BgNS TRANSACTIONS volume **25** number 1 (2020/21) pp. 6–8

Conditions for Prevention of Water Hammers at Start-Up of Emergency Feed-Pumps with a Steam-Driver of Nuclear Power Plants

V. Skalozubov, D. Pirkovskiy, N. Bilous, I. Kozlov, V. Kolyhanov, O. Sedova

Odessa National Polytechnic University, Shevchenka av. 1, Odessa, 65044, Ukraine

Abstract. The initial event of severe accidents and devastating explosions at Fukushima-Daiichi NPP in 2011 was the complete loss of long-term power supply due to the combined effects of beyond-design tsunamis and an earthquake. Lessons from the Fukushima accident identified the need for further development of safety systems for nuclear power plants that do not require power. A promising approach to managing accidents with complete loss of long-term power supply is the development of emergency feed-pumps 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. 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 and pressure amplitudes due to the inertia of the pressure characteristics of emergency feed pumps with a steam-driver from a steam-generator of a nuclear power plant are determined. The pressure amplitude of the water hammer is determined by the conditions for the transition of the kinetic energy of the flow deceleration into the energy of the water hammer pulse.

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.

Keywords: emergency feed pump with steam-driver; water hammer; nuclear power plant.

1 Introduction

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

A promising approach to managing accidents with CLFTPS is the development of emergency feed pumps with a steam-driver from a steam generator (EFPSDSG) [3]. A schematic diagram of the EFPSDSG connection is shown in Figure 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 in relation 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 electro-pumps to perform safety functions for the removal of heat from the reactor and maintain 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 hammer (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 issues of studying the State University in heat engineering equipment and pipelines (for example, [4–10] 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

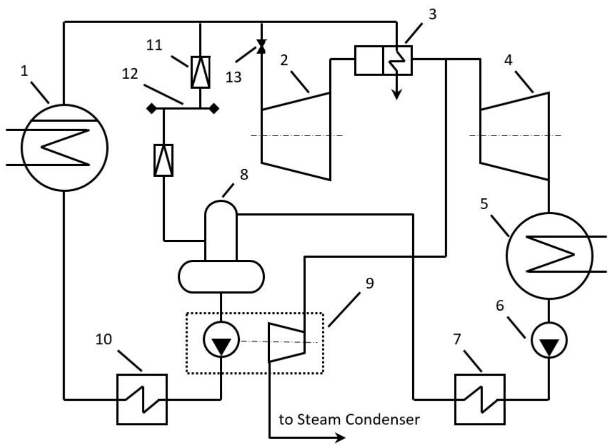

Figure 1. The feed water system (circuit diagram): 1 – steam generator; 2, 4 – parts of high and low pressure turbines; 3 – steam super heaters; 5 – steam condenser; 6 – condensate pump; 7 – low pressure heater; 8 – deaerator; 9 – feed pump with a turbo drive; 10 – high pressure heaters; 11 – BRU SN; 12 – own needs steam collector; 13 – Main Steam Isolation Valve (MSIV).

a possible cause of the hydraulic pump. The authors of [12] showed that the determining mechanism of WH is the occurrence of oscillatory hydrodynamic flow instability in the system caused by the inertia of the pressure-flow characteristic of pumps. With vibrational instability, the oscillation amplitudes of hydrodynamic parameters also increase significantly and contribute to the emergence of WHs for equipment and elements of pipeline systems.

The feed water system provides a reliable supply of the required amount of feed water to the steam generators from high-pressure deaerators through pipe systems of low-pressure heat exchangers. The feed water system (FWS) operates during starts from various thermal states and shutdowns of the power unit as a whole (planned and emergency). In addition, FWS operates in the mode of scheduled or emergency cooling of the unit, serves to preheat and fill the second circuit, as well as to remove residual heat from the reactor when NPP unit stopped or maintained in hot standby.

The feed water system includes:

- two deaerators of high pressure;
- two main feed pumps with a turbo drive (TPN) and two auxiliary feed pumps (VPN);
- high pressure regeneration system (heat exchangers);
- main lines of feed water supply to the steam generator and bypass feed water supply lines to the steam generator with shut-off valves on these lines;
- pipelines and fittings.

A turbine drive with a condensing drive turbine with its own condenser and condensate supply from it to the main condenser is provided for VVER-1000 nuclear power plants. The turbine is fed with steam taken after the intermediate super heater of the main turbine (260°; 1.44 MPa), but the supply of reduced fresh steam through the auxiliary steam collector is also provided. In addition, two more starting feed pumps are installed with a feed of 150 m^3/h, performed with an electric drive.

Unlike electrically driven pumps, in which the developed pressure head depends on the flow rate in the system, the pressure characteristic of the EFPSDSG is determined by the steam pressure in the steam-generator. These differences determine the characteristics of the conditions for the occurrence of WH. The goal of the proposed work is to analyze the conditions for the occurrence of a WH when an EFPSDSG is launched, which determines its relevance.

