Research relevance. Increasing the reliable operation of thermal and nuclear power plant pumps represents a high relevance task for ensuring safe NPP operation. A large number of scientific studies has been devoted to the increase in the reliability of power system pumps, being aimed primarily at developing more reliable and improved pumping equipment, upgrading pumping system individual components, reducing their vibration level, with the increase of steady performance level, qualifying pumps’ performance in accident conditions etc. [1–12].

In analyzing the reliability probabilistic indicators, given in the Safety Analysis Reports of Ukrainian nuclear power plants (NPP), for WWER-1000 NPP active safety system (ASS) components, the study showed that the least reliable ASS components are pumps and valves, and the greatest probability of failure takes place in pump start-up. Therefore, the issues of increasing the ASS pumps’ reliable operation are relevant for ensuring the required safety level of WWER-1000 NPPs.

Assessing the possible reasons for the relatively low reliability of ASS pumps, we consider among most probable the hydraulic impacts (HI) on pumps’ operating components in transient and operating modes. The HI is accompanied by impulse hydrodynamic impact on equipment and local hydraulic resistances of pipeline systems. At critical hydraulic impacts (CHI) the failure of respective equipment (including pumps) occurs.

In addition, numerous studies have been devoted to the conditions of HI occurrence and elimination in pipeline systems (e.g. [13–17]). However, the main limitations for the application of known results on determining the conditions for HI occurrence and elimination to ASS pumps are related to the following provisions.

1. We assume that resonant effects are the mechanisms determining fluctuations in hydrodynamic parameters (pressure and flow velocity): coincidence between the pipeline system natural frequency and the one of pumped working fluid. However, the resonant mechanism corresponds to extremely particular cases of HI occurrence and is not critical for most of the pumps in transient and emergency modes.

2. CHI emergence conditions which result in the pump failure during its start-up or operation are not defined.

3. Technical measures to reduce fluctuations in hydrodynamic parameters to avoid HIs are mainly implemented for the pipeline system components located downstream the pumps. These technical measures do not eliminate the preconditions for CHI at pumps.

The methods to identify the HI onset conditions due to the pumps’ inerterance under stationary modes are discussed in references [18–20].

Thus, the relevant problem consists in both definition and analysis of conditions leading to safety-critical HI in NPP ASS transient modes.

Main provisions of the method for determining CHI preconditions at pumps.

The CHI determining mechanism at pressure pumps refers to the pump’s head-flow characteristic (HFC) delay:

\[ \Delta P_p = f(G) \quad \Delta P_p = f(v) \]

where \( \Delta P_p \) is the pump head; \( G, v \) are the flow rate and average velocity, respectively.

The HFC is determined by the specific pumps’ design and technical characteristics.

The pump HFC delay here means the response time lag needed for change in the pipeline system hydrodynamic parameters.
parameters under transient modes (e.g. at pump start-up). The pump HFC delay determining parameter is the delay time $\Delta t$ of system feedback to the change in system’s hydrodynamic parameters, which depends both on the design and technical characteristics of system components (including pump) and on the hydrodynamic parameters’ change rate in transient mode.

Figure 1 shows an example of HI conditions formed at a pressure pump, taking into account the HFC delay in the transient mode (starting the pump).

At the pump’s start, the head is the maximum. Further increase in the pipeline system flow according to the design HFC should lead to a feedback reducing the pump head. However, this HFC feedback does not occur instantaneously, but because of the hydrodynamic processes’ inertance, with some delay $\Delta t$. Therefore, at subsequent time moments ($\Delta t < t < 2 \Delta t$), there will be a decrease in flow rate and a corresponding HFC increase in the pump head. Further, due to the hydrodynamic processes’ inertance in the time interval $2 \Delta t < t < 3 \Delta t$, the corresponding HFC increase in the flow rate and pump head drop will occur with a delay.

