  | 1.25                     | 42.08                    |
| \( p = 20 \) bar  | 1.25                     | 25.12                    |
| \( p = 40 \) bar  | 1.25                     | 27.75                    |
For a better transparency these results are presented on Figs. 1, 2 and 3 for different pipe diameters. With this useful representation we can immediately see the dangerous CIWH range between the upper and lower flooding mass flow rates. For completeness we explain additional technical details of our investigations. In all calculations we used the same nodalisation in the sense that the actual length of the node is equal to the actual pipe diameter.

In all calculations the same Courant–Friedrich–Levy (CFL) limit was applied with 0.8. As numerical scheme the MIN-MOD limiter was used. There are only two exceptions at D = 50 cm, L/D = 50 and 75, p = 20 bar. The temperature of the cold water was fixed to 293 K. Each presented system (e.g. D = 10 cm, L/D = 25, p = 20 bar minimal mass flow rate) means at least 10 independent calculations with slightly different mass flow parameters. For the maximal flow a calculation takes 20 minutes or even less but for the minimal flow rate one calculation might take 20 hours. To determine if a CIWH event happened we simply checked the pressure-time history closed to the cold water inlet visually. If a sharp peak with a 2 millisecond of Full Width at Half Maximum (FWHM) can be seen that means that the conditions of the system are in the dangerous water hammer regime. It is worthy to note that there is a very sharp border at both sides (minimal and maximal mass flow rates, respectively) of the CIWH regime in this WAHA3 code. The curves in Figs. 1, 2 and 3 are not parallel and cross each other. The reason of this crossing is not fully clarified till now, it can be a real effect as well as a numerical uncertainty. As explanation we think to say that, with additional very time consuming tuning of all the technical parameters (limiter, CFL condition, nodalisation) some of the border points could be slightly modified, but this was not possible.

| System parameters | Minimal flow rate (kg/s) | Maximal flow rate (kg/s) |
|-------------------|-------------------------|-------------------------|
|                   |                         |                         |
| L/D = 50          |                         |                         |
| p = 10 bar        | 1.187                   | 28.89                   |
| p = 20 bar        | 1.41                    | 25.43                   |
| p = 40 bar        | 1.41                    | 25.75                   |
| L/D = 75          |                         |                         |
| p = 10 bar        | 1.26                    | 26.38                   |
| p = 20 bar        | 1.26                    | 25.12                   |
| p = 40 bar        | 1.41                    | 26.7                    |
| D = 50 cm         |                         |                         |
| L/D = 25          |                         |                         |
| p = 10 bar        | 9.8                     | 266.5                   |
| p = 20 bar        | 9.8                     | 156.8                   |
| p = 40 bar        | 9.8                     | 160                     |
| L/D = 50          |                         |                         |
| p = 10 bar        | 9.8                     | 266.55                  |
| p = 20 bar        | 7.8                     | 519.4                   |
| p = 40 bar        | 13.7                    | 509                     |
| L/D = 75          |                         |                         |
| p = 10 bar        | 9.8                     | 262.66                  |
| p = 20 bar        | 9.8                     | 490                     |
| p = 40 bar        | 9.8                     | 505.6                   |

Fig. 1. Minimum and maximum mass flow rates for D = 10 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar

Fig. 2. Minimum and maximum mass flow rates for D = 20 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar

Fig. 3. Minimum and maximum mass flow rates for D = 50 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar
till now; further work is in progress. However, we do believe that the presented results are important because – as a rule of thumb – they show us the approximate range of the flood velocity where CIWH happens with very high probability.

4 Conclusions

We presented results using the WAHA3 code which is capable to describe supersonic two-phase flow transients in pipe lines. After our former CIWH studies [5, 6] we presented now a database where the minimal and maximal mass flow rates can be determined for large number of flow systems. Further studies are planned to cover a wider range of relevant physical parameters, like pressure, pipe length, diameter and inclination etc.

