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SLUG MODELING WITH 1D TWO-FLUID MODEL

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Abstract

Simulations of condensation-induced water hammer with one-dimensional two-fluid model requires explicit modeling of slug formation, slug propagation, and in some cases slug decay. Stratified flow correlations that are more or less well known in 1D two-fluid models, are crucial for accurate description of the initial phase of the slug formation and slug propagation. Slug formation means transition to other flow regime that requires different set of correlations. To use such two-fluid model for condensation induced water hammer simulations, a single slug must be explicitly recognized and captured. In the present work two cases of condensation-induced water hammer simulations performed with WAHA code, are described and discussed: injection of cold liquid into horizontal pipe filled with steam and injection of hot steam into horizontal pipe partially filled with cold liquid.

Introduction

In the present work, two different Condensation Induced Water Hammer (CIWH) mechanisms are discussed. They represent examples of stratified flow, slug flow and transitional flows and are analyzed with 1D computer code WAHA (Tiselj et. al. 2004). The focus of the research is modeling of slug formation, slug propagation, and slug decay. The WAHA code was developed and tested for the column separation water hammer phenomena. WAHA code is based on one-dimensional six-equation two-fluid model with correlations for heat, mass, momentum transfer in stratified and dispersed flow. The name "two-fluid" has been historically used to describe the models based on spatial, temporal or ensemble averaged flow equations. The "two-fluid model" is used to name the models of two immiscible fluids as well as for two-phase flow models that describe a single fluid in the form of two phases. Recent development of the code is being performed in the field of condensation-induced water hammer in horizontal pipes.

Despite the fact that this work considers modeling of 1D slug flow with two-fluid models, the existing slug flow correlations are not directly applicable for predictions of condensation induced water hammer, because they give an averaged heat, mass and momentum transfer correlations instead of instantaneous local values needed for the water hammer studies. A single slug must be explicitly captured in the present study with 1D two-fluid model. Such tasks are expected to be performed with multidimensional CFD analysis using some of the free surface tracking algorithms and not in 1D two-fluid models. However, while the current CFD codes might be able to describe the stratified flow with condensation and also slug formation and development, one can certainly expected problems with modeling of the thin condensate film on the cold walls and water hammer shock waves followed by the flashing of the liquid. And while we do intend to test CFD models for condensation-induced water hammer in the future, our present goal is to develop a suitable 1D two-fluid model capable to describe slug formation, slug propagation and water hammer pressure surge when the slug hits the wall or another slug.

Two-fluid model of the WAHA code

Mathematical model of the WAHA code is similar to the models of RELAP5 (Carlson et al, 1990) or CATHARE (Bestion, 1990) computer codes. The basic equations are mass, momentum and energy balances for vapor and liquid. Continuity equations for liquid and vapor (gas) phase are:

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

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

where, for the present study, temporal changes of cross-section $A(x,t)$ are neglected equations (1) and (2) (and also in Eqs. (5) and (6)). Momentum balance equations for both phases are:

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

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

Internal energy balance equations without wall-to-fluid heat transfer terms are:

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

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

Specific total energy of liquid or gas is $e = u + v^2/2$. Differential terms are collected on the left-hand side of the equations and the non-differential terms are collected on the right-hand side.

Closure relations

The WAHA code uses several differential and non-differential closure relations. Closure relations in two-phase flow are used to describe interfacial heat, mass and momentum transfer, wall friction, interfacial pressure, virtual mass term, equations of state etc. The equations of state for each phase *k*, where *k* is *f* for fluid and *g* for steam are:

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

Derivatives on the right-hand side of the Eq. (7) are determined by the fluid property subroutines developed for the WAHA code using pressure and temperature or specific internal energy as input. Such subroutines currently exist for water, ammonia and mercury.

The virtual mass term CVM in Eqs. (3) and (4) is used to obtain hyperbolicity of the system in dispersed flow (see WAHA code manual). Value of the coefficient C_{vm} was tuned to ensure the hyperbolicity of the two-fluid model equations. Applied virtual mass term does not ensure unconditional hyperbolicity of the equations. For very large relative velocities (comparable to sonic velocity) complex eigenvalues may appear, however these velocities are not relevant in realistic two-phase flows.

Stratified flow regime, which is crucial for slug modeling with two-fluid models, can be described with introduction of the interfacial pressure term p_i that is applied to describe pressure differences due to the gradients of vapor (liquid) volume fractions:

$$p_i = S\alpha(1-\alpha)(\rho_f - \rho_g)gD \tag{8}$$

where S presents the stratification factor. This interfacial pressure term is of crucial importance for the modeling of stratified and slug flows, as it changes the basic nature of the two-fluid model: instead of time/space averaged picture used for dispersed flows, term (8) changes the two-fluid model equations into a shallow water equations that are capable to predict stratified flows, propagation of surface waves and with the help of some empirical correlations - transition to slug flow and slug capturing.