Thus, due to HFC inertance, the pipeline system hydrodynamic parameters fluctuate relative to the HFC design curve. The effect of HFC inertia on the hydrodynamic parameters’ fluctuation amplitude will be insignificant under the condition (see curves 1 and 2 in Fig. 2):

$$I = \frac{\Delta t G_0}{\rho F L} \ll 1, \quad (2)$$

where $I$ is the HFC inertia parameter; $G_0$ is the mass flow in the system under steady-state conditions; $\rho$ is the fluid density; $F$ is the pipeline section equivalent area; $L$ is the pipeline total length.

The inertia parameter can be presented in the simplified form by A.V. Korolev’s formula:

$$I = \frac{\Delta t G_0}{\rho F L} = \frac{\Delta t \cdot W^2 \cdot F \cdot \rho}{F \cdot L} = \frac{\Delta t \cdot W^2}{L} = \frac{\Delta t}{\Delta T}, \quad (3)$$

where $\Delta t$ is the delay time and $\Delta T$ is the time required for fluid element passage along the whole pipeline at constant flow.

As inertia $I$ parameter increases, the hydrodynamic parameters’ fluctuation amplitude increases and reaches the limits, values determining preconditions for CHI occurrence (see curves 3 and 4 in Fig. 2).

CHI — area of mode parameters that correspond to the CHI conditions.

Under the assumptions of fluid incompressibility and isothermal processes, the flow equations for the considered pipeline system and the current change in the pump hydraulic head are:

$$\rho L \frac{dv}{dt} = \Delta P_p(v) + P_1 - P_2 - \Delta P_1(v) - \Delta P_2(v), \quad (4)$$

$$\Delta P_p = \int_0^t f'(v) \frac{dv}{d\tau} d\tau \quad (5)$$

At initial conditions

$$v(t = 0) = 0, \quad (6)$$

$$\Delta P_p(t = 0) = \Delta P_{pm}, \quad (7)$$

where $\rho$ is the medium flow density; $L$ is the pipeline length; $\Delta P_{pm}$ is the maximum possible hydrodynamic head of the pump, determined by its technical characteristics; $t$ is current time; $v$ is the average velocity; $f'$ is the current sensitivity of the pump’s flow characteristic; $P_1, P_2$ are static pressure in the source and target, respectively.

Pressure losses in suction line $L_1$ and charging line $L_2$ can be calculated using the following formulas:

$$\Delta P_1 = \left[ \xi_{pf} \frac{L_1}{D} + \sum_{i=1}^2 \xi_{flf} (L_i) \right] \rho v_i^2 - \rho g \sum_{j=1} h_j \text{sign} \left( v_j (L_j) \right), \quad (8)$$

$$\Delta P_2 = \left[ \xi_{pf} \frac{L_2}{D} + \sum_{i=1}^2 \xi_{flf} (L_i) \right] \rho v_i^2 - \rho g \sum_{j=1} h_j \text{sign} \left( v_j (L_j) \right), \quad (9)$$

where $\xi_{pf}$, $\xi_{flf}$ are the pipeline friction and form loss factors, respectively; $D$ is the pipeline cross-section diameter; $g$ is the gravity acceleration; $h_j$ is the height of the pipeline system vertical sections;

$$\text{sign}(v) = \begin{cases} 1, \text{ descending } \; \text{flows}; \\ -1, \text{ ascending } \; \text{flows}. \end{cases}$$

The supply (network) characteristic sensitivity to changes in flow rate/flow velocity is:

$$f' = \frac{d \Delta P_p}{d G}, \quad \text{or} \quad f' = \frac{d \Delta P_p}{dv}. \quad (10)$$
For pressure pumps, the supply (network) characteristics design sensitivity is:

\[ f'(G,v) \leq 0 . \quad (11) \]

CHI conditions for the pump at the maximum permissible (critical) velocity are:

\[ v \geq v_{\text{max}} = \min \left\{ \frac{2 \sqrt{N_{\text{max}}}}{\rho}, \sqrt{\frac{2 \left( P_L(L) - P_L \right)}{\rho}} \right\} . \quad (12) \]

where \( N_{\text{max}} \) is the maximum admissible hydrodynamic load on the pump working components.

