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

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.

Analytische Untersuchung der durch Dampfkondensation verursachten Kondensationsschläge in horizontalen Leitungen. *Neue Ergebnisse aktueller analytischer Untersuchungen zu durch Dampfkondensation verursachten Kondensationsschlägen werden vorgestellt. Dabei wurden die Rechnungen mit dem Programm WAHA durchgeführt, bei dem die sechs partiellen Differentialgleichungen erster Ordnung zur Beschreibung der Zweiphasenströmung durch eindimensionale oberflächengemittelten Massen-, Impuls und Energiebilanzen angenähert werden. Zusätzlich wurde in diesen Analysen ein hochauflösender und Druckschläge erkennender Algorithmus zweiter Ordnung mit verschiedenen Limitern angewendet. Dieser Algorithmus wurde anhand der Nachrechnung ausgewählter Experimente in der ungarischen Versuchsanlage PMK-2 (Volldruckmodell eines WWER-440/312) und in der japanischen Versuchsanlage ROSA validiert. In diesem Beitrag wird der erste Teil einer geplanten großen Datenbank vorgestellt, in dem unteren und oberen Massenstromgrenzen für verschiedene Rohrgeometrien zusammengestellt werden, innerhalb deren Kondensationsschläge infolge Dampfkondensation auftreten können.*

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 disperse, 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:

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

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

$$\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w)}{\partial x} + A(1-\alpha)\frac{\partial p}{\partial x} - A\cdot CVM - Ap_i\frac{\partial \alpha}{\partial x} = AC_i|v_r|v_r - A\Gamma_g v_l + A(1-\alpha)\rho_l\cos\vartheta - AF_{l,wall} \quad (3)$$

$$\frac{\partial A\alpha\rho_g v_g}{\partial t} + \frac{\partial A\alpha\rho_g v_g(v_g - w)}{\partial x} + A\alpha\frac{\partial p}{\partial x} + A\cdot CVM + Ap_i\frac{\partial \alpha}{\partial x} = -AC_i|v_r|v_r + A\Gamma_g v_g + A\alpha\rho_g\cos\vartheta - AF_{g,wall} \quad (4)$$

$$\frac{\partial A(1-\alpha)\rho_l e_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l e_l(v_l - w)}{\partial x} + p\frac{\partial A(1-\alpha)}{\partial t} + \frac{\partial A(1-\alpha)p(v_l - w)}{\partial x} = AQ_{il} - A\Gamma_g(h_l + v_l^2/2) + A(1-\alpha)\rho_l v_l g\cos\vartheta \quad (5)$$

$$\frac{\partial A\alpha\rho_g e_g}{\partial t} + \frac{\partial A\alpha\rho_g e_g(v_g - w)}{\partial x} + p\frac{\partial A\alpha}{\partial t} + \frac{\partial A\alpha p(v_g - w)}{\partial x} = AQ_{ig} + A\Gamma_g(h_g + v_g^2/2) + A\alpha\rho_g v_g g\cos\vartheta \quad (6)$$

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 ρ_i). Terms on the right hand side are 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. 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 *Tiselj 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

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

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 *Seynhaeve* [9].

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

$$\underline{\underline{A}}\frac{\partial \overline{\Psi}}{\partial t} + \underline{\underline{B}}\frac{\partial \overline{\Psi}}{\partial x} = \overline{S} \quad (8)$$

where $\overline{\Psi}$ represents a vector of the non-conservative variables $\overline{\Psi}(p, \alpha, v_l, v_g, u_l, u_g)$, $\underline{\underline{A}}$, $\underline{\underline{B}}$ are 6×6 matrices and $\overline{S}$ 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($\underline{\underline{A}} - \lambda\underline{\underline{B}}$). 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		
L/D = 25		
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		
L/D = 25		
p = 10 bar	1.25	42.08
p = 20 bar	1.25	25.12
p = 40 bar	1.25	27.75

Table 1. (continued)

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

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 MINMOD 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

