Research of condensation induced water hammer under filling a horizontal pipe with subcooled water

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Abstract. Experiments at the KGU test facility, devoted to condensation induced water hammers (CIWH) 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 performed experimental study of CIWH showed that in the investigated range of parameters, the development of CIWH occurs in different ways. At the stage of water propagation along the filled with steam horizontal pipe, water hammer was not observed. At the stage of free drainage of water from the outlet end of the pipe, water hammer was realized only when the water was sufficiently subcooled. At the stage of water level rise in the horizontal pipe, water hammer occurred in all tests. At the last stage of filling the upper part in the separation vessel, there were small water hammers due to the collapses of the remaining steam bubbles. Numerical modelling of these experiments with the WAHA code revealed the shortcomings of the interphase heat transfer model developed for this code, which have a noticeable effect on the numerical solution.

1. Introduction
Condensation induced water hammers (CIWH) in pipelines, arising from the contact of an isolated vapor volume with the surrounding water, subcooled to saturation temperature, systematically occur during the operation of a nuclear power plant (NPP). CIWH is dangerous to the NPP staff and damaging the integrity of the equipment [1-3]. As a rule, the cause of their occurrence is equipment failure or personnel errors [1].

Experimental studies of CIWH in horizontal channels [4-9] allowed to establish a qualitative picture of this phenomenon. At the interface of the initially stratified flow of steam and water, with an increase in the relative velocity of the phases, a growing wave begins to form, the crest of which reaches the "ceiling" of the pipe. Water overlaps the full cross-section of the pipe. A water slug is
formed. Because of this, a closed steam cavity arises, in which steam, "cut off" from a steam source located "upstream" of the steam flow, begins to condense on the surface of the water subcooled to saturation temperature, which leads to a pressure decrease in the cavity. As a result, a pressure drop arises on the edges of the water slug, which moves it and accelerates it to such velocities at which, during the collision of the slug with an obstacle, significant water hammer occurs.

Basically, all researchers agree that the reason for the growth of the wave crest is Kelvin-Helmholtz instability. Above the wave crest, steam flows with increased velocity due to a decrease of steam flow cross section, which leads to a pressure decrease and suction of the wave crest upward. Based on this approach, the well-known Taitel-Dukler criterion for the formation of a liquid slug from a stratified flow [10] was obtained, which is used in many system thermalhydraulic codes of the RELAP5 type [11].

However, the appearance of the wave itself can have the nature of gravitational waves, when the initial disturbance of the liquid after entering the horizontal channel transforms to a single gravitational wave (soliton). A detailed discussion of studies of the mechanisms of wave crest growth and the formation of a liquid slug in a horizontal channel is contained in review [12]. A number of more recent works in this direction can be mentioned [13-16].

Condensation of vapor on the surface of subcooled water under stratified flow of vapor and liquid is another process that radically affects the development of CIWH. The rate of vapor condensation determines its flow rate on the water surface and, accordingly, the velocity of steam supply from its source to the stratified flow region. Thus, the rate of vapor condensation determines the velocity of vapor flow over the water surface, which directly affects the growth of the wave crest and the formation of a water slug. In addition, after the formation of a water slug in the channel and an isolated vapor cavity, this process (condensation of vapor on the water surface under their stratified arrangement) determines the rate of pressure decrease in this cavity and thereby the acceleration of the water slug and the force of the water hammer.

In [17], the results of 6 independent experimental studies of heat transfer during steam condensation under stratified two-phase flow were compared, and it was shown that the values of the heat transfer coefficient are in the range of 1-30 kW/(m²°C), depending on the parameters of the experiments. At the same time, discrepancies in the values of this value obtained for close system parameters are noted several times. Approximately the same order of discrepancies is stated in [18], where a comparison was made of correlations for heat transfer in two-phase stratified flows used in various system thermalhydraulic codes.