Pump CHI conditions at pump minimum permissible head \( \Delta P_{\text{min}} \) are:

\[ 2 \leq \Delta P_{\text{min}} = P_1 - P_2 - \Delta P_1 - \Delta P_2 . \quad (13) \]

**Results of computational modeling.** The above method for determining the pumps’ CHI emergence conditions was applied to the following ASSs of WWER-1000 NPPs:

- high-pressure safety boron injection system TQ13;
- high-head safety boron injection system TQ14.

Structural and technical characteristics for components of the TQ13 and TQ14 systems (including pumps and their HFCs) are presented in [22].

Pumps’ HFC are defined with the approximation of design relations:

\[ \Delta P_p = \sum_{i=1}^{n} a_i v^i, \quad (14) \]

where \( a_i \) are the approximation coefficients for a specific pump type.

Conservatively (in relation to HFC invariance), the hydraulic resistance coefficients of pipeline systems and pumps are assumed constant.

Equations (4) — (14) for the TQ13 and TQ14 systems have been solved using a mathematical model with the Runge-Kutta numerical method.

The main results of computational modeling are shown in Fig. 3 and are as follows.

1. For both TQ13 and TQ14 systems, there are no conditions for CHI occurrence in pump start-up:

\[ \frac{v(t)}{v_{\text{max}}} < 1; \quad \Delta P_p(t) \leq \Delta P_{\text{min}} . \quad (15) \]

2. Variations in the hydrodynamic parameter amplitudes and oscillation frequencies for different types of pumps are determined by their HFC differences: for CNS50/160—110 pumps, HFC is similar to the HFC curve shown in Fig. 2; and for PT16-C pumps, HFC is much less inertial.

3. The obtained results testify that there are no conditions under which the CHI would occur in start-up of TQ13 and TQ14 pumps are quite conservative, since the assumptions accepted in computational modeling determine the limiting conditions for the CHI emergence. Thus, for example, when the nonstationary nature of hydraulic resistance coefficients for valves is more realistically taken into account in pump start-up, the effect of HFC inertia onto preconditions for CHI occurrence is less significant.

**Conclusions**

1. To analyze the reliability of nuclear power plant active safety systems, an original method for determining the conditions for the critical (for operability) hydraulic impacts at pipeline system components in transient operation modes is proposed.

The proposed method is based on the inertance of the headflow pump characteristic determining the effect on the conditions involving hydraulic impact occurrence when the pipeline system hydrodynamic parameters change in transient modes (for example, when pumps are starting). The determining factor for inertia of the pressure-supply characteristic is the delay time of response to the change in the system hydrodynamic parameters, which depends both on the structural and technical parameters of system components and on the hydraulic parameters’ change rate in transient modes.

2. It is established that with a sufficiently large inertance of pumps’ pressure-head characteristic, the critical hydraulic impact may occur on the pumps both at the maximum permissible flow rate in the system and at the minimum allowable pump head.

3. Using the developed method, the conditions for the CHI occurrence at components of the primary emergency boron injection systems of serial power units with WWER-1000 reactors have been analyzed.

The analysis shows that for all systems considered, there are no conditions for the critical hydraulic impacts in pump start-up.

4. The proposed method can be applied to any pipeline systems of thermal and nuclear power plants that include pressure pumps.

**References (BSI)**

Аналіз критичних умов надійності при гідроударах в активних системах безпеки ядерних енергетичних установок з ВВЕР-1000

Скалоузов Б. І., Козлов І. Л., Чупін О. О., Комаров Ю. О., Піонтковський О. І.

Одеський національний політехнічний університет, м. Одеса, Україна

Для аналізу надійності активних систем безпеки ядерних енергетичних установок запропоновано оригінальний метод визначення умов виникнення критичних для працездатності гідралічних ударів. Пропонований метод заснований на визначенні критичності енергетичних установок при зміні гідродинамічних параметрів у трубопровідній системі в переходних режимах (наприклад, при запуску насосів). Визначальним критерієм є відносна різниця між значеннями гідродинамічних параметрів у переходних і стационарних режимах.

Ключові слова: насос, гідроудар, інерція, напірно-витратна характеристика.