

## ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ТА МОДЕЛЮВАННЯ

UDC 629.031

### Analysis of similarity criteria for experimental models and equipment of nuclear plant safety systems

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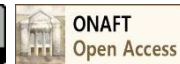
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*A criterial method is proposed for analyzing the adequacy of real pipeline systems with pumps of nuclear power plants and experimental installations. The method is based on an analysis of the identity of the determining criteria for the similarity of hydrodynamic processes in real and experimental conditions. The criteria for similarity of real and experimental conditions and conditions of water hammer for pipeline systems with pumps of nuclear power plants in transient and operating modes are determined. Water hammers in transient regimes are a consequence of aperiodic hydrodynamic instability of the flow; and in operating conditions – a consequence of oscillatory hydrodynamic instability. The determining factor of hydrodynamic oscillatory instability is the inertia of the pressure-supply characteristic of pumps. On the basis of the proposed method, an example of the practical application of the similarity criteria obtained for real active safety systems and an experimental plant A.V. Korolev is presented. It is shown that the necessary conditions for identity of similarity criteria are not met and extrapolation of the results of known experiments to real conditions of active safety systems of nuclear installations with WWER reactors is not justified.*

**Key words:** similarity criteria; nuclear plant safety systems; experimental models

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#### 1. Relevance

The urgency of experimental modeling of emergency processes at nuclear power plants (NPP) is determined by the fundamental absence of the possibility of "artificial" creation of accidents on real equipment of systems important for the safety of nuclear power plants; as well as the need for experimental verification of calculated emergency codes (CEC).

After the accident at the NPMI TMI-2 (USA), numerous integrated experimental installations were designed to study accidents involving decompression of the reactor circuit with WWER / PWR: ICB / PCB, PM-5, KMC (Russia); PMR-NVH, PMK-2 (Hungary); SEMISCALE (USA); LOBI-MOD2 (CEC-ISPRA); UMCP (United States); SPES (Italy); PKL (Germany); BETHSY (France); LOFT (USA); ROSA-IV, PWR (Japan); REWET, PACTEL (Finland) and others. The basic design and technical parameters of these

experimental installations can be found, for example, in [1].

However, the adequacy of experimental and real conditions and structural and technical parameters have not been adequately studied.

One of the effective approaches to solving these issues is the analysis of the identity of the criteria for the similarity of processes in experimental and real conditions. For example, in the monograph of the authors [2] it was shown that the similarity criteria adopted in the design of the ICB / PCB-WWER experimental installations are not enough to justify the adequacy of the experimental and real WWER / PWR conditions; as well as for a reasonable extrapolation of the results of experimental verification to real conditions of CEC using physically unjustified closing relations of mathematical models [2].

When simulating accidents and safety analysis of nuclear power plants with WWER / PWR, the following initial accident events (IAE) are usually

considered: depressurization / leakage of the reactor circuit; leaks / ruptures of steam lines and pipelines of boiler feedwater; complete de-energization of the power unit and others. One of the lessons of the big accident at the Fukushima-Daiichi nuclear power plant is the need for modeling and analysis of beyond-design accidents with multiple failures of systems important for safety (SIS).

Many years of experience in the operation of power equipment (pumps, fittings, heat exchangers, etc.) have shown that the most critical for reliability are water hammers (WH) [8] for equipment / elements of piping systems accompanied by pulsed high-amplitude pressure increase and appropriate braking of the oncoming stream velocity. Under WH conditions, the kinetic energy, when the flow is decelerated, is partially or completely converted into the energy of the WH pulse.

The characteristic statistics of the State Institution for various equipment of the SIS of NPP with the PWR reactors is given, for example, in [3]. According to the statistics given in [3], more than 90% of registered WH are accounted for by safety systems with pumping equipment.

Critical for the reliability / availability of equipment, the WH can be both design-basis failures in the process of accident development, and directly IAS.

Numerous studies have been devoted to the problems of computational modeling of WH (the reviews of these studies are given, for example, in [3, 4, 5]). In most works, the well-known formula of N.E. Zhukovsky [6]:

$$\Delta P_{WH} = \rho \cdot \Delta U \cdot C_m \quad (1)$$

where  $\rho$  – the density of the flow medium;  $\Delta U$  – the difference between the average flow velocity before and after the WH;  $C_m$  – speed of sound in the metal equipment and pipelines.

However, formula (1) does not determine the conditions for the formation of WH in various pipeline systems and does not take into account the determining effects of the kinetic energy transition when the flow brakes the pulse energy. Thus, in the works of A.V. Korolev in the experimental model of the WWER-440 pressure compensator [7] established significantly underestimated values  $\Delta P_{WH}$  according to formula (1) with respect to the experimental data.

In the monograph of the authors [5] original methods for determining the conditions and parameters of hydraulic attacks on power

equipment of SIS of NPP due to vibrational and aperiodic hydrodynamic instability are presented.

However, the assumptions/ simplifications adopted in the methods [5] determine the need for experimental verification. The key issue of verification is the analysis of the criteria for the similarity of design, technical and operational parameters of experimental and real installations, which determines the relevance of the work.

