Analysis of experiments on condensation induced water hammers at KGU test facility by WAHA code

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Abstract. Experiments at the KGU test facility, devoted to steam induced water hammers were analysed with the WAHA code. Test section of the KGU test facility is slightly inclined horizontal pipe of 3 m length and of 64 mm inner diameter. Subcooled water was supplied to the pipe inlet, pipe outlet was connected to separator vessel. Upper part of separator vessel was connected to steam source. Experiments were performed for different system pressure, different water subcooling and different mass flow rate of water supply. The WAHA code has been developed for simulation of condensation induced water hammers in pipelines. It is based on two-fluid approach, WAHA numerical scheme is based on Godunov numerical methods. Numerical simulations of the KGU tests revealed disagreement between numerical and experimental occurrences of water slug formations and water hammer events. Methodological calculations with variation of heat transfer to subcooled water showed, that this value significantly influences on water slug and water hammer formation.

1. Introduction

Development of some accidents or incorrect actions of personnel can lead to saturated steam and subcooled water may be in direct contact in certain elements of a nuclear power plant (NPP) [1, 2]. Under these conditions, due to the heat transfer into subcooled water from the interphase surface separating steam and water, intense steam condensation begins, which in certain situations can lead to dynamic processes that affect integrity of the installation. As a rule, such interaction of steam and water takes place on horizontal sections of pipelines with a stratified flow of steam and liquid water. Under these conditions, the formation of a vapor cavity surrounded by subcooled water is possible, which leads to condensation of the steam, a pressure decrease in the steam cavity and its subsequent collapse. Development of such process is schematically shown at figure 1. In this case, the mass of water surrounding the disappeared cavity acquires kinetic energy sufficient to produce a significant impact when it collides with an obstacle (valves, bending of the pipeline), which poses a threat to the integrity of the structure. This phenomenon, known as condensation induced water hammer, due to its importance for safety in industry, in particular for nuclear power plants, is the subject of numerous studies, starting with the classical work of Rayleigh [3]. Their rather detailed review is presented in [1,
2], we also mention [4-6] and the International Research Project within the framework of the 5 EURATOM Framework of the European Union, devoted to the study of the features of condensation induced water hammer and the development of a WAHA computer code for modeling such phenomenon [7].

![Figure 1. Schematics of condensation induced water hammer in horizontal channel](image)

Analysis of possibilities of condensation induced water hammers in the primary circuit of VVER reactors has been performed in [1, 2]. It is emphasized, that there are no conditions for condensation induced water hammers under normal VVER operation. They can occur in accidental conditions of primary circuit depressurization due to loss of coolant accidents. Several detailed scenarios of condensation induced water hammer development in VVER-1000 are described in [1, 2].

It is necessary to conclude, that despite the studies performed, a reliable analytical tool for predicting condensation induced water hammers and estimating their parameters has not yet been developed, which is explained by the complexity of the phenomenon and the variety of forms of its realization. New experimental studies and their theoretical analysis are needed. In the present work, the results of an experimental study of the interaction of subcooled water with saturated steam in a horizontal pipe at the KGU test facility, in which condensation induced water hammers were observed, and their calculation analysis with WAHA code are presented.

### 2. Description of the KGU test facility

For experimental research, KGU test facility has been constructed at Electrogorsk Research and Engineering Center on NPP Safety, which included a test section (slightly inclined horizontal pipe with an inner diameter of 64 mm and a length of 3 m), a steam generator; water and steam supply and drain lines; measuring equipment, figure 2.
At one end, the horizontal pipe was connected to a subcooled water supply line; at the other end, it was connected to a vertical separation vessel (SV). The pipe was equipped with pressure sensors P1, P2 and thermocouples T1, T2, which measure the pressure and temperature of the medium under investigation. Pressure sensors P1 and P2 (measurement frequency 1 kHz) were located on the upper surface of a horizontal pipe at a distance of 500 mm from its ends. Thermocouples T1 and T2 are installed respectively on the lower side and upper side of a horizontal pipe. The thermocouple T1 was located at a distance of 500 mm from the water supply line, and the thermocouple T2 was located at a distance of 1000 mm from the SV. To monitor the flow of incoming subcooled water, the hot junction of the T1 thermocouple was located at a distance of 10 mm from the lower pipe surface, and to monitor the flow of saturated steam, the hot junction of the T2 thermocouple was located at a distance of 20 mm from the upper pipe surface.