Terms that don't include derivatives are source terms and they are flow regime dependent. Source terms in Eqs. (1)-(6) are:
1) Terms with inter-phase drag (C_i).
2) Terms with inter-phase exchange of mass and energy (vapor generation rate - Γ_g, interface heat transfer terms - Q_{if}, Q_{ig}).
3) Terms due to the variable pipe cross-section.
4) Terms with wall friction ($F_{f,wall}$, $F_{g,wall}$).
5) Term with volumetric forces ($g\cos\theta$).

Sources from the points 1. and 2. are the so-called relaxation source terms. They play crucial role in the case of condensation-induced water hammer modeling and therefore their detailed description is given in the next section. Relaxation source terms are inter-phase mass, momentum, and energy exchange terms, which tend to establish thermal and mechanical equilibrium between the phases. Characteristic time scale of relaxation source terms can be much shorter than the characteristic time scale of the acoustic waves (terms are stiff and need special numerical treatment). Relaxation source terms are flow regime dependent. Other, non-relaxation source terms are of minor importance for the present work.

A very crude flow regime map (described below) has been applied in the WAHA code, which is actually nothing more than search for the best fit of the macroscopic data, and is open for improvement with the further comparison with the experimental data. More detailed flow regime maps were abandoned as they are developed for the steady-state flow regimes. The accuracy of the existing more detailed flow regime maps in the area of fast transients comparing to our crude flow regime map, is in our opinion not significantly higher, and does not justify their use in the WAHA code. The main goal of the WAHA correlations is to have correct correlations in the limit of high and low vapor volume fractions with their smooth transition into the single-phase flow, with possibility of their further tuning on the basis of the experiments. It is important to note that even the "standard" single-phase wall friction correlations (RELAP, CATHARE) turn out to be insufficient in the area of the fast transients.

The WAHA code distinguishes two flow regimes: dispersed flow with stratification factor S=0 and horizontally stratified flow with S=1. Flow is dispersed with S=0 when the relative velocity v_r is larger than the critical velocity:

$$|v_r| \geq v_{crit} \qquad v_{crit} = \sqrt{gD(\rho_f - \rho_g)\left(\frac{\alpha}{\rho_g} + \frac{(1-\alpha)}{\rho_f}\right)} \tag{9}$$

This expression is an approximation based on the Kelvin-Helmholtz instability. This critical velocity is at the same time maximum relative velocity, where two-fluid model with applied interfacial pressure term and without virtual mass term, is still hyperbolic. Flow is horizontally stratified with stratification factor S=1 for $|v_r| < v_{critical}/2$. Flow is transitional between dispersed and horizontally stratified, if $v_{critical}/2 \leq |v_r| \leq v_{critical}$. Stratification factor S is linearly interpolated between 0 and 1 in such case. This approach is similar to the well-known Taitel-Dukler correlation for transition from stratified to slug flow (Taitel, Dukler 1976). From the standpoint of condensation-induced water hammer modeling, this model represents a possible area of the future work. However, the original formulation (9) was not changed in the two types of simulations described below: results obtained with the minor modifications of the parameters in stratification factor *S* and in Eq. (9) did not justify the use of modified correlations.

The most important set of correlations for the present research are stratified flow correlations that are crucial for accurate description of the initial phase of the transient including the formation of the slug. Such correlations are usually not present in the codes like RELAP or CATHARE, since the heat transfer in the horizontal pipes is not of a major concern for the western light water reactors. Some special upgrades of these codes used for analyses of VVER reactors with horizontal steam generators contain such additional set of correlations. Slug formation means transition in different flow regime that requires different set of correlations. Despite the fact that this work considers modeling of 1D slug flow with two-fluid models, existing slug flow correlations (see Lin, Hanratty 1986, or Issa, Kempf, 2003 for example) are not directly applicable as they give an averaged heat, mass and momentum transfer correlations instead of instantaneous local values needed for the present study. A single slug is being explicitly followed in the results presented below.

1.1 Inter-phase momentum transfer

The interfacial friction coefficient C_i in momentum equations is calculated from correlations, which are valid for two-phase flow water-vapor and for two-component flow water-ideal gas (similar to RELAP5 model). The original WAHA correlations remain unchanged for the present simulations and analyses have shown rather low sensitivity of the results to the inter-phase friction coefficients in stratified, dispersed and transitional flow.

Horizontally stratified flow interfacial friction coefficient is calculated from the equation, which states that magnitude of the drag force of the gas on the liquid is equal to the drag force of the liquid on gas:

$$|F_f| = |F_g| = C_i\left(v_g - v_f\right)^2 \tag{10}$$

interfacial friction coefficient is then calculated as:

$$C_i = \frac{1}{8}\rho_k f_k \frac{(v_k - v_i)^2}{(v_g - v_f)^2} a_{gf} \qquad k = g, f \tag{11}$$

where f_k are friction factors, v_i is interface velocity and a_{gf} is interfacial area. that can be easily determined in the stratified flow (WAHA manual).

