

Analysis of Reliability-Critical Hydraulic Impact Conditions at WWER-1000 NPP Active Safety Systems

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An original method to determine the onset of conditions for reliability-critical hydraulic impacts for reliability analysis of active safety systems of nuclear power installations is proposed. The suggested method is based on determining the effect of head-flow characteristic delay onto hydraulic impact preconditions during the changes of pipeline system hydrodynamic parameters under transitional modes (e.g. in pump start-up). The delay time of responses to change in the hydrodynamic system parameters embodies the determining factor of head-flow characteristic's inertance, depending on both design and technical parameters of system components (including pumps), and the hydrodynamic parameters change rate under transitional modes.

Using the proposed method, the analysis of conditions for critical hydraulic impacts is performed for the primary high-pressure safety injection system of serial WWER-1000 nuclear power plants. The analysis results allow a conclusion that for this system the conditions leading to hydraulic impact due to the pump start are not reached.

The developed method can be applied to any thermal and nuclear power facilities' pipeline systems equipped with pumps.

Keywords: pump, hydraulic impact, response delay, head-flow characteristic.

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' inertance 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:

$$\Delta P_p = f(G); \Delta P_p = f(v), \quad (1)$$

where ΔP_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

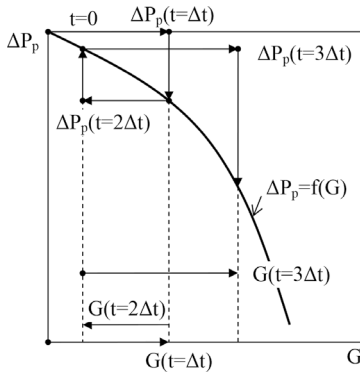


Fig. 1. Formation of hydraulic impact conditions taking into account the pump head-flow delay and flow characteristics in the transient mode (starting the pump)

parameters under transient modes (e.g. at pump start-up). The pump HFC delay determining parameter is the delay time Δt 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 Δt . Therefore, at subsequent time moments ($\Delta t < t \leq 2\Delta t$), 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 $2\Delta t < t \leq 3\Delta t$, 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):

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

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

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

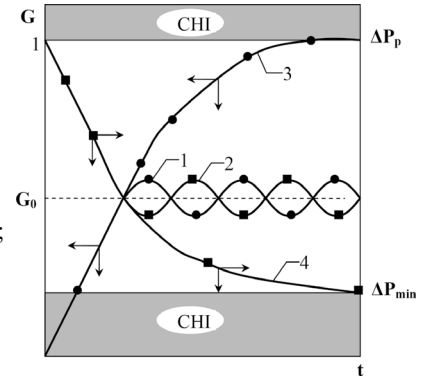
$$I = \frac{\Delta t G_0}{\rho FL} = \frac{\Delta t \cdot W \cdot F \cdot \rho}{\rho \cdot F \cdot L} = \frac{\Delta t \cdot W}{L} = \frac{\Delta t}{\Delta T}, \quad (3)$$

where Δt is the delay time and ΔT 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

Fig. 2. Regions of mode parameters corresponding to the conditions of critical hydraulic impacts at pumps: 1 — flow at relatively low HFC inertia; 2 — pump head at relatively low HFC inertia; 3 — flow rate at extreme HFC inertia; 4 — pump head at the maximum HFC inertia;



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

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

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

At initial conditions

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

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

where ρ is the medium flow density; L is the pipeline length; ΔP_{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:

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

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

where ξ_{pf} , ξ_{fi} 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;

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

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

$$f' = \frac{d\Delta P_p}{dG} \quad \text{or} \quad f' = \frac{d\Delta P_p}{dv}. \quad (10)$$

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:

$$v \geq v_{\max} = \min \left\{ \sqrt{\frac{2N_{\max}}{\rho}}, \sqrt{\frac{2[P_1(L_1) - P_s]}{\rho}} \right\}. \quad (12)$$

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

Pump CHI conditions at pump minimum permissible head ΔP_{\min} are:

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

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 inertance), 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.