A steam supply line from the pressurizer of the PSB VVER integral test facility was connected to the upper part of the SV, and the condensate drain line was connected to the bottom of the SV to empty the test section before the experiment start. The SV was equipped with a level gauge. The temperature, pressure, and flow rate of the subcooled water supplied to the test section were measured with a thermocouple Tin, a pressure sensor Pin, and a flow meter Gin, respectively.

3. Experimental results obtained at the KGU test facility
It was performed about 20 runs at the KGU test facility to study condensation induced water hammers. The values if system pressure P0 were 0.6 MPa and 1.0 MPa; subcooled water flow rates were 1 t/h, 3 t/h, 5 t/h. Temperatures of subcooled water were 30 °C and 60 °C.

Figure 3 shows the readings of the sensors of the test section for the experimental regime: steam pressure in the test section 1.0 MPa, temperature of the supplied subcooled water 60 °C, mass flow rate of the supplied subcooled water 1 t/h. Such regime was performed 3 times to verify reproducibility and results of all runs are presented in figure 3. Nevertheless, that condensation induced water hammer is stochastic phenomenon, figure 3 demonstrates, that general trends of the curves are identical for all runs, and test reproducibility at the KGU test facility takes place. It is necessary to pay attention on behaviour of P2 measurements. Its values always exceed ones of pressure gauge P1, and after last water hammer P2 curves are constantly increasing with time, although there are no reasons for this. Thus P2 readings can be considered only as some indicator of water hammers.
It can be seen on figure 3 the propagation of subcooled water along a horizontal pipe, fixed by T1 sensor, filling first the lower part of the separator vessel, fixed by water level sensor, and then the horizontal pipe and the upper part of the separator vessel. Condensation induced water hammer (CIWH) with intervals of 3 - 4 seconds and with an amplitude of pressure increase of 0.6 - 1.2 MPa occurred during filling of a horizontal pipe (see P1 and P2 curves).

**Figure 3.** Sensors readings in experimental run with a water flow rate of 1 t/h, a water temperature of 60 °C and system pressure of 1 MPa
The amplitudes of pressure increase during condensation induced water hammers recorded in the experiments indicate that the magnitude of condensation induced water hammers reaches maximum values at the stage of filling the horizontal pipe. It becomes significantly lower at the stages of filling the lower and upper parts of the SV. Increasing of system pressure leads to increasing of condensation induced water hammers. Increase of mass flow rate of subcooled leads to diminishing of condensation induced water hammers.

4. Description of the computer code WAHA

For numerical analysis of the experiments performed at the KGU test facility, the WAHA code [7] was applied. This code was developed directly for the calculation of condensation induced water hammer. The code uses mathematical model of the steam-water mixture based on the two-fluid approach, in which the vapor and liquid phases are described using interpenetrating and interacting continua, for which the equations of conservation of mass, momentum and energy are formulated taking into account the interaction between the phases and the interaction of phases with the channel walls [8].

Mathematical model of the WAHA code takes into account following regimes of two-phase flow^ includes dispersed-bubbly flow, dispersed-droplet flow, dispersed-bubbly-to-droplet transitional flow, horizontally stratified flow, dispersed-to-horizontally stratified transition flow. Transition from horizontally stratified flow to dispersed flow (including single water flow and condensation induced water hammers)) is based on the criterion for critical relative velocity of phases $v_{critical}$ [9], developed on the base of Kelvin-Helmholtz instability theory

$$v_{critical} = \sqrt{g \cdot D \cdot (\rho_f - \rho_g) \cdot \left( \frac{\alpha}{\rho_g} + \frac{(1-\alpha)}{\rho_f} \right)}$$

where $g$ is gravity acceleration, m/s$^2$; $D$ is inner diameter of the tube, m; $\rho_f, \rho_g$ are densities of liquid and vapor, kg/m$^3$; $\alpha$ is vapor volume fraction.