2 The Main Provisions of the Method of Modeling a Water Hammer When Starting an Emergency Feed-Pump with a Steam-Driver

The equations of motion and energy conservation of feed water during the start-up of EFPSD

$$\frac{L}{\Pi}\frac{dG}{dt} = \Delta P_P - \Delta P_{VG} - \frac{\xi}{\rho\Pi^2}G^2\,, \tag{1}$$

$$\frac{d}{dt}\Big(\frac{G^2}{2\rho\Pi^2} + i\Big) = 0\,, \tag{2}$$

$$G\,(t=0) = 0\,; \quad i\,(t=0) = i_0\,, \tag{3}$$

where G – the mass flow rate; t – the time, L, Π – the length and area of the bore of the EFPSDSG pipeline; $\Delta P_{VG} = P_V - P_G$ – the pressure drops in the steam generator and hydraulic tanks of feed water; ξ – the coefficient of total hydraulic resistance of the system; ρ – the density of feed water; i – the specific feed water enthalpy (per mass unit).

Pressure head developed by EFPSDSG,

$$\Delta P_p(t) = \int\limits_0^t \frac{dG}{d\tau}\, I_p(P_V\,,\,\tau - \Delta\tau)\,d\tau\,, \tag{4}$$

where pressure characteristics of EFPSDSG

$$I_p = \frac{dP}{dG}(P_V) \quad \text{with} \quad \tau \geq \Delta\tau\,. \tag{5}$$

The pressure characteristic of the EFPSDSG can be determined on the basis of operational tests and/or data of operating experience of similar pumps with a steam driver (for example, a turbo feed pump of a steam generator) and/or experiments on installations that meet the criteria for hydrodynamic similarity [12].

In the steady state (operating) mode of the EFPSDSG with the flow rate G_0, the necessary pressure head

$$\Delta P_{P0} = \Delta P_{VG} + \frac{\xi}{\rho\Pi^2}G_0^2\,. \tag{6}$$

The condition for the occurrence of WH when starting EFPSDSG

$$\Delta P_p\,(t) > \Delta P_{P0}\,. \tag{7}$$

Under condition (7), the system with EFPSDSG is in a non-equilibrium unstable state. This leads to pulsed flow deceleration (aperiodic hydrodynamic instability).

The maximum amplitude of the impulse of pressure of the main pump is determined by the conditions for the transition of the kinetic energy of the flow deceleration to the energy of the impulse of pressure of the main pump ΔP_A. From equation (2) it follows:

$$\Delta P_A = \left(\frac{di}{dP}\right)^{-1} \frac{G^2(t_0) - G_0^2}{2\rho\Pi^2}\,, \qquad (8)$$

where t_0 – the start time of the EFPSDSG.

In the general case, the conditions for the occurrence and amplitude of WH (7), (8) can be solved by numerical methods of equations (1), (3)–(5) for certain values of I_p and t_0.

3 Conclusions

1. A promising approach for managing accidents on nuclear power plants with a complete loss of long-term power supply is the use of 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 study of their reliability. One of such issues is the qualification for water hammer during the start-up of 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 and pressure amplitudes due to the inertia of the pressure characteristics when starting 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.

References

[1] IAEA (2011) International Fact Finding Expert Mission Of The Fukushima Daiichi NPP Accident Following The Great East Japan Earthquake and Tsunami: IAEA Mission Report.

[2] Скалозубов В.И., Оборский Г.А., Козлов И.Л., Ващенко В.Н. (2013) Комплекс методов переоценки безопасности атомной энергетики с учетом уроков экологических катастроф в Чернобыле и Фукусиме, Одесса: Астропринт.

[3] Королев А.В., Деревянко О.В. (2014) Композиционная конструкция турбоприводов насосного агрегата для резервной подпитки парогенераторов АЭС. *Праці Одеського політехнічного університету* **43**(1) 93-97.

[4] Brennen C.E. (2011) Hydrodynamics of pumps. Cambridge University Press.

[5] Jelali M., Kroll A. (2012) Hydraulic servo-systems: modelling, identification and control. Springer Science Business Media.

[6] Paszota Z. (2009) The operating field of a hydrostatic drive system parameters of the energy efficiency investigations of pumps and hydraulic motors. *Polish Maritime Research* **16**(4) 16-21.

[7] Johansson A., Ovander J., Palmberg J.O. (2007) Experimental verification of cross-angle for noise reduction in hydraulic piston pumps. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering* **221**(3) 321-330.

[8] Zettel A.M., et. al. (2009) Method and apparatus to monitor operation of an auxiliary hydraulic pump in a transmission. U.S. Patent, no. 7544151.

[9] Tianyi Z., Jili Z., Liangdong M.(2012) On-line optimization control method based on extreme value analysis for parallel variable-frequency hydraulic pumps in central air-conditioning systems. *Building and Environment* **47** 330-338.

[10] Derakhshan S., Nourbakhsh A. (2008) Theoretical, numerical and experimental investigation of centrifugal pumps in reverse operation. *Experimental Thermal and Fluid Science* **32**(8) 1620-1627.

[11] Mazurenko A.S., Skalozubov V.I., Kozlov I.L., Pirkovskiy D.S. (2017) Determing the Conditions for the Hydraulic Impacts Emergence at Hydraulic Systems. *Problemele Energetichi Regionale. Termoenergetica* **34**(2).

[12] Мазуренко А.С., Скалозубов В.И., Пирковский Д.С., Чулкин О.А. (2017) Анализ применимости результатов экспериментальных исследований гидродинамики к насосным системам тепловых и ядерных энергоустановок. *Ядерна енергетика та довкілля* **19**(1) 49-52.