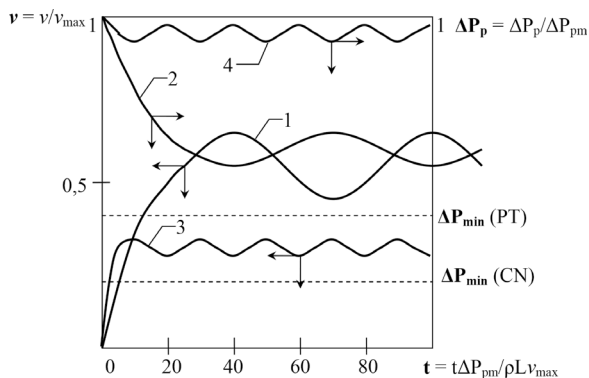


Fig. 3. Results of computational modeling of fluctuations in hydrodynamic parameters in start-up of TQ13,14 safety system pumps:

- 1 — relative average velocity at starting pumps CN 150–110, CN 160–110;
- 2 — relative pressure of pumps CN 150–110, CN 160–110;
- 3 — relative average flow rate at starting pumps PT 6/160-C;
- 4 — relative head of pumps PT 6/160-C

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:

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

2. Variations in the hydrodynamic parameter amplitudes and oscillation frequencies for different types of pumps are determined by their HFC differences: for CN50/160–110 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 testifying 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 inertance 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 head-flow 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 hydrodynamic 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.

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Анализ критических условий надежности при гидроударах в активных системах безопасности ядерных энергетических установок с ВВЭР-1000

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Для анализа надежности активных систем безопасности ядерных энергетических установок предложен оригинальный метод определения условий возникновения критических (для работоспособности) гидравлических ударов. Предлагаемый метод основан на определяющем влиянии инерционности напорно-расходной характеристики на условия возникновения гидроударов при изменении гидродинамических параметров в трубопроводной системе в переходных режимах (например, при запуске насосов). Определяющим фактором инерционности напорно-расходной характеристики является время запаздывания обратных реакций на изменение гидродинамических параметров в системе, которое зависит как от конструктивно-технических параметров элементов системы (в том числе и насосов), так и от скорости изменения гидродинамических параметров в переходных режимах.

На основе разработанного метода проведен анализ условий возникновения критических гидроударов в системе аварийного ввода бора в первый контур серийных энергоблоков с реакторами типа ВВЭР-1000. В результате проведенного анализа установлено, что для рассмотренной системы отсутствуют условия возникновения критических гидроударов при запуске насосов.

Предложенный метод может быть распространен на любые трубопроводные системы тепловых и ядерных энергетических установок, в состав которых входят напорные насосы.

Ключевые слова: насос, гидроудар, инерционность, напорно-расходная характеристика.

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

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Для аналізу надійності активних систем безпеки ядерних енергетичних установок запропоновано оригінальний метод визначення умов виникнення критичних (для працездатності) гідравлічних ударів. Пропонований метод засновано на визначальному впливі інерційності напірно-витратної характеристики на умови виникнення гідроударів при зміні гідродинамічних параметрів у трубопровідній системі в перехідних режимах (наприклад, при запуску насосів). Визначальним чинником інерційності напірно-витратної характеристики є час запізнювання зворотних реакцій на зміну гідродинамічних параметрів у системі, який залежить як від конструкційно-технічних параметрів елементів системи (у тому числі і насосів), так і від швидкості зміни гідродинамічних параметрів у перехідних режимах.

На основі розробленого методу проведений аналіз умов виникнення критичних гідроударів в системі аварійного введення бору в перший контур серийних энергоблоків з реакторами типу ВВЕР-1000. У результаті проведенного аналізу встановлено, що для розглянутої системи відсутні умови виникнення критичних гідроударів при запуску насосів.

Запропонований метод може бути поширений на будь-які трубопровідні системи теплових і ядерних енергетичних установок, до складу яких входять напірні насоси.

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

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