Present two-fluid models of a steam-water mixture, implemented in system thermalhydraulic codes, are able to simulate the development of CIWH: a stratified flow of saturated steam and subcooled water in a horizontal channel, subsequent formation of a wave crest, a water slug, an isolated vapor cavity, a pressure decrease in this cavity, accelerated motion a water slug and its collision with an obstacle (pipe bend, valves, etc.), leading to a water hammer. However, the first-order numerical schemes used in these codes require a very detailed computational nodalization in order to resolve the fine wave processes accompanying the development of CIWH. The WAHA code [19], specially designed for modeling CIWH, is devoid of this drawback, this code uses second-order TVD schemes focused on calculating wave processes. However, its application to the study of CIWH often leads to contradictory results, as, for example, in [20], where the boundaries of the occurrence of CIWH in horizontal pipes were calculated. This is due to the substantially nonlinear nature of this phenomenon, first of all, with the growth of the wave crest and the formation of a water slug.

In this work, the experimental study of CIWH in a horizontal pipe filled with saturated steam, when subcooled water is supplied to the pipe, has been carried out. The successive stages of the process have been studied: the propagation of the water front, the stratified flow of water with free drainage, the rise of the water level in the pipe up to the complete flooding of the pipe. At each stage, the features of CIWH were investigated. Experimental results were analyzed using the WAHA code.

2. Description of the KGU test facility
For CIWH experimental studies, KGU test facility has been constructed at Electrogorsk Research and Engineering Center for Nuclear Power Plants 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 1.

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. 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 separation vessel, and the condensate drain line was connected to the bottom of the SV to empty the test section before the experiment start. The separation vessel 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 $T_{in}$, a pressure sensor $P_{in}$, and a flow meter $G_{in}$, respectively.

As a result of such an organization of the water flow, successive stages of the pipe filling have been observed in the horizontal pipe: 1) the propagation of the water stream along the initially steamed pipe, 2) the quasi-stationary flow of the water "river" along the bottom surface of the pipe with a free discharge into the lower part of the separation vessel, 3) the level rise in the horizontal pipe after filling the lower part of the separation vessel, 4) raising the level in the upper part of the separation vessel.

3. Experimental results
A series of experiments with a water flow rate of 1 t/h was carried out at the KGU test facility. The vapor pressure was 0.6 and 1 MPa. The water supply temperature was 30 and 60 °C.
Figure 2 shows the end times of the fill stages for all of these experimental regimes. It can be seen that the first stage (the initial propagation of water through the pipe) was 4-5 seconds, no water hammer was observed at this stage.

The second stage (free water discharge into the separation vessel) ended at 13-15 seconds after water supply start for regimes without water hammer at this stage and at 23-28 seconds after water supply start for water hammer regimes. Thus, the duration of the second stage was from 10 to 22 seconds. Such a wide range in the filling time of the lower part of the separation vessel is due to the fact that during water hammer, a significant part of the water is thrown to the inlet of the pipe, and its discharge into the separation vessel is delayed due to this. Additional time is required for the water to reach the separation vessel again. As a result, in the experimental regimes with water hammer at this stage, the filling of the lower part of the separation vessel was delayed, and the next stage of filling the horizontal pipe was reduced.

![Figure 2. End time of the stages of filling the test section](image)

The third stage (filling the horizontal pipe) for all regimes ended at approximately the same time, 45-46 seconds after the start of water supply. This is due to the fact that the same flow rate of the supplied water in all regimes provided the same filling rate of a fixed volume (the lower part of the separation vessel and the horizontal pipe). The redistribution of water after water hammer, naturally, did not affect the rate of filling of this entire volume. In all regimes, water hammer were recorded at this stage.

The fourth (final) stage in all regimes also ended at about the same time - by the time moment 48-51 seconds. The difference is associated with slightly different actual water flow rates in these regimes. Small water hammers were also observed at final stage, apparently produced by the collapses of bubbles remaining in the horizontal pipe.

