CONDITIONS FOR PREVENTION OF WATER HAMMERS AT START-UP OF EMERGENCY FEED PUMPS WITH A STEAM DRIVER OF NUCLEAR POWER PLANTS

A promising approach to accident management in nuclear power plants with a complete loss of long-term power supply is an emergency feed pump with a steam driver from a steam generator. The main advantages of this approach in relation to the known systems of passive heat removal with natural circulation are the fundamental possibility of fully compensating for the failure of design safety systems with electric pumps, as well as the absence of the need to remove the safety system elements to a greater height beyond the containment / container. However, the use of steam driven emergency pumps requires a deep study of their reliability. One such issue is the qualification of reliability when starting an emergency pump with a steam driver. An original method for modeling the conditions for the occurrence of a water hammer when starting a steam-driven pump is proposed. The conditions for the prevention of water hammer due to the inertia of the pressure-flow characteristics of emergency feed pumps with a steam driver from the steam generator are determined. The results obtained can be used in the design of emergency feed pumps with a steam driver from a steam generator subject to additional experimental qualifications.

Key words: emergency feed pump; steam driver; water hammer; nuclear power plant

References.

The initial event of severe accidents and destructive explosions at Fukushima-Daiichi NPPs in 2011 was the complete loss of long-term power supply (CLLPS) due to the combined effects of beyond-design tsunami and an earthquake [1, 2]. The lessons of the Fukushima accident determined the need for further development of the safety systems of nuclear power plants (NPPs) that do not require electrical power.

A promising approach to managing accidents with CLLPS is the development of emergency feed pumps with a steam driver from a steam generator (EFPSDSG) [3]. A schematic diagram of the connection EFPSDSG is shown in Fig. 1.

Steam from the steam generator enters the steam driver of the central pump, which feeds the feed water...
from the hydraulic containers of the design emergency electric pumps directly to the steam generator. Exhaust steam enters the deaerator. The main advantages of this approach with respect to the known systems of passive heat removal based on the principle of natural circulation are as follows:

- The principal possibility of fully compensating for the failure of the design of emergency electric pumps to fulfill the safety functions of removing heat from the reactor and maintaining the required level in the steam generator.

- No need to locate security system elements at high altitude outside the containment of the reactor.

However, the design and implementation of EFPSDSG requires a deep study of their performance and reliability. One of these questions is the analysis of the conditions for the occurrence of water hammers (WH) during the launch of the EFPSDSG.

The occurrence of WH is accompanied by a pulsed high-amplitude hydrodynamic effect and can significantly affect the performance and reliability of the safety systems of nuclear power plants. A lot of research has been devoted to the study of state-of-the-art facilities in heat engineering equipment and pipelines (for example, [4-10] [1, 2] [1, 2] and others). However, the issues of causes and effects of WH caused by the operation of pumping equipment have not been studied enough.

Using the example of reciprocating electric pumps, the authors of [11] showed that the inertia of the pressure-flow characteristics of pumps, which leads to aperiodic or oscillatory hydrodynamic instability in the system, can be a possible cause of the hydraulic pump.

The purpose of the proposed work is to analyze the conditions for the occurrence of the WH when the EFPSDSG is launched due to the inertia of its pressure-flow characteristics.

In the absence of the influence of the inertia of the pressure-flow characteristics of the pump (PFC) on the change of parameters for some time \( t_1 \), the EFPSDSG system will turn into a stable steady state with flow \( G_s \) and a corresponding pressure of the pump \( \Delta P_s(G_s) \). By inertia of PFC is meant the delay in the response time of the pump head pressure to the change in the flow rate in the system: with an increase in flow rate \( G \), the corresponding changes in the pump head pressure \( \Delta P \) do not occur instantaneously, but with a certain delay time \( \Delta t \) (Fig. 2).

The parameter \( \Delta t \) is determined by the design and technical characteristics of the system EFPSDSG and the pressure in the steam generator \( (P_r) \). In general, the parameter \( \Delta t \) can be determined on the basis of operational tests and / or on experimental installations that meet the criteria for hydrodynamic similarity [12].

