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Method for determination of water hammer conditions and consequences in pressurizers of nuclear reactors

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Abstract: Results of known experimental and computed studies of conditions for water hammers (WHs) in reactor pressurizers are analyzed. It is found that when emergency opening of pilot-operated safety valves of the pressurizers of nuclear reactors happens, WHs can be generated on pressurizer elements, and amplitudes of hydrodynamic load pulses significantly override the limiting values. An original method for determination of the WH conditions and consequences in the case of emergency filling of the pressurizers of nuclear reactors is proposed. Unlike the traditional Joukowski formula, the presented method considers the key features and effects of the WH conditions and consequences in the pressurizers of nuclear reactors. The results of computer modeling of the maximum amplitudes of a pressure pulse of WHs using the presented method are in satisfactory agreement with Korolyev's experiments on the pressurizer model of nuclear reactor. The proposed method is universal for all types of water-cooled nuclear reactors (including the Akkuyu reactor plants). Variation calculations using the presented method have found that a considerable increase in total hydraulic resistance of internal elements can be an effective action to prevent WHs in the pressurizers of nuclear reactors.

Key words: Water hammer, pressurizer, safety, nuclear reactor

1. Introduction

The pressurizer is a safety-related system in nuclear power plants with nuclear reactors, and it is designed to generate pressure in a reactor loop when the reactor plant is started up, to hold pressure within the prescribed limits in the normal operational modes and when the reactor is shut down, and to limit the pressure fluctuations in the transitional modes in reactor plants.

In the case of malfunction and accidents, the pilot-operated safety valves (POSVs) of the pressurizer provide pressure release into a reactor loop when the limiting values are exceeded and management of accident processes in the "release - feed" mode of a reactor loop.

The provided depressurization of the pressurizer in the case of malfunction and accidents defines the possibility of the water hammers (WHs) on the pressurizer's body and elements. WHs are followed by high-amplitude hydrodynamic loads on the elements of the pressurizer system that can exceed limiting values and lead to inadmissible damage to the pressurizer's elements (especially in the junction of branch pipes and unions) under certain conditions. Thus, in case of WHs at intensive filling of the pressurizer, the experimental pressurizer analogue stands have registered pressure pulses with amplitudes that twice exceeded normal pressure in the

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equipment [1–3]. In full-scale pressurizers of nuclear reactors, we can expect still greater relative amplitudes of WH pressure pulses, as in the case of emergency opening of the pressurizer's POSVs, the pressurizer is filling with significant differential pressure to environment.

For the determination of the maximum amplitudes of WH pressure, ΔP_{gm}, the known Joukowski formula [2], is traditionally used for different systems and equipment [4,5]:

$$\Delta P_{gm} = \rho \Delta \nu c, \tag{1}$$

where ρ is the flow density, $\Delta\nu$ is the change of flow rate before and after WH, and c is the sonic speed in the equipment/pipeline environment.

The authors of [3] also applied Eq. (1) to assess ΔP_{gm} for filling of the VVER-440 pressurizer experimental model. However, such an approach is not well substantiated for modeling of WH conditions and consequences in full-scale pressurizers of nuclear reactors, as Eq. (1) does not consider specific features or effects in the case of WH generation (e.g., an operating filling level of the pressurizer, considerable differential pressure in the pressurizer and containment in the case of WHs caused by opening of the pressurizer's POSVs, hydraulic characteristics of the elements of pressurizer system, or the coolant charging in the pressurizer).

Therefore, the development of a method for determination of WH conditions and consequences in the case of an intensive filling of a pressurizer is an important problem.

2. Basic provisions of the method for determination of WH conditions and consequences in the case of emergency filling of the pressurizer

The design model of the WH conditions in pressurizers of nuclear reactors is given in Figure 1.