Interfacial friction in dispersed flow is several orders of magnitude larger that in the stratified flow. When transition from stratified or slug flow into the dispersed flow occurs, the exact values of C_i coefficient are actually not very important: in most cases setting C_i=infinity (very large) does the work. Very large value of C_i actually means homogeneous flow assumption, which is sufficiently accurate for our simulations.

1.2 Inter-phase heat and mass transfer

The "standard" inter-phase mass transfer (vapor generation rate Γ_g) is calculated as:

$$\Gamma_g = -\frac{Q_{if} + Q_{ig}}{h_g^* - h_f^*} \qquad Q_{ih} = H_{ih}(T_{sat} - T_f) \qquad k = f, g \tag{12}$$

where h_k^* are specific enthalpies and Q_{ik} are liquid-to-interface and gas-to-interface heat fluxes. The heat transfer coefficients H_{ik} depend on flow regime.

Calculation of inter-phase heat transfer coefficients were based on two different models:

1) For condensation induced water hammer due to the flooding of the hot steam with cold liquid, a simple model for horizontally stratified flow heat and mass transfer coefficients for both phases were derived as approximations of the heat transfer coefficient for the turbulent flow near a flat wall:

$$H_{ik} = \frac{Nu_k \, a_{gf} \, k_k}{\sqrt{A_k}\,(1+\sqrt{2})} \tag{13}$$

where N_{uk} are Nusselt numbers, k_k are thermal conductivity and A_k are parts of the pipe cross-section occupied by liquid or gas. This model is used in current version of WAHA code.

2) For CIWH due to the injection of hot steam into a horizontal pipe partially filled with cold liquid, a new heat transfer model was used (see Tiselj and Martin 2010). Original WAHA correlations do not take into account wall heat transfer, which is an important mechanism for such case. Thus, condensation on the wall is taken into account as:

$$\Gamma_{g-wall} = -\frac{H_{ig-wall}(T_{wall} - T_{sat})}{h_g^* - h_f^*} \tag{14}$$

Chato-Dobson correlation (Dobson, Chato, 1998) for condensation rate in the horizontal pipe was implemented:

$$Nu = Nu_{film} + (1-\theta_f/\pi) Nu_{forced} = \frac{0.23\,\mathrm{Re}_{go}^{0.12}}{1+1.11 X_{tt}^{0.58}} \left[\frac{Ga\,\mathrm{Pr}_f}{Ja_f}\right]^{0.25} + (1-\theta_f/\pi)\,0.0195\,\mathrm{Re}_f^{0.8}\,\mathrm{Pr}_f^{0.4}\,\Phi_f(X_{tt})$$

$$H_{ig-wall} = Nu_{film}\frac{4k}{D^2} \qquad H_{if} = (1-\theta_f/\pi) Nu_{forced}\frac{4k}{D^2} \tag{15}$$

The first term in Chato-Dobson correlation represents part of the coefficient, which represents contribution of the film condensation on the wall and the second term represents contribution of the forced-convective condensation on the liquid-gas interface. The following variables are used in Eq. (15): Re_{go} - Gas only Reynolds number, Ga - Galilei number, Ja - Jacob number, $\Phi_f(X_{tt})$ function of turbulent-turbulent Lockhart-Martinelli parameter given in Dobson, Chato, 1998. Each term of Chato-Dobson correlation is used separately: film condensation term in Eq. (15) and forced-convection inter-phase exchange coefficient in Eq. (15).

The vapor heat transfer coefficient H_{ig} is calculated as (similar in the RELAP5 code):

$$H_{ig} = a_{gf} \frac{k_g}{D} 0.023 \, \mathrm{Re}_g^{0.8} \tag{16}$$

Dispersed flow heat transfer is actually not present during the transients - the closest "approximation" of dispersed flow can be seen at the head of the slugs, where wave breaking appears and causes much more efficient inter-facial heat transfer than predicted by (13) or (15) correlation. This phenomena can be seen from the air-water experiments and simulations of Bartosiewitz (2008) and experiment of Vallée et. al. (2010). Thus a very crude inter-phase heat and mass transfer is used at the location of the slug head:

$$\begin{aligned} & \textit{if} \quad \textit{slug} \quad \textit{head} \quad \textit{identified}: \\ & \quad H_{if} = -C_1 \alpha (1-\alpha) \, |\nabla \alpha|^{C_2} \; f(T_f, T_g) \, |v_r|^{C_3} \\ & \textit{else} \\ & \quad H_{if} = 0 \\ & \textit{endif} \end{aligned} \qquad f(T_f, T_g) = \begin{cases} |T_f - T_g|^{C4} & ; T_g < T_f \\ |T_f - T_g|^{C5} & ; T_g > T_f \end{cases} \tag{17}$$

Values C_1=1.5, C_2=1, C_3=0, C_4=1, C_5=1 were used in the calculations collected in the Table 1 below. Head of the slug is located with the gradient of the liquid superficial velocity:

$$\textit{if} \quad \nabla((1-\alpha) v_v) < -0.05, \, \textit{slug head identified} \tag{18}$$

This is rather unusual approach for 1D two-fluid model and actually represents some kind of inter-phase tracking within the 1D two-fluid model. However, according to our experience, this is the best way to perform condensation-induced water hammer simulations with 1D two-fluid model. If the slug, and especially the head of the slug (where stratified heat and mass transfer correlations are not applicable) is not successfully recognized and condensation rate increased in that area, the simulations exhibit rather poor results.