Nomenclature

\begin{align*}
A & \quad \text{pipe cross section (m}^2) \\
C_i & \quad \text{internal friction coefficient (kg/m}^4) \\
CVM & \quad \text{virtual mass term (Nm}^2) \\
e_i & \quad \text{specific total energy} \ [e = u + v^2/2] \ (J/kg) \\
F_{g,\text{wall}} & \quad \text{wall friction per unit volume (N/m}^3) \\
g & \quad \text{gravitational acceleration (m/s}^2) \\
h_i & \quad \text{specific enthalpy} \ [h = u + p/p_i] \ (J/kg) \\
p & \quad \text{pressure (Pa)} \\
p_i & \quad \text{interfacial pressure} \ [p_i = \rho \alpha(1-\alpha) \ (Pa)] \\
Q_i & \quad \text{interfacial liquid/gas heat transfer per volume rate (W/m}^3) \\
t & \quad \text{time (s)} \\
u_i & \quad \text{specific internal energy (J/kg)} \\
v_i & \quad \text{velocity (m/s)} \\
v_r & \quad \text{relative velocity} \ [(v_r = v_g - v_i) \ (m/s)] \\
w & \quad \text{pipe velocity in flow direction (m/s)} \\
x & \quad \text{spatial coordinate (m)}
\end{align*}

Greek letters

\begin{align*}
\alpha & \quad \text{vapour void fraction} \\
\Gamma_g & \quad \text{vapour generation rate (kg/m}^3) \\
\rho_i & \quad \text{density (kg/m}^3) \\
\theta & \quad \text{pipe inclination (degree)}
\end{align*}

Subscripts

\begin{align*}
l & \quad \text{liquid phase} \\
g & \quad \text{gas phase}
\end{align*}

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References

1 Tiselj, I.; Petelin, S.: Modeling of Two-Phase Flow with Second-Order Accurate Scheme. Journal of Comput. Phys. 136 (1997) 503, DOI:10.1006/jcph.1997.5778

2 Carlson, K. E.; Rienkne, R. A.; Rouhani, S. Z.; Shumway, R. W.; Weaver, W. L.: RELAP5/MOD3.3 Beta Code Manual, Vol 1–7, NUREG-CR-5535, EG&G Idaho, Idaho Falls 2003

3 Lies, D. R. et al.: TRAC-PFI/MOD1: An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Thermal-Hydraulic Analysis. NUREG/CR-3858, Los Alamos, Safety Code Development Group, June 1982

4 Bestion, D.; Geffraye, G. T.: The Code for Analysis of Thermalhydraulics during an Accident of Reactor and Safety Evaluation (Cathare) CE A Grenoble Report. DTP/SMTH/LMDS/EM/22001-63, April 2002

5 Barna, I. F.; Imre, A. R.; Baranyai, G.; Ézsöl, Gy.: Experimental and theoretical study of steam condensation induced water hammer phenomena. Nucl. Eng. and Des. 240 (2010) 146, DOI:10.1016/j.nucengdes.2009.09.027

6 Barna, I. F.; Ézsöl, Gy.: Multiple condensation induced water hammer events, experiments and theoretical investigation. Kerntechnik 76 (2011) 231, DOI:10.3139/124.110154

7 Stewart, H. B.; Wendroff B.: Two-Phase flow: Models and Methods. J. Comp. Phys. 56 (1984) 363. DOI:10.1016/0021-9991(84)90103-7

8 Menikoff, R.; Plohr, B.: The Riemann Problem fluid flow of real materials. Rev. Mod. Phys. 61 (1989) 75. DOI:10.1103/RevModPhys.61.75

9 Seynhaeve, J. M.: Water properties package. Catholic University of Louvain (1992) Project Built with IAPS from Lester, Gallagher and Kell, McGraw-Hill 1984

10 LeVeque, R. J.: Numerical Methods for Conservation Laws. Lecture in Mathematics, ETH, Zurich, (1992), DOI:10.1007/978-3-0348-8629-1

The authors of this contribution

Imre Ferenc Barna (corresponding author)

E-mail: barna.imre@wigner.mta.hu

Wigner Research Center of the Hungarian Academy of Sciences

1121 Budapest, Konkoly Thege ut 29–33

Hungary

and

ELI-HU Nonprofit Kft., Dugonics tér 13, 6720 Szeged, Hungary

Mihály András Pocsai

E-mail: pocsai.andras@wigner.mta.hu

Wigner Research Center of the Hungarian Academy of Sciences

1121 Budapest, Konkoly Thege ut 29–33

Hungary

and

University of Pécs

Faculty of Sciences

Institute of Physics

7624 Pécs, Ifjúság útja 6

Hungary

Attila Guba

E-mail: guba.attila@energia.mta.hu

Energy Research Center of the Hungarian Academy of Sciences

1121 Budapest, Konkoly Thege ut 29–33

Hungary

Attila Rikárd Imre

E-mail: imre.attila@energia.mta.hu

Energy Research Center of the Hungarian Academy of Sciences

1121 Budapest, Konkoly Thege ut 29–33

Hungary

and

Budapest University of Technology and Economics

Faculty of Mechanical Engineering

Department of Energy Engineering

Muegyetem rkp. 3, D208, H-1111 Budapest, Hungary

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