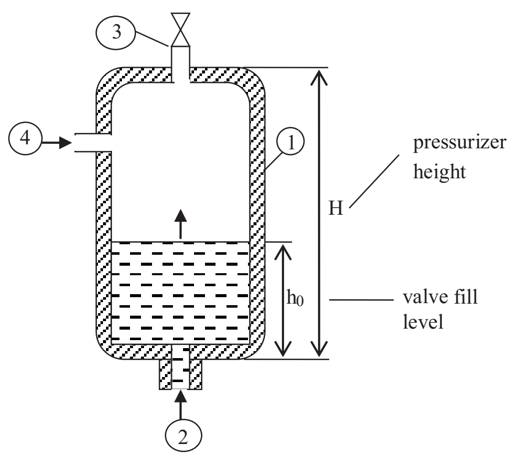


Figure 1. Design model of the WH conditions in the case of filling of the pressurizer of a nuclear reactor: 1 - pressurizer; 2 -reactor loop; 3 - pressurizer s POSV; 4 - coolant charging system of pressurizer.

The basic provisions and assumptions of the design model are as follows:

1) Filling of the pressurizer can result from overcharging of a reactor loop by the relevant systems G_b and/or emergency opening of the pressurizer's POSVs and/or realizing of the "release - feed" mode to manage accident processes.

2) Nonisothermality of the processes is conservatively negligible.

3) The amplitude of the pressure pulse at the WH is determined from the condition for the transition of the kinetic energy of the flow deceleration to the energy of the pressure pulse of the WH.

4) It is assumed that the pressurizer is a regular cylinder with length H and throat area (as shown in Figure 1).

5) The constructional and technical and hydraulic characteristics of full-scale pressurizers of nuclear plants were accepted according to [6].

The whole generating process of WH conditions is separated into two nonuniformly time scaled stages: the stage of filling of pressurizer with the coolant t and the stage of interaction between a WH pulse and the pressurizer's inner surface t_c.

Taking into account the accepted assumptions, in the first stage $(0 \leq t \leq t)$ the balance equation of mass of the pressurizer's steam volume and the motion equation of coolant level in pressurizer is:

$$\Pi_\kappa \frac{d}{dt}\left[\rho_v(H-h)\right] = -G_\kappa - G_f - \Delta G_b, \tag{2}$$

$$\frac{d}{dt}(hG_\kappa)^2 = (P_\kappa - P_0)\Pi_\kappa - \frac{\xi_\kappa}{2}\frac{G_\kappa^2}{\rho\Pi_\kappa} - \rho\Pi_\kappa g h, \tag{3}$$

$$G_f = \Pi_f\sqrt{\frac{2(P_\kappa - P_0)\rho}{\xi_f}}, \tag{4}$$

$$\Delta G_b = G_b\frac{i_v - i_b}{i_b}. \tag{5}$$

Under initial conditions:

$$G_\kappa(t=0) = 0; \qquad h(t=0) = h_0. \tag{6}$$

Necessary condition for a WH when the pressurizer is filling:

$$h(t = t_\kappa) = \kappa. \tag{7}$$

Taking into account the accepted assumptions, in the second stage $(0 \leq t \leq t_c)$, the equation of conservation laws under the necessary condition of Eq. (7) is:

$$H\Pi_\kappa\frac{d\rho}{d\kappa}\frac{d\Delta\kappa_g}{dt} = G_\kappa - G_f, \tag{8}$$

$$H\frac{dG_\kappa}{dt} = -\Delta\kappa_g(\Pi_\kappa - \Pi_f), \tag{9}$$

$$\frac{d}{dt}\left(\frac{G_\kappa^2}{2\rho\Pi_\kappa} + \rho\Delta i_g\right) = 0, \tag{10}$$

where t is process time; ρ_v and ρ are the steam and coolant density, respectively; h is the coolant level height in the pressurizer; G_k is the coolant mass flow in the pressurizer; G_f is the mass flow through the pressurizer's

POSVs; and $_0$ are the pressures in the coolant and containment, respectively; ξ is the total coefficient of hydraulic resistance in the pressurizer; ξ_f is the coefficient of hydraulic resistance of the pressurizer's POSVs; $_f$ is the throat area of the pressurizer's POSVs; i is the specific enthalpy (per mass unit); G_a is the rated flow of the coolant through the reactor core; and ΔP_g and Δi_g are the pressure and enthalpy pulse in the WH zone, respectively.