2. Results

2.1 PMK-2 cold liquid injection CIWH

Condensation-induced water hammer experiment at the PMK-2 device and the initial conditions are based on the recommendations of the NUREG/CR-6519 report, prepared by Griffith (1996). The PMK-2 is a Hungarian integral test facility for VVER-400/213 safety studies. The steam-line of the PMK-2 device, schematically shown in Fig. 1, was used as a test section for the condensation induced water hammer studies (see Štrubelj et. al. 2010). The main part of the test section is 2.8m long horizontal pipe with inner diameter 73mm. Initial conditions for one of the modeled PMK experiments are: pressure inside the pipe *p = 14.5 bar,* steam and water temperature T_{steam} = *470 K,* T_{water} = *297 K* and mass flow at the inlet of the pipe G_{water} = *1.01 kg/s*, (corresponding velocity *v = 0.242 m/s*). In order to avoid numerical difficulties, two vertical volumes are added, one at the beginning and one at the end of the pipe. Total length of the pipe is $L = 2.95\ m$ (= 59 volumes). Influence of the wall friction on the transient and the pressure peak was found to be negligible.

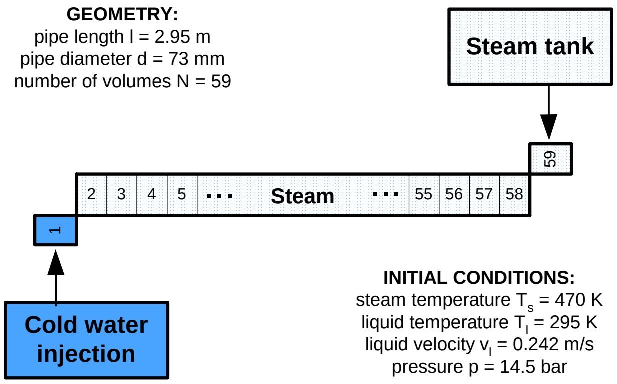

Figure 1 Simplified scheme of PMK experimental facility.

At time $t = 0.0\ s$, the system is filled with hot steam except the vertical section of the pipe inlet, which is filled with cold liquid. When water starts to flow from the vertical volume into the horizontal part of the pipe, sub-cooled water and steam are separated and the flow is horizontally stratified. Figure 2-left shows longitudinal profile of the vapor volume fraction. As the flooding continues, interfacial surface area is increasing, vapor condensation is stronger, and the relative velocity above the head of the liquid wave is growing. However, according to the WAHA results, the criteria for the onset of Kelvin-Helmholtz instability and transition into dispersed flow is not achieved until the liquid wave hits and reflects from the opposite end of the horizontal section. Figure 2-right shows formation of the slug wave and corresponding stratification factor. When dispersed flow correlations are applied at forehead of the wave, vapor generation rate and interfacial friction coefficient are drastically enlarged comparing to horizontally stratified flow in Fig 2-left. Pressure difference, initiated by the rapid condensation, accelerates the slug and the slug hits the inlet end of the pipe. Pressure at this point is shown in Fig. 3.

While the results shown in Figs. 1 to 3 look like successful simulation of a CIWH transient at the PMK-2 experimental device, the sensitivity analysis shows, that the value of these results is rather poor. It is important to stress that the calculated value of the pressure surge may vary between 0 and 60 MPa with only minor changes of the parameters, which govern the transition from stratified into dispersed flow. It turns out - not only in simulation, but also in experiment - that even the exact timing and location of the slug formation is a rather stochastic variable, which is very sensitive even to the minor changes of the closure models, boundary and initial conditions or grid density. As a consequence, the timing and magnitude of the pressure surge are also very sensitive to the initial and boundary conditions. According to our experience with the PMK-2 condensation induced water hammer modeling, one should not expect accurate predictions of the water hammer timing or accurate peak pressures from the simulations, but in the best case identification of the circumstances that can lead to the transient with or without water hammer.

Simulations of other test cases have shown the same chaotic behavior, and is thus not mentioned in this paper.