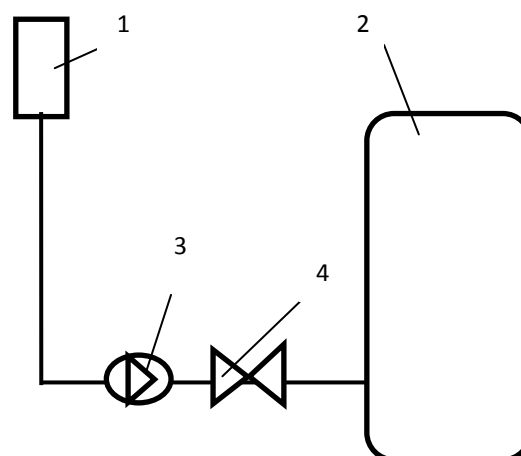
## 2. Criteria for the similarity of hydrodynamic processes in real and experimental conditions

An analysis of the similarity criteria for hydrodynamic processes is presented on an example of a typical scheme of NPP safety systems. A typical scheme of the channel of active safety systems (ASS) with NPP pumps with WWER / PWR is shown in Fig.1.

ASS WWER – emergency cooling systems of the reactor with high and low pressure pumps; a system for feeding and injecting a solution of boric acid into the reactor; systems of emergency and auxiliary make-up of the steam generator and others.

Two characteristic modes of operation of ASS are analyzed:

- transient start-up / stopping of the pump or opening / closing the valve;
- stationary steady-state operation modes.



1 – water capacity of the water reserve;  
2 – reactor / steam generator; 3 – the pump;  
4 – the valve

*Figure 1 – Typical scheme of the ASS channel*

With conservative assumptions of fluid incompressibility and isothermal processes, the nonstationary equations of motion and energy

conservation in the criterion (dimensionless) format for transient regimes have the form [5] after the transformations:

$$\frac{d\mathbf{U}}{dt} = \Delta P_{po}(t=0) + \int_0^t f'(\mathbf{U}) \cdot \frac{d\mathbf{U}}{d\tau} \cdot d\tau - (1 - K_p) - K_\xi \cdot \mathbf{U}^2$$

$$\mathbf{U}(t=0) = 0 \tag{2}$$

$$\frac{d}{dt} \left( \frac{\mathbf{U}^2}{2} + K_i \cdot \mathbf{P} \right) = 0 \tag{3}$$

where  $\mathbf{U} = U / U_s$ ;  $t = t \cdot P_{out} / (\xi L U_s)$ ;  $\Delta P_{po} = \Delta P_{po}(t=0) \cdot P_{out}$ ;  $f'(\mathbf{U}) = d\Delta P_p / d\mathbf{U} \leq 0$  – flow-rate characteristic of the pump, corresponding to the type of pump and its design and technical parameters;  $\Delta P_{pm}$ ,  $\Delta P_p$  – the maximum and current head of the pump, respectively;  $P = P / P_{out}$ ,  $U$  – average (in terms of cross-sectional area of the pipeline) flow rate;  $U_s$  – average speed in pipelines in steady-state steady mode;  $P$ ,  $P_{ent}$ ,  $P_{out}$ , – respectively, the pressure in the pipelines, in the hydraulic reservoirs of the water reserve and in the reactor / steam generator;  $t$  – time of the process;  $\rho$  – the density of the liquid;  $L$  – total length of pipelines;  $i$  – the specific enthalpy of the flow.

Equations (2), (3) follow the criteria for the conditions for the appearance of the WH:

$$\frac{d\mathbf{U}}{dt} < 0; \frac{d\mathbf{P}}{dt} > 0 \tag{4}$$

The conditions for the similarity of real ASS and experimental installations in transient regimes are determined by the identity of the criteria:

$$K_p = \frac{P_{ent}}{P_{out}} \equiv iden;$$

$$K_\xi = \left[ \xi_p + \xi_k(t) \right] \frac{\rho U_0^2}{2 \cdot P_{out}} \equiv iden;$$

$$K_i \frac{1}{U_s} \cdot \frac{di}{dp} \equiv iden;$$

$$\Delta P_{po} \equiv iden;$$

$$f'(\mathbf{U}) \equiv iden;$$

$$t = \frac{P_{out}}{\rho L U_s} t \equiv iden;$$

where,  $\xi_p$ ,  $\xi_k(t)$  – the coefficients of the hydraulic resistance of the pump and valve, respectively.

The conditions for the appearance of WH (4) are a consequence of aperiodic hydrodynamic

instability in the pipeline system with pumps (Figure 1) and in the general case can be determined by solving the systems of equations (2), (3) by numerical methods [5].

In steady-state stationary regimes with speed  $U_s$  and pressure  $\Delta P_{po}(U_s)$ , the cause of the WH appearance can be oscillatory hydrodynamic instability: a random (fluctuation) change in the flow velocity  $\delta U$  (caused, for example, by the pump) under certain conditions can lead to pressure and flow velocity fluctuations [5].