Eqs. (2)–(10) are in criteria (dimensionless) format:

$$\frac{d}{dt_1}\left[\rho_v(1-h)\right] = -\mathrm{K}_1 - \mathrm{K}_2 - G_\kappa, \tag{11}$$

$$\frac{d}{dt_1}(hG_\kappa) = \mathrm{K}_3 - \mathrm{K}_4 G_\kappa^2 - \mathrm{K}_5 h, \tag{12}$$

$$\mathrm{K}_7 \frac{d\rho}{dP}\frac{d\Delta P_g}{dt_2} = G_\kappa(h=1) - \mathrm{K}_1, \tag{13}$$

$$\mathrm{K}_8 \frac{dG_\kappa(h=1)}{dt_2} = -\mathrm{K}_3(1-\Pi_f), \tag{14}$$

$$\frac{d}{dt_2}\left[\frac{G_\kappa^2(h=1)}{\rho}\right] = -\frac{d}{dt_2}\left(\rho\frac{di}{dP}\Delta P_g\right), \tag{15}$$

$$G_\kappa(t_1=0) = 0; \quad h(t_1=0) = \mathrm{K}_6, \tag{16}$$

where:

$$\mathrm{K}_1 = \frac{\Pi_\kappa}{G_\kappa}\sqrt{\frac{2(P_\kappa - P_0)\rho_v}{\xi_f}}; \quad \mathrm{K}_2 = \frac{G_b}{G_\kappa}\frac{i_v - i_b}{i_b};$$

$$\mathrm{K}_3 = \frac{\Pi_\kappa^2(P_\kappa - P_0)\rho_\kappa}{G_\kappa^2}; \quad \mathrm{K}_4 = \frac{\xi_\kappa}{2}; \quad \mathrm{K}_5 = \frac{\rho_\kappa^2\Pi_\kappa^2 Hg}{G_\kappa^2};$$

$$\mathrm{K}_6 = \frac{h_0}{H}; \quad \mathrm{K}_7 = \frac{\rho\kappa\Pi_\kappa}{G_\kappa}; \quad \mathrm{K}_8 = \frac{G_\kappa\kappa}{\kappa_\kappa\Pi_\kappa};$$

$$\rho = \frac{\rho}{\rho_\kappa}; \quad t_1 = \frac{tG_a}{\rho_\kappa H\Pi_\kappa}; \quad h = \frac{h}{H}; \quad G_\kappa = \frac{G_\kappa}{G_\kappa}; \quad \Pi_f = \frac{\Pi_f}{\Pi_\kappa};$$

$$i = \frac{i\rho^2\Pi_\kappa^2}{G_\kappa^2}; \quad P = \frac{P}{P_\kappa}; \quad t_2 = \frac{tc}{H}; \quad \Delta P_g = \frac{\Delta P_g}{P_\kappa};$$

where c is the speed of disturbance propagation (sonic speed) in the metal of the pressurizer's inner surface.

The maximum amplitude of a WH pressure pulse is:

$$\Delta P_{gm} = \int_0^1 \frac{d\Delta P_g}{dt_2}\left(h=1;\mathrm{K}_1;...;\mathrm{K}_8\right)dt_2. \tag{17}$$

Generally, Eqs. (11)–(17) can be solved by numerical methods.

Unlike the traditional Joukowski formula of Eq. (1), the found solution of Eq. (17) considers the background of generating WH conditions in the pressurizer (K_1, ..., K_6), and also the effects of direct generating and consequences of a WH pressure pulse in the case of a spontaneous (sharp) flow stagnation against the inner surface of the pressurizer body (Eqs. (7) and (8)) (K_7, K_8).

3. Analysis of the results of the computed modeling

The known experimental data of Korolyev et al. [3] on the VVER-440 pressurizer model were used to verify the presented method for the determination of the WH conditions and parameters in the pressurizer. Figure 2 presents the experimental data on the maximum WH amplitude ΔP_{gm} [3] for different lock diameters of the pressurizers of nuclear reactors' models (pressurizer's POSV simulator) and the relevant calculations for Eqs. (1) and (17). The presented results show that calculations for the Joukowski formula of Eq. (1) have understated values of ΔP_{gm} versus the experimental data, and the solutions of Eqs. (11)–(17) have satisfactory conservative estimates.