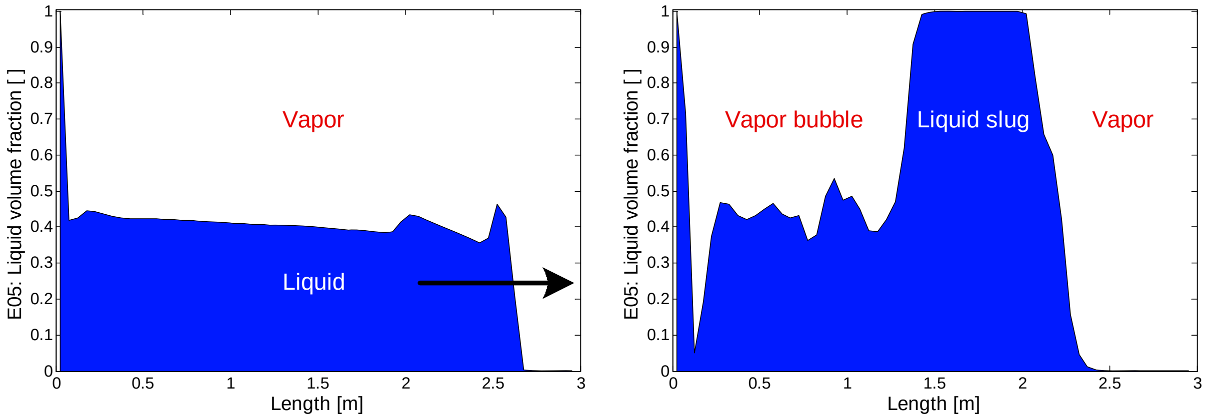

Figure 2 Liquid volume fraction profiles at t=3.7 s (left) and t=4.8 s (right).

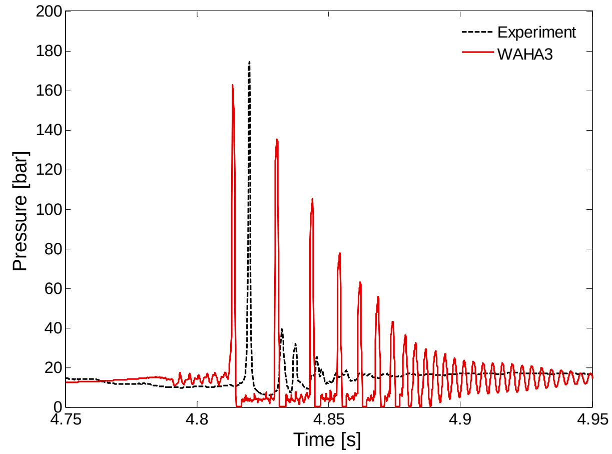

Figure 3 Pressure near the inlet side of the horizontal pipe of PMK device.

2.2 Hot steam injection CIWH by C.S. Martin

An apparatus was designed by Martin et.al. (2007) to simulate an industrial environment whereby ammonia liquid is standing in a partially-filled horizontal pipe in thermal equilibrium with ammonia gas above it. The essential elements of the test setup consist of a horizontal pipe and a high pressure tank containing hot (ambient temperature) ammonia gas, which injects hot steam into the cold (~ -40 ^{0}C), isolated horizontal section shown in Figure 4. The test pipe was a nominal 150 mm diameter, 6 m long schedule 80 carbon steel pipe, having internal diameter of 146.3 mm, and wall thickness 11 mm. Between the pressure tank and test pipe were three valves – angle valve, solenoid valve, and throttle valve - and a metering orifice, which allowed measurements of the inlet mass flow rate.

The principal measurements were (1) receiver gas pressure (ambient temperature), (2) orifice-metered gas flow (up to 0.45 kg/s), (3) static temperature and pressure of saturated liquid and gas in test section (225-250 K, ~0.45-1.6 bar), (4) dynamic gas pressures and shock pressures in several points of the test section that reached up to 50 bar.

Fig. 4 shows schematic description of the condensation-induced water (or better "ammonia") hammer phenomena. Initial depth of the liquid and initial temperature and corresponding saturation pressure were modified in different experimental runs. When the valve on the hot gas inlet pipe is opened, hot gas enters the test section and can induce slugging if the relative velocity between phases is high enough. Gas velocity above the liquid interface depends on inlet mass flow rate and on the condensation rate of the gas on the cold walls of the pipe and cold surface of the liquid. Once the slug is formed, very efficient heat transfer at the head of the slug causes pressure difference between the tail and the head of the slug and pushes the slug towards the closed end. During the slug propagation the mass of the liquid inside the slug grows and the water hammer pressure surge is registered when the slug hits the closed pipe end.

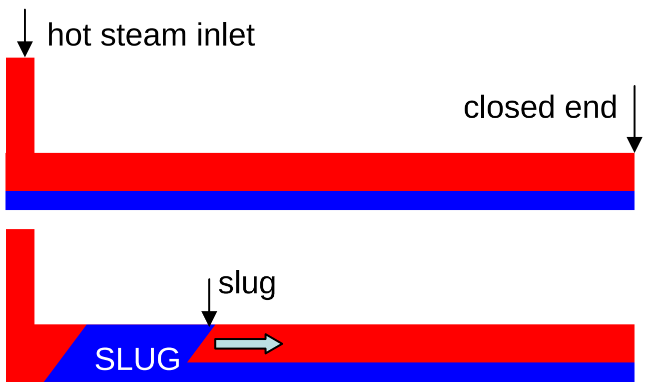

Figure 4: Simplified scheme of the Martin's CIWH device.