For the system under consideration (Fig. 1), the inertial "delay" of the reaction of the pressure-supply characteristic (PSC) of the pump during the time  $\Delta t$  for fluctuational changes in the hydrodynamic parameters is the determining factor for the onset of the vibrational instability. The parameter of inertia  $\Delta t$  depends on the design and technical data of the pump and affects the amplitude and frequency of velocity and pressure fluctuations (in antiphase velocity) of the flow.

Under the conditions when the hydrovolumes of objects 1 and 2 (Figure 1) are much larger than the volume of liquid in the pipeline system by fluctuational disturbances  $\delta U$ ,  $\delta P$ , objects 1 and 2 can be conservatively neglected. Then, the equations of flow and conservation of energy in the pipeline system in the perturbation parameters  $\delta U$ ,  $\delta P$ , in this case have the form:

$$\frac{d\delta \mathbf{U}}{dt} = \int_0^t f'(\Delta t) \cdot \frac{d\delta \mathbf{U}}{d\tau} \cdot d\tau - 2 \cdot K_\xi \cdot \delta \mathbf{U} + \Delta P_{po}(U_s) \tag{6}$$

$$K_i \frac{d\delta P}{dt} = - \frac{d\delta \mathbf{U}}{dt};$$

$$\delta U(t=0) = \delta \mathbf{U}_0 \tag{7}$$

In the general case, solutions (6), (7) can be obtained by numerical methods, and the amplitudes and frequencies of oscillations of the hydrodynamic parameters depend on the criteria; [5].

Thus, the conditions for the similarity of real WH and experimental installations in steady-state regimes are determined by the identity of the criteria: (8)

$$f' = \begin{cases} 0, & \text{при } t \leq \Delta t \\ f'(\delta U) & \text{при } t > \Delta t \equiv iden \end{cases}$$

Practical application of the obtained similarity criteria can be demonstrated on the results of experimental studies [9]. The experimental setup

[9] represents a closed circulation circuit with piston pumps and valves. As a result of the experiments carried out in [9], the amplitude of the pressure oscillations over 30% of the mean value was recorded at operating conditions. To reduce the amplitude of pressure and WH fluctuations, damping devices (DD) were installed at the pump outlet. Effective to reduce the amplitude of WH, the design and technical characteristics of remote control were determined by experimental methods.

The above analysis of the similarity criteria in real and experimental conditions [9] showed that the conditions for the similarity of the hydrodynamic processes (8) in the experimental setup [9] and in real ASS of nuclear power plants with WWER are not fulfilled. Therefore, the extrapolation of the experimental results to the solution of the SIS of NPP condition with WWER is unreasonable.

### 3. Main conclusions

1. A criterial method is proposed for analyzing the adequacy of real pipeline systems with pumps of nuclear power plants and experimental installations. The method is based on an analysis of the identity of the determining criteria for the similarity of hydrodynamic processes in real and experimental conditions.

2. The criteria for similarity of real and experimental conditions and conditions of hydrodynamic impacts for pipeline systems with pumps of nuclear power plants in transient and operating modes are determined. Hydrodynamic shocks in transient regimes are a consequence of aperiodic hydrodynamic instability of the flow; and in operating conditions - a consequence of oscillatory hydrodynamic instability. The determining factor of hydrodynamic oscillatory instability is the inertia of the pressure-supply characteristic of pumps.

3. On the basis of the proposed method, an example of the practical application of the similarity criteria obtained for real active safety systems and an experimental plant is presented A.V. Korolev. It is shown that the necessary conditions for identicality of similarity criteria are not met and extrapolation of the results of known

experiments to real conditions of active safety systems of nuclear installations with WWER reactors is not justified.

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## Аналіз критеріїв подібності експериментальних моделей і устаткування систем безпеки ядерних установок

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*Запропоновано критеріальний метод аналізу адекватності реальних трубопровідних систем з насосами ядерних енергоустановок і експериментальних установок. Метод заснований на аналізі ідентичності визначальних критеріїв подібності гідродинамічних процесів в реальних і експериментальних умовах. Визначено критерії подібності реальних і експериментальних умов і умов гідродинамічних ударів для трубопровідних систем з насосами ядерних енергоустановок в перехідних і робочих режимах. Гідродинамічні удари в перехідних режимах є наслідком аперіодичної гідродинамічної нестійкості потоку; а в робочих режимах - наслідком коливальної гідродинамічної нестійкості. Визначальний фактор гідродинамічної коливальної нестійкості - інерційність напірно-видаткової характеристики насосів. На основі запропонованого методу представлений приклад практичного застосування отриманих критеріїв подібності для реальних активних систем безпеки і експериментальної установки О.В. Королева. Показано, що необхідні умови ідентичності критеріїв подібності не виконуються і екстраполяція результатів відомих експериментів на реальні умови активних систем безпеки ядерних установок з реакторами ВВЕР не обґрунтована.*

**Ключові слова:** критерії подібності; системи безпеки ядерних установок; експериментальні моделі

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