The WAHA code employs an explicit numerical method that focuses on modeling wave processes. Numerical scheme applied in WAHA code is based on the Godunov methods i.e. high-resolution shock-capturing methods, which are widely used in aerodynamics. The numerical scheme of the WAHA code is non-conservative due to the choice of the basic variables, but it does not seem to be a big deficiency for short transients like condensation induced water hammer events.

The WAHA code was used to analyze the experiments performed at the PMK-2 test facility (Hungary) and ROSA test facility (Japan) [5, 10, 11], in which condensation induced water hammers were investigated. The results of this validation activity demonstrated good agreement between the calculated results and experimental data.

5. Results of the numerical analysis of the KGU performed experiments

The WAHA code was applied to analyze the KGU experiments on condensation induced water hammers. Initially a detailed computational nodalization scheme to approximate the KGU test section was developed. But WAHA calculation runs were emergency stopped, when subcooled water began to flow into the separator vessel. For modeling of horizontal pipe and separator vessel connection it was used “branch” model, developed in the WAHA code. This model operates without any problem, when pure liquid or pure vapor flows through the branch. But for case of two-phase flow this model fails. Developers of WAHA code emphasized in the WAHA manual [7]: “Branch model was tested and verified for the single-phase flows, but has not been tested in the two-phase flow. Thus, the model is to be used with caution in two-phase systems.”

Therefore, a simplified nodalization was developed, when only inlet vertical pipe and horizontal pipe were simulated, figure 4. Boundary condition of constant pressure was used for pipe outlet, it models separator vessel as region of constant pressure. Boundary condition of constant inlet velocity of subcooled water was used for pipe inlet. There were 48 identical computational cells for modeling.
of vertical and horizontal pipes, their length was 64 mm. Time step of numerical calculations appropriates to Courant number 0.4

![Diagram](image)

**Figure 4.** WAHA nodalization scheme.

Simulation of the KGU tests with the WAHA code revealed, that WAHA overpredicts initiation of condensation induced water hammers at the stage of separator vessel bottom part filling. WAHA predicts water slug formation and subsequent water hammer, when subcooled water only propagates through the horizontal pipe and does not enter separator vessel yet, see figure 5.

![Graph](image)

**Figure 5.** WAHA calculation of the KGU test (subcooled water temperature is 30 °C, mass flow rate is 1 t/h, system pressure is 1 MPa). It is shown distributions of liquid volume fractions (bars) and flow stratification parameter (1 full stratification, 0 – no stratification) (curves).

It can be seen from figure 5, that disturbance of the water surface is increased during water propagation, and before the outlet water slug is formed, and water hammer takes place. But in the test water hammer took place only after the moment, when water entered separator vessel. It can be suggested, that WAHA overestimates heat transfer to the water from interphase surface. Diminishing
of this heat transfer by 20% permits to condensation induced water hammers occurrence at the stage, when water enters separator vessel, see figure 6.

Figure 6. WAHA calculation of the KGU test (subcooled water temperature is 30 °C, mass flow rate is 1 t/h, system pressure is 1 MPa) for reduced heat transfer. It is shown distributions of liquid volume fractions (bars) and flow stratification parameter (1 full stratification, 0 – no stratification) (curves)

It can be seen from figure 6, that water achieves separator vessel, and only after this event water slug is formed at the end of the pipe and water hammer occurs.

6. Conclusion

In general, it can be stated that the WAHA code reproduced experiments on condensation induced water hammers, performed at the KGU test facility, relatively good. For first stage of the process (separator vessel bottom part filling) the code predicts earlier moments for water slug formation and water hammer occurrence, then in the tests. For last stage of the process (water filling of other part of the test section) WAHA does not predict water slug formation for several KGU tests. Methodological WAHA calculations showed that the possible reason for this is an insufficiently adequate WAHA description of heat transfer during steam condensation in a stratified two-phase flow, when the liquid and steam move in opposite directions.

Additional finding of our numerical study is revealing, that branch model in the WAHA code does not operate in two-phase cases.

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