The most important issue in simulations of the phenomena was upgrade of the two-fluid model with a procedure that can recognize the head of the slug, where inter-phase heat and mass transfer is much more efficient than predicted by the Chato-Dobson correlation. Slug head identification model from Eq. (18) was found to predict the area of the slug head. Increase of the heat transfer coefficients in the slug head region is performed with a general model of Eq. (17). These two models with the current values of the coefficients were being developed by fitting of the calculations with the measurements and remain open for further improvements.

Table 1: Martin's CIWH - overview of the selected experimental cases and corresponding simulations. Times of pressure peaks are given with respect to the start of the gas injection. Times in Figures are given with respect to the starting time of the measurements.

case number /experiment	initial pressure in the test section (bar)	initial temperat-ure in the test section (K)	initial vapor volume fraction	approximate hot gas mass flow rate (kg/s)	hot gas temperat-ure (K)	measured pressure peak (bar)	time of measured pressure peak (s)	calculated pressure peak (bar)	time of calculated pressure peak (s)
1/03.01.01-13	0.51	226.8	0.4736	0.31	293	51	0.58	71	0.61
2/03.01.01-14	0.55	228.6	0.4736	0.11	293	20	2.39	33	1.22
3/03.01.01-16	1.36	244.8	0.4736	0.32	295	27	0.63	53	0.52
4/05.21.01-12	0.45	224.8	0.4736	0.081	296	22	1.94	29	1.40
5/05.21.01-14	0.50	225.1	0.4736	0.15	296	44	0.81	47	1.04
6/11.13.00-31	0.52	227.8	0.4736	0.14	288	41	0.88	43	0.86
7/11.14.00-11	0.53	231.7	0.793	0.34	286	no shock	/	73	0.46
8/11.14.00-12	0.57	232.1	0.793	0.42	287	25	0.98	44	0.87
9/11.14.00-13	0.65	233.9	0.883	0.43	287	no shock	/	81	0.37

Capabilities of the described two-fluid model with slug recognition technique for simulations of the condensation-induced water hammer are given in Table 1, where last 4 columns show measured and calculated magnitude and time of the pressure peak. Good agreement of pressure peak and timing is seen for Cases 1, 5 and 6. Fig. 5 shows two measured and calculated pressures for the Case 1, which can be considered as a successful simulation. Secondary shock waves are seen in computation and experiment. They are caused by a classical "water column separation" mechanism.

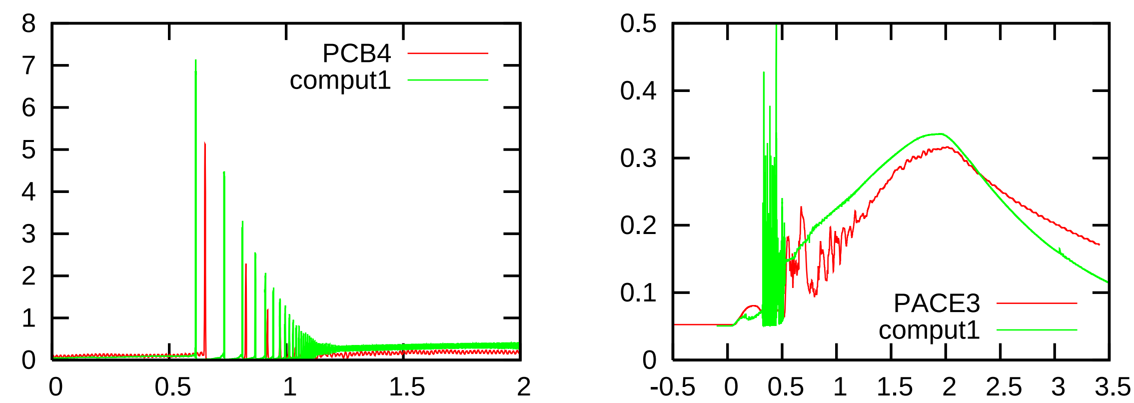

Figure 5: Pressure (MPa) vs. time (s) at the closed end (left) and in the middle of the pipe (right) of the Martin's CIWH experiment, Case 1. Red - experiment, green - computation.

Fig. 6 shows an example of a simulation of modest accuracy: Case 4. Similar pressure peak is measured and calculated, however, calculated pressure peak occurs too late. Similar results are obtained for Cases 2 and 3. The Case 3 was performed at higher initial temperature than other tests.