As already noted, at the second stage in a number of regimes, water hammers were observed. It was found that water hammer occurs both at a pressure of 1.0 MPa and 0.6 MPa under the condition that the subcooling of the supplied water is greater than 121.5 °C, as shown in Figure 3.
Thus, at sufficiently large subcooling of water in the experiments at this stage, CIWHs were
observed, which is explained as follows. Under the regime parameters of this series of experiments, a
stratified countercurrent two-phase flow is realized in a horizontal pipe, since in these experiments the
Froude number for a water flow $Fr = \frac{V}{\sqrt{g \cdot D}}$ was of the order of 0.1, which indicates the stratified
two-phase flow \[21\]. As the subcooling of water increases, steam condensation on the water surface
increases, which leads to an increase of steam velocity and the appearance of waves at water surface.
Wave crests increase, and a water slug is formed, cutting off the vapor region above the water surface
from the “steam” part of the horizontal pipe. As a result of steam condensation, a pressure decrease
occurs in this isolated steam region. The water slug moves to the left end of the pipe, producing a
water hammer when it collides with water near the left end of the pipe.

4. Numerical modelling of experiments with WAHA code
Numerical simulation of the experiments performed at the KGU test facility using the WAHA code
was carried out. Initially the developed nodalization scheme of the test section included: inlet pipe for
water supply to the horizontal pipe, the horizontal pipe itself, a vertical separation vessel attached to,
the horizontal pipe. The upper end of the separation vessel was connected to the boundary condition
of constant steam pressure. Unfortunately, this nodalization led to the termination of the calculation when
the flow of water began to enter the separation vessel. This corresponded to the information in the
code manual that the code was not verified for the case when two-phase mixture flows through the
“tee” element (which was used in this nodalization scheme to connect the horizontal pipe to the
separation vessel). This restriction of the WAHA code prevented numerical simulation of the full
experiment from the first stage to final one.

Two different nodalization schemes were used in the calculations. The first scheme (Figure 4) was
used for numerical simulation of the first two stages of the experiment. The size of the computational
cell was 32 mm (half the pipe diameter), the Courant number, which determines the time step, was 0.3.
Water was supplied through a vertical pipe, simulated by 4 cells of the same length. At the right end of
the horizontal pipe (that connects to the separation vessel) a constant pressure condition was set.

Figure 4. The first nodalization scheme of the test section of the KGU test facility

Variation of time step and computational cell size has confirmed that numerical solution does not
depend on these numerical parameters for values, used in our calculations \[18\].

The second nodalization scheme (Figure 5) was used to simulate the third and fourth stages of the
experiment. In comparison with the first scheme, in this case, the horizontal pipe was extended into
two cells (approximation of a part of the separation vessel volume opposite the horizontal pipe) and
connected to a vertical pipe approximating the upper part of the separation vessel. At the upper end of this vertical pipe, a constant pressure condition is set.

Numerical modeling by the WAHA code of the first two stages showed that the code qualitatively correctly describes the propagation of water through the steamed pipe, the formation of a wave crest, the formation of a water slug and the subsequent water hammer. However, the code models processes after the water hammer incorrectly. Let us consider this on the example of the calculation of the experimental regime at a system pressure of 1 MPa and a temperature of the supplied water of 30 °C.

![Figure 5](image.jpg)

**Figure 5.** The second nodalization scheme of the test section of the KGU stand with partial modeling of the separation vessel

Figure 6 shows the distributions of the water volume fraction at successive moments of time preceding the first water hammer and during the water hammer. It is clearly seen how the wave crest is formed, increases in size, and covers the full section of the pipe. After that, the water slug quickly moves to the left end of the pipe (due to the pressure difference at its sides) and produces the first water hammer.

![Figure 6](image.jpg)

**Figure 6.** The distribution of water volume fraction before and during the first water hammer
Further evolution of the flow is shown in Figure 7. It follows from this figure that in the calculation after the first water hammer, water does not spread out as long developed tongue. Water is localized in the left part of the pipe. From the outlet end of the pipe, water practically does not discharge, which does not correspond to the experimental data, which recorded a rise of the water level in the separation vessel.

![Figure 7. Distribution of water volume fraction after the first water hammer](image)

Figure 8 shows the calculated pressure histories at the left end of the pipe and at the point at which the P1 pressure transducer is located.