For the computed modeling of WHs in a full-scale VVER pressurizer, the estimate disarrangement of ΔP_{gm} for Eqs. (1) and (17) can be even more considerable as differential pressures in the pressurizer and environment are two orders more under natural conditions than in the experimental model.

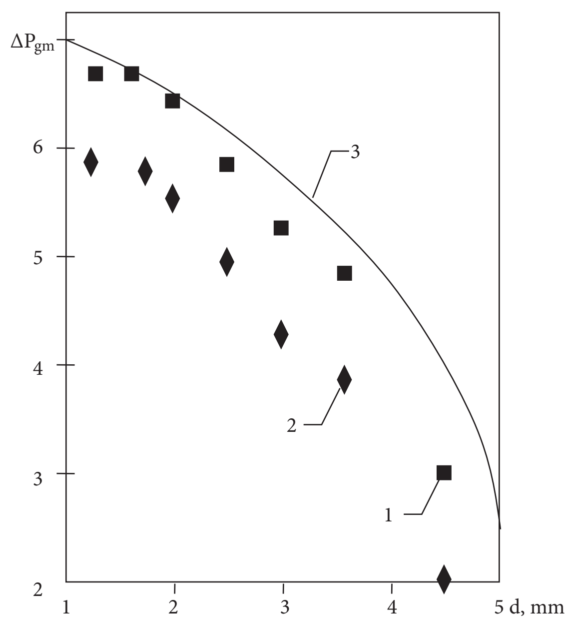
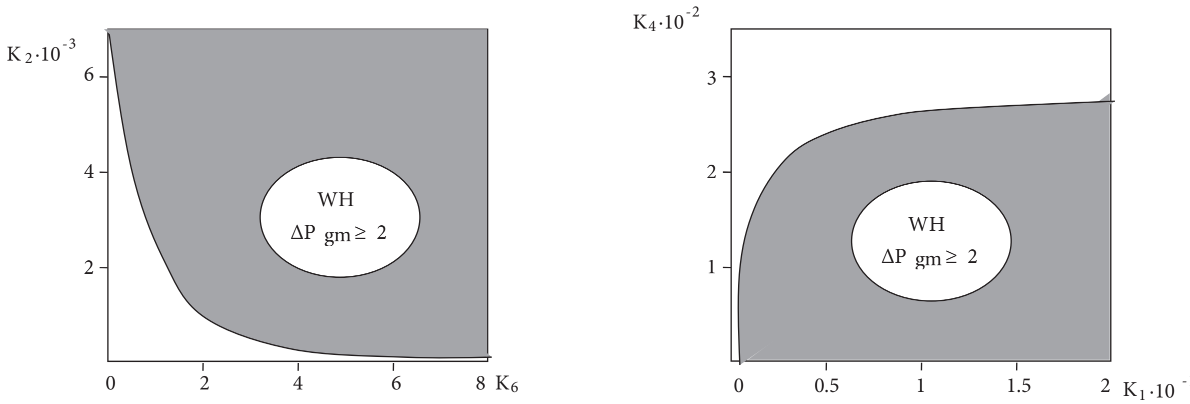


Figure 2. Maximum WH amplitudes when the VVER-440 pressurizer experimental model is filling depending on lock diameter d (pressurizer s POSV simulator): 1 – experiment; 2 – calculation for Eq. (1); 3 – calculation for Eqs. (11)–(17).

The main results of the numerical integration of Eqs. (11)–(17) by the Runge–Kutta method for a full-scale VVER-1000 pressurizer are presented in Figure 3.

As a result of variation calculations with a possible range of criteria K_1, ..., K_8 it was found that K_1, K_2, K_4, K_6 are the key criteria of change of the WH conditions and amplitudes of the WH pressure pulses ΔP_{gm} at a fixed differential pressure in the pressurizer and containment.