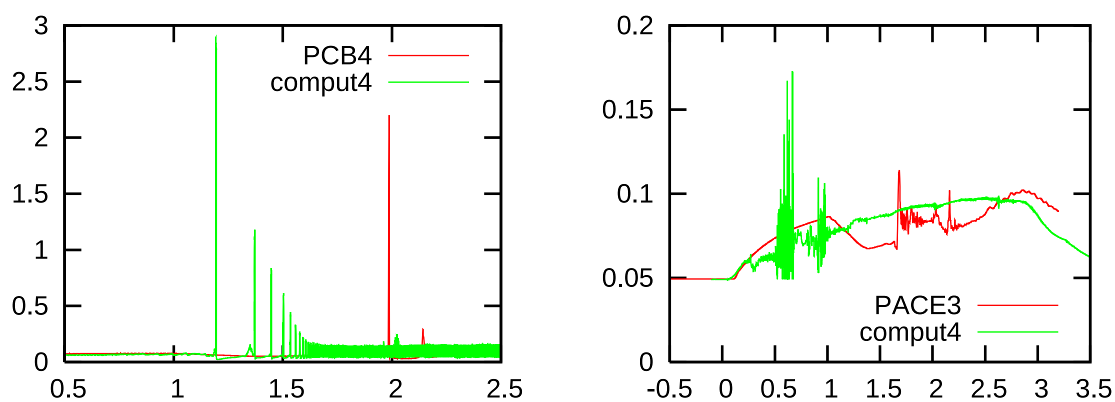

Figure 6: Pressure (MPa) vs. time (s) at the closed end (left) and in the middle of the pipe (right) of the Martin's CIWH experiment, Case 4. Red - experiment, green - computation.

The worse results are obtained for high initial vapor volume fractions. An example of poor simulation is given in Fig. 7 for the Case 7. Despite low amount of liquid, 1D two-fluid model predicts formation of the slug in all 3 Cases 7, 8, 9. Slug formation is followed by a strong water hammer, which is not seen in the measurements at all, except a pressure peak of medium magnitude in the Case 8. The problem does not stem from the inter-phase heat and mass transfer correlations but from the basic two-fluid equations and their capabilities to model stratified flows. Non-existing slug in the case of Fig. 7 simulation is predicted even with correlations for stratified flow. Pressure interface term that makes the two-fluid model to behave like a shallow water equations, is more accurate at vapor volume fractions around 0.5, where circular pipe behaves like a rectangular channel; i.e. equation (8) is derived for rectangular channel. At low (less than 0.2) or high (higher than 0.8) vapor volume fractions the pressure interface term has a different form, however, our latest simulations with interfacial pressure computed in hexagonal pipe (improved approximation of circular pipe) did not show significant improvements over results collected in Table 1 and shown in Fig. 7. Our further attempt should be upgrade of the basic two-fluid model with a term that will empirically model the break-up of the waves, which does not exist in the current model. This will prevent the formation of very narrow slugs that are being observed in current simulations at low liquid levels and are obviously not seen in the experiments.

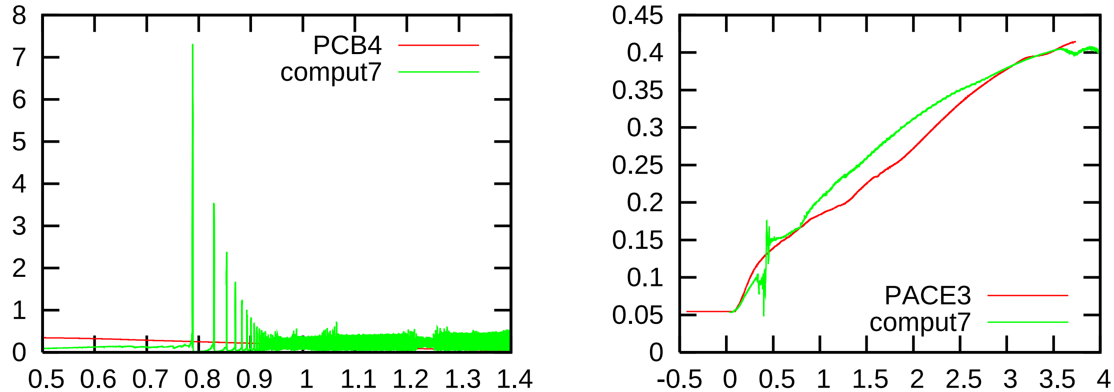

Figure 7: Pressure (MPa) vs. time (s) at the closed end (left) and in the middle of the pipe (right) of the Martin's CIWH experiment, Case 7. Red - experiment, green - computation.

All computations were performed with an input model consisting of ~170 volumes with the horizontal test section discretized in 60 volumes. Grid refinement was performed for all cases in the Table 1 with test section discretized into 120 volumes. Pressure peaks and times of the peaks obtained on the refined grid were typically up to 5% different. Comparing to the simulations of the KFKI type of CIWH, the second mechanism of CIWH turns out to be much more predictable and less sensitive on the initial and boundary conditions or modifications of the correlations. Nevertheless, even for Martin's type of CIWH, tuning of the models cannot be performed on a single experimental case. The basic nature of the phenomena is still quite stochastic and all the changes in the models are continuously tested for all 9 test cases of the Table 1.