![Figure 8. Time dependences of pressure at the left end of the pipe (cell 5) and at the location of the P1 sensor (cell 20)](image)

As can be seen from Figure 8, at the left end of the pipe, the pressure rises to 60 MPa. At the same time, the calculated pressure at the point of location of the P1 sensor is 2.7 MPa, which corresponds in order of magnitude to the water hammer observed in the experiment. As the pipe is further filled, water hammer do not appear in the calculation, since there is no spreading of water as long developed tongue, and the conditions for their occurrence are not realized.

The study of the features of numerical modeling by the WAHA code of the processes accompanying CIWH in horizontal channels revealed a significant effect of the model of interphase heat transfer. The WAHA code considers two regimes of two-phase flow: 1) horizontally stratified and
2) dispersed. The second regime essentially includes several sub-regimes (bubble, dispersed-droplet, single-phase liquid or vapor flow) with corresponding correlations for interfacial friction and heat transfer. In particular, the movement of a water slug in the channel, which leads to the water hammer, is considered by the code as dispersed two-phase flow.

In the WAHA code the horizontally stratified regime and the dispersed regime are separated by the transition area (transition regime), in which the interfacial friction and heat transfer are calculated by interpolation procedure between the dispersed regime and the horizontally stratified one.

Under modeling the formation of a water slug from a stratified flow, the WAHA code makes a transition from considering the two-phase flow as horizontally stratified flow to considering the two-phase flow as dispersed flow. In this case, during a certain time period, when the wave crest grows immediately before the formation of a water slug, the two-phase flow regime is interpreted as a transition one. During this period the strong influence of the heat transfer model on the obtained numerical solution takes place.

As already noted, for the transition flow regime, interfacial friction and heat transfer are calculated using interpolation. First, it is assumed that all the water in the considered computational cells in the region of the growing wave crest is in the form of a layer lying on the bottom surface of the horizontal pipe (stratified flow), and in accordance with this flow configuration, the characteristics of interfacial friction and heat transfer are calculated. Then it is assumed that all the water in these cells is in the form of droplets surrounded by steam (dispersed flow), and the characteristics for this configuration are also calculated. Then linear interpolation is performed. The interpolation point is determined by the deviation of the relative velocity of the phases from the critical velocity at which the formation of a water slug occurs. Since the surface area of the droplets is orders of magnitude larger than the surface area of the water in the stratified case, the interpolation procedure leads to a sharp increase in heat transfer from the interface to the water, intensive steam condensation, and a local pressure decrease in this region.

Such, in essence, an artificial significant overestimation of heat transfer to water leads to a distortion of the numerical simulation of the processes under study; in the calculations, deeper pressure decrease in the formed isolated steam cavity and stronger water hammers are observed in comparison with the experiment. In addition, in the numerical modeling of the processes after the first water hammer, as already noted, subsequent water hammers are not reproduced, since the stratified flow in the entire region is not modeled, only steep phase boundary is obtained in the calculations. The nature of this calculated flow with steep phase boundary is also associated with the application of the model of interphase heat transfer in a dispersed regime to describe heat transfer in the transition area.

The calculations have shown, that after the first water hammer in the computational cells, where the void fraction is low, calculated flow parameters are such that the code considers the two-phase flow in these cells as a flow in a transition regime, including interphase heat transfer in dispersed regime. Therefore, intensive heat transfer into water, steam condensation and local pressure decrease take place here, which "attracts" water to this location and does not allow it to spread out in the form of a stratified flow.

5. Conclusion
The performed experimental study of CIWH showed that in the investigated range of parameters, the development of CIWH occurs in different ways. At the stage of water propagation in steamed horizontal pipe, water hammer was not observed. At the stage of free drainage of water from the outlet end of the pipe, water hammer was realized only when the water was sufficiently subcooled. At the stage of the water level rise in the horizontal pipe, water hammer occurred in all tests. At the last stage of filling the upper part of the separation vessel, there were small water hammers due to the collapses of the remaining steam bubbles.

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