Figure 3a presents the computed values of the WH area boundaries for $\Delta P_{gm} \geq 2$ in the format of the key criteria K_2 and K_6, reflecting an initial filling level of the pressurizer with the coolant of a reactor loop



a) WH area boundaries in a format of K_2 and K_6

b) WH area boundaries in a format of K_1 and K_4

Figure 3. WH area boundaries in the format of the key criteria: a) WH area boundaries in the format of $\mathbf{?}_2$ and $\mathbf{?}_6$, b) WH area boundaries in a format of $\mathbf{?}_1$ and $\mathbf{K}_4$.

and charging systems. The results in Figure 3a show that the initial level of the coolant in pressurizer h_0 has the greatest influence on the WH conditions (with other factors being equal): when $K_{\mathbf{6}} = h_{\mathbf{0}}/H \geq 0.7$, high-amplitude WHs in the pressurizer are generated regardless of the rate of opening of the pressurizer's POSVs. It should be noted that the filling level of the pressurizer is $h_0/H \approx 0.7$ in a rated operating mode of the reactor. For the pressure fluctuations in a reactor loop, this filling level can be even higher. Thus, when the pressurizer's POSV is opened emergently there are prerequisites for critical WHs (for reliability) on the pressurizer elements. WH generation can also prevent the necessary closing of POSVs at pressure release and loss of the coolant in a reactor loop. Such an emergency effect of not closing the POSVs and its consequences took place during the "hot shutdown" tests of the pressurizer's POSVs at Rivne-4 in 2009.

The "hot shutdown" tests for opening and closing of the pressurizer's POSVs are usually carried out at initial filling levels of pressurizer $h_{\mathbf{0}}/H = 0.5$–0.6 after an overhaul of the system. Perhaps, therefore, WHs could not be observed during the tests for opening and closing of the pressurizer's POSVs as there was no full filling of the pressurizer (as shown in Figure 3a).

Figure 3b presents the computed values of the WH area boundaries for $\Delta P_{gm} \geq 2$ in the format of the key criteria $K_{\mathbf{1}}$ and $K_{\mathbf{4}}$, reflecting the hydraulic characteristics of the pressurizer system. The results in Figure 3b show that the total hydraulic resistance of pressurizer ξ affects the generating of high-amplitude WHs in the pressurizer. When great values of ξ are reached "artificially" (as shown in Figure 3b), high-amplitude WHs can be prevented at a different rate of opening of the pressurizer's POSVs and without great charging of the pressurizer.

Thus, the presented results of the computer modeling show that increasing the total hydraulic resistance of the flow path of the pressurizer is the most effective action to prevent high-amplitude WHs in the pressurizer.

4. Conclusions

First, the results of the known experimental and computed studies of conditions for WHs in the reactor pressurizers were analyzed. It was found that when emergency opening of POSVs of the pressurizer of a nuclear reactor happens, WHs on pressurizer elements can be generated, and amplitudes of hydrodynamic load pulses significantly override the limiting values. The proposed method is universal for all types of water-cooled nuclear reactors (including the Akkuyu reactor plants).

Second, the original method for the determination of WH conditions and consequences in the case of emergency filling of the pressurizers of nuclear reactors is proposed. Unlike the traditional Joukowski formula, the presented method considers the key features and effects of the conditions and consequences of WHs in the pressurizers of nuclear reactors.

Third, the results of the computer modeling of the maximum amplitudes of a pressure pulse of WHs using the presented method are in satisfactory agreement with Korolyev's experiments on the VVER-440 pressurizer model.

Finally, variation calculations using the presented method have found that considerable increase in total hydraulic resistance of internal elements can be an effective action to prevent WHs in the pressurizers of nuclear plants.

4. Nomenclature

ΔP_{GM}	Maximum amplitudes of water hammer (WH) pressure
ρ	Flow density
$\Delta\nu$	- Change of the flow rate before and after WH
C	Sonic speed
T	Process time
ρ_V , ρ	Steam and coolant density
H	Coolant level height in the pressurizer
G_K	Coolant mass flow in the pressurizer
G_F	Mass flow through the pressurizer s pilot-operated safety valves (POSVs)
ρ_f , ρ_0	Pressure in the coolant and containment, respectively
ξ_f	Total coefficient of hydraulic resistance in the pressurizer
ξ_F	Coefficient of hydraulic resistance of the pressurizer s POSV
η_F	Throat area of the pressurizer s POSVs
i	Specific enthalpy (per mass unit)
G_A	Rated flow of the coolant through the reactor core
ΔP_G , ΔI_G	Pressure and enthalpy pulse in WH zone, respectively
C	Speed of disturbance propagation (sonic speed) in metal of a pressurizer s inner surface

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