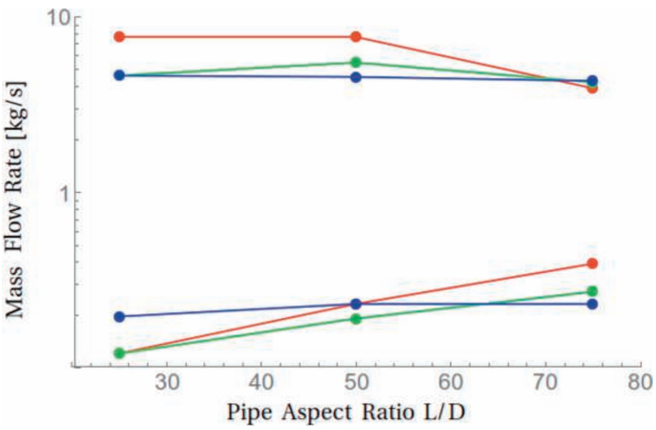

Fig. 1. Minimum and maximum mass flow rates for D = 10 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar

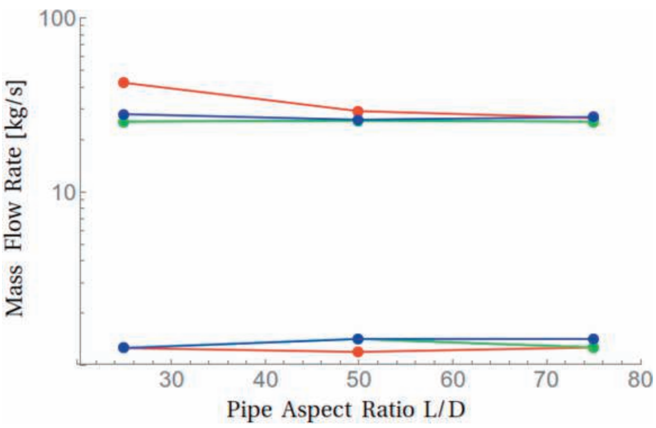

Fig. 2. Minimum and maximum mass flow rates for D = 20 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar

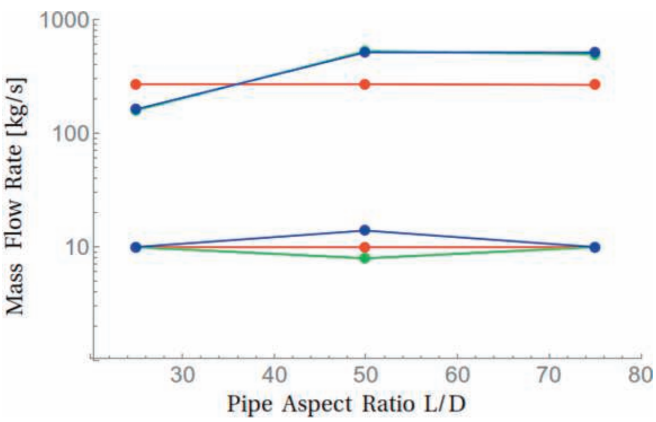

Fig. 3. Minimum and maximum mass flow rates for D = 50 cm diameter pipelines with L/D = 25, 50, 75 tube aspect ratios; red curve is for p = 10 bar, green curve is for p = 20 bar and the blue one is for p = 40 bar

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

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}	interfacial liquid/gas heat transfer per volume 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)

Greek letters

α	vapour void fraction
Γ_g	vapour generation rate (kg/m^3)
ρ_i	density (kg/m^3)
ϑ	pipe inclination (degree)

Subscripts

l	liquid phase
g	gas phase

Acknowledgements

We thank to Prof. Dr. *Iztok Tiselj* (Jozef Stefan Institute, Ljubljana, Slovenia) for his fruitful discussions and valuable comments. This study was partially supported by the grant "Korea-Hungary Joint Laboratory for Advancement of Nuclear Thermal Hydraulics Safety".

(Received on 30 March 2015)

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DOI 10.3139/124.110537
KERNTECHNIK
80 (2015) 5; page 420–423

ISSN 0932-3902