3. Conclusion

Two types of condensation induced water hammer simulations performed with 1D computer code WAHA based on 6-equation two-fluid model are reviewed. The first type appears when the pipe filed with hot steam is slowly flooded with cold water. This type of the CIWH was shown to be a stochastic and thus very unpredictable phenomena (see also Bjorge and Griffith, 1984, Štrubelj et. al., 2010). Calculated results are compared to experimental data from Hungarian KFKI-PMK2 device. It was shown that 1D can qualitatively predicts the phenomena of the slug formation, steam bubble condensation and pressure surge. However we did not manage to accurately predict where and when the slug will form, or if the slug will form at all. Predictions of the pressure surge magnitudes is also beyond the capabilities of the applied two-fluid model.

Second type of CIWH can appear when hot gas enters a pipe that is partially filled with cold liquid. The most unstable part of the interface is always near the gas inlet into the pipe, thus, it is more or less known where the slug will appear. Experimental results for this type of the CIWH were obtained by C.S. Martin (Georgia Tech, 2007). Since the position of the slug formation is known, this type of CIWH is less stochastic and more predictable than the first type of the CIWH. Nevertheless, even for this type of water hammer, one should not expect accurate predictions of the water hammer timing or accurate peak pressures, but rather identification of the circumstances that can lead to the transient with or without water hammer.

Further work is focused on upgrade of the basic 1D two-fluid model with additional term, which will allow the tuning of the 1D two-fluid models in the transitional between stratified and slug flow regime. Such term should be able to control the speed of the slug formation and the possibility of the dissipation of the slug. We did not manage to achieve these effects with existing terms of the two-fluid models.

4. References

[1] Bartosiewicz Y., Seynhaeve J.-M., Vallée C., Höhne T., Laviéville J.-M., Modeling free surface flows relevant to a PTS scenario: Comparison between experimental data and three RANS based CFD-codes. Comments on the CFD-experiment integration and best practice guideline. Nuclear Engineering and Design, Volume 240, Issue 9, September 2010, Pages 2375-2381.

[2] Bestion D., The Physical closure laws in the CATHARE code, Nuclear Engineering and Design, 124, pp. 229-245, 1990.

[3] Bjorge R.W., Griffith P., Initiation of Waterhammer in horizontal and nearly horizontal pipes containing steam and subcooled water, ASME Journal of Heat Transfer 106, pp8350840, 1984.

[4] Carlson K.E., Riemke R.A., Rouhani S.Z., Shumway R.W., Weaver W.L., RELAP5/MOD3 Code Manual, Vol. 1-7, NUREG/CR-5535, EG&G Idaho, Idaho Falls, 1990.

[5] Issa R.I., Kempf M.H.W., Simulation of slug flow in horizontal and nearly horizontal pipes with the two-fluid model, International Journal of Multiphase Flow 29, pp 69-96, 2003.

[6] Lin P.Y., Hanratty T.J., Prediction of the initiation of slugs with linear stability theory, International Journal of Multiphase Flow 12(1), pp 79-98, 1986,

[7] Martin C. S., R. Brown R., J. Brown J., Condensation-Induced Hydraulic Shock Laboratory Study, ASHRAE 970-RP, June 2007

[8] Martin C.S. Condensation-induced water hammer in a horizontal refrigerant pipe, Proceedings of BHR Pressure Surges,, 581-589, 2004.

[9] Štrubelj L., Ézsol G., Tiselj I., Direct contact condensation induced transition from stratified to slug flow. Nucl. Eng. Des.. vol. 240, no. 2, 266-274, doi: 10.1016/j.nucengdes.2008.12.004, 2010

[10] Taitel Y., Dukler A.E., A model for predictiong flow regime transitions in horizontal and near horizontal gas-liquid flows, AICHE Journal 22, pp. 47-55, 1976.

[11] Tiselj I., Horvat A. , Černe G., Gale J., Parzer I., Mavko B., Giot M., Seynhaeve J. M., Kucienska B., Lemonnier H., WAHA3 Code Manual, Jožef Stefan Institute Report, IJS-DP-8841, 2004

[12] Tiselj I., Petelin S., Modelling of Two-Phase Flow with Second-Order Accurate Scheme. Journal of Computational Physics, vol. 136, pp. 503-521, 1997

[13] Wylie E.B., Streeter V.L., Fluid Transients, McGraw-Hill, 1978.

[14] Vallée C., Lucas D., Beyer M., Pietruske H., Schütz P., Carl, H., Experimental CFD grade data for stratified two-phase flows, Nuclear Engineering and Design, Vol. 240 (9), 2347-2356, 2010.

[15] Tiselj I. Martin C.S., Two-fluid model for 1D simulations of water hammer induced by condensation of hot vapor on the horizontally stratified flow, 7th International Conference on Multiphase Flow, ICMF 2010, Tampa, FL USA, May 30-June 4, 2010

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