![Fig. 1. Connection diagram of the emergency feed pump with steam driver: 1 – reactor; 2 – steam generator; 3 – the main circulation pump; 4 – quick-closing check valve of the turbine; 5 – feed pump with steam driver; 6 – hydraulic capacity; 7 – deaerator; 8 – valve](image)

![Fig. 2. Formation of the hydraulic impact conditions at the start-up of the EFPSDSG: \( \Delta P, \Delta P_m, \Delta P_s \) – current, maximum, stable pressure of the pump pressure; \( G, G_m, G_s \) – current, maximum, stable mass flow rate of feed water; 1 – design PFC pump; 2, 3 – changes in the flow rate and pressure head of the pump, respectively, during the inertial delay of the PFC reaction; 4 – water hammer conditions](image)
The maximum possible flow $G_m$ follows from the solution of equation (3) under conditions (5) and $\Delta P = \Delta P_m$ over the time interval $t \in [0, \Delta t)$:

$$G_m = \sqrt{\frac{\alpha(\Delta P_m)}{b} \left( \frac{1}{\exp\left(\frac{2}{\alpha(\Delta P_m)b} \cdot \Delta t\right)} - 1 \right)} \left( \frac{1}{\exp\left(\frac{2}{\alpha(\Delta P_m)b} \cdot \Delta t\right)} + 1 \right),$$

(7)

where $\alpha = \Gamma \cdot \left( \Delta P - \Delta P_{vo} \right)/L$; $b = \xi / (\rho \Pi L)$.

In the general case, the time of complete deceleration of the flow with WH, taking into account (3) and $\Delta P = \Delta P_s$, follows from the solution of the equation:

$$G_m = a(\Delta P_s) \cdot t_0 - a(\Delta P_s) \cdot \int_0^{b} \left( \frac{\exp\left(\frac{2}{\alpha(\Delta P_s)b} \cdot \tau\right)}{\exp\left(\frac{2}{\alpha(\Delta P_s)b} \cdot \tau\right)} - 1 \right) d\tau \cdot \left( \frac{1}{\exp\left(\frac{2}{\alpha(\Delta P_s)b} \cdot \tau\right)} + 1 \right),$$

(9)

Approximate solution (9):

$$t_0 \approx G_m / a(\Delta P_s).$$

(10)

Then, the maximum pressure amplitude $WH$ (6) at full flow braking:

$$\delta P_A = \frac{1}{\rho \Pi^2} \frac{dP}{dt} \left( \frac{\alpha(\Delta P_s)}{b} \cdot \int_0^b \left[ \frac{b \cdot G^2(\Delta P_s, \tau)}{\Delta P_s} \right] d\tau \right).$$

(11)

Analysis of the above results showed that the conditions for the absence of WH with the maximum pressure amplitude in the EFPSDSG system are:

$$\frac{\Delta t}{t_s} < 1 \text{ і } \frac{\Delta P}{\Delta P_s} < 1.3,$$

(12)

The obtained conditions (12) are proposed to be taken into account when designing EFPSDSG nuclear power plants.

**Conclusions.**

1. A promising approach to managing accidents on nuclear power plants with complete loss of long-term power supply is an emergency feed pump with a steam driver from a steam generator. The main advantages of this approach in relation to the known systems of passive heat removal with natural circulation are the fundamental possibility of fully compensating for the failure of design safety systems with electric pumps, as well as the absence of the need to remove the safety system elements to a greater height beyond the containment / container. However, the use of steam driven emergency pumps requires a deep study of their reliability. One such issue is the qualification of reliability when starting an emergency pump with a steam driver.
2. An original method for modeling the conditions for the occurrence of a water hammer when starting a steam-driven pump is proposed. The conditions for the prevention of water hammer due to the inertia of the pressure-flow characteristics of emergency feed pumps with a steam driver from the steam generator are determined.

3. The obtained results can be used in the design of emergency feed pumps with a steam driver from a steam generator, subject to additional experimental qualifications.

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