Experimental and numerical study of the interaction of subcooled water with saturated steam in a horizontal pipe

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Abstract. Interaction of subcooled water with saturated steam in horizontal tube can produce so-called condensation induced water hammers, which may be dangerous for integrity of NPP equipment. This phenomenon has been investigated at the special test facility developed at Electrogorsk Research and Engineering Center. Test section of the test facility is horizontal tube of inner diameter of 64 mm and a length of 3 m. It has been performed several experimental runs, where subcooled water was supplied to the end of the tube filled by saturated steam. Another end of the tube was connected to separator vessel. System pressure, water subcooling and water flow rate were variable parameters. There were a lot of condensation induced water hammers, observed during experiments. Experimental data have been analysed with thermal-hydraulic codes WAHA and RELAP5, based on two-phase, two-fluid model.

1. Introduction

Some emergency situations or incorrect actions of personnel can lead to the fact that in certain elements of a nuclear power plant saturated steam and subcooled water may be in direct contact [1, 2]. Under these conditions, due to the heat transfer into subcooled water from the interphase surface separating steam and water, intense condensation of steam begins, which in certain situations can lead to dynamic processes that affect piping valves and equipment. As a rule, such interaction of steam and water takes place on horizontal sections of pipelines with a stratified flow of a two-phase medium. Under these conditions, the formation of a vapor cavity surrounded by subcooled water is possible, which leads to condensation of the steam, a decrease in pressure in the cavity and its subsequent collapse. 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 this phenomenon [7].

Despite the studies, 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 in which condensation induced water hammers were observed, and their calculation analysis are presented.

2. Description of the test facility

For experimental research, a test facility has been developed, which included a test section (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. 1.

![Figure 1. Scheme of the test facility.](image)

At one end, the pipe was connected to a cold water supply pipe; 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 study. 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 pipe, and the thermocouple T2 was located at a distance of 1000 mm from the SV. To monitor the flow of incoming cold 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 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. The results of experimental studies

Fig. 2 shows the readings of the sensors of the test section for one of the experimental runs (steam pressure in the test section 1.0 MPa, temperature of the supplied subcooled water 30 °C, flow rate of the supplied subcooled water 1 t/h). It can be seen the moving of subcooled water along a horizontal pipe, filling first the lower part of the SV, and then the horizontal pipe and the upper part of the 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.

![Figure 2](image)

**Figure 2.** Sensors readings in experimental run with a water flow rate of 1 t/h, a water temperature of 30 °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 in the area of the P2 sensor reaches maximum values (up to 1.2 MPa) 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. The system pressure
affects the value of condensation induced water hammers. The amplitude of pressure jumps at the system pressure in the test section of 0.6 MPa is about 0.1–0.2 MPa, and at a pressure of 1.0 MPa it is 0.6–1.2 MPa. With an increase in flow rate from 3 to 5 t/h, the amplitude of the maximum pressure increase decreases from 1.2 to 0.9 MPa, respectively.

4. Brief description of calculation codes for CIWH simulation

For mathematical modeling of the experiments performed, the WAHA [7] and RELAP5 [8] codes were used. As already noted, the WAHA code was developed directly for the calculation of condensation induced water hammer. It was used to analyze the experiments performed at the PMK-2 (Hungary), ROSA (Japan) facilities and at the test facility located at the Physics and Energy Institute [5, 9–11], in which this phenomenon was studied. These works demonstrated good agreement between the calculated results and experimental data. The RELAP5 code is one of the most popular for the analysis of thermal hydraulic processes at nuclear power plants. A huge amount of validation of this code on experimental data provides a fairly reliable simulation of unsteady two-phase processes that occur in emergency conditions. Both codes WAHA and RELAP5 have similar mathematical models 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 [12].

The largest difference between these codes is associated with numerical methods for solving the differential equations of a two-fluid model of a steam-water mixture. The RELAP5 code uses a semi-implicit difference scheme, which is quite common for such codes, which allows one to universally calculate both fast wave processes and slow convective flows. The WAHA code employs an explicit numerical method that focuses on modeling wave processes.

5. Results of the numerical analysis of the performed experiments

Using WAHA and RELAP5 codes, a number of experiments were performed numerically. It turned out that the use of a detailed computational nodalization to approximate the test section when performing the WAHA code calculation led to an emergency stop of the calculation when water began to flow into the SV. Therefore, a simplified nodalization was used when only a horizontal pipe was simulated, while the flow rate was set at the left end and constant pressure was set at the right end of the pipe. There was no such problem for the RELAP5 code, therefore, in this case, a detailed computational nodalization was used, with the help of which not only a horizontal pipe was simulated, but also a feed water supply line and a SV.

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In general, it can be stated that both codes reproduced condensation induced water hammers relatively good (in frequency and amplitude) at the stage of filling a horizontal pipe. However, at an earlier stage of the quasi-stationary water flow with free discharge into the vessel, the steam induced water hammers observed in the experiments were not reproduced in the calculations. Methodological calculations showed that the reason for this is an insufficiently adequate description of heat transfer during steam condensation in a stratified two-phase flow, when the liquid and steam move in opposite directions

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