CORROSION SCIENCE AND TECHNOLOGY, Vol.20, No.1(2021), pp.1~6
[Research Paper]

pISSN: 1598-6462 / eISSN: 2288-6524
DOI: https://doi.org/10.14773/cst.2021.20.1.1

Cause Analysis for a Lining Damage in Sea Water System Piping Installed in a Korean Industrial Plant

K. M. Hwang[1,†] and S. K. Park[2]

[1]*KEPCO E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660*
[2]*KHNP, 70, 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon, 3410*

(Received October 13 2020; Revised December 11, 2020; Accepted December 11, 2020)

Many Korean industrial plants including nuclear and fossil power plants use seawater as the ultimate heat sink to cool the heat generated by various facilities. Owing to the high corrosivity of seawater, facilities and piping made of metal material in contact with seawater are coated or lined with polymeric materials to avoid direct contact with seawater. However, polymeric materials used as coating and lining have some level of permeability to water and are degraded over time. Korean industrial plants have also experienced a gradual increase in the frequency of damage to pipes in seawater systems due to prolonged operating periods. In the event of a cavitation-like phenomenon, coating or lining inside the piping is likely to be damaged faster than expected. In this paper, the cause of water leakage due to base metal damage caused by the failure of the polyester lining in seawater system piping was assessed and the experience with establishing countermeasures to prevent such damage was described.

Keywords: *Lining, Coating, Seawater piping, Cavitation, Computational fluid dynamics*

1. Introduction

Typically, the energy flow process of pressurized light water nuclear plants can be divided into three parts such as, the primary system for generating heat, the secondary system for generating electricity, and the auxiliary system for supporting the primary and secondary systems. In nuclear power plants, the seawater system is categorized as an auxiliary system because it is used for rooms and facilities cooling, condensate production, etc. on the primary and secondary systems. In Korea, seawater is utilized as final coolant (or ultimate heat sink) at nuclear power plants because the Korean Peninsula is surrounded by the sea on three sides. However, various piping systems consisting of power plants are made of steel and seawater flowing into pipes is more corrosive than ordinary water, so that the pipe inside is fabricated with polymeric materials to avoid direct contact with seawater. It is called coating if the thickness is less than 50 mils and it is lining if the thickness is 50 mils or more depending on the thickness of the application [1]. Since most of the polymeric materials applied to the seawater system piping in the plants are 50 mils or more, the materials will be specified as linings from now on.

Coatings or linings shall not be permanently used and shall be replaced at an appropriate time because they are hardened as increasing the operating time and deformed not only physically but also chemically. Except for the two reactors (Kori unit 1 and Wolsong unit 1) that were permanently shut down two or three years ago, there are seven plants that have been in operation for 30 years, and seven have been in operation for 20 years [2]. Therefore, much attention needs to be given to managing lining inside the seawater piping. However, since it is costly to replace the entire lining of the inside of the facilities or piping contacting with seawater, and not entire parts are damaged, it is best to identify, inspect and replace areas where damage is expected early.

This paper introduces a case in which the cause of occurrence was analyzed through engineering evaluation and computational fluid dynamics (CFD) analysis for the recent seawater leakage event in the piping of the seawater system of a particular nuclear power plant in Korea, and countermeasures to prevent recurrence were sought. The damaged piping is a part of the component cooling seawater system, which cools the heat generated from the

---

[†]Corresponding author: hkm@kepco-enc.com
K. M. Hwang: General Manager, S. K. Park: General Manager

primary side of the plant with seawater, and is a system independent of radioactivity.

2. Types and Damage Characteristics of Lining

2.1 Types of Lining

Types of resins used as materials for lining include epoxy resin, novolac resin, phenol resin, coal-tar, etc. Epoxy resin is a resinous substance with more than one epoxy monomer in a molecule and a thermosetting resin produced by polymerization of epoxy. Phenol resin is a thermosetting resin produced by the heating reaction of phenol and formaldehyde. Novolac resin, a type of phenol resin, is made using acid catalyst and is used for surface finishing or adhesion as a yellowish transparent, alcohol varnish. A coal-tar is an oil-based liquid that is produced from by-products when coal is heated and dried. In addition, there are vinyl esters and cement, and a number of products have recently been released that have improved physical and chemical properties by mixing various resin. The lining materials, which is mainly used in the piping of the seawater system of Korean nuclear power plants, can be largely divided into coal-tar epoxy, polyester, and epoxy resin. The characteristics of each material are as follows.

- Coal-tar epoxy: A mixture of coal-tar and epoxy resin that was widely used from the 1960s to the 1990s. Amercot 71P/325 used in power plants with long operational life in Korea is also a type of coal-tar epoxy. The coal-tar epoxy is cheaper than the tar-free epoxy and is advantageous in blocking water or moisture in underground buried pipes. However, it is known to have a lifespan of about 10 to 15 years due to its large build-up and lack of adhesion during prolonged contact with moisture.
- Polyester: Polyester is widely used because it is easy to produce with a low cost, similar to vinyl esters. However, the structure is complex and is not suitable for high or low temperature conditions. Archcoat coating materials, which have been applied to nuclear power plants in Korea recently, are also a type of polyester. Polyester has lower tensile strength compared to vinyl ester or epoxy resin due to its unsaturated nature, which has many double bonds in the ester family.
- Epoxy resin: Epoxy resin is generally of superior quality compared to polyester or vinyl ester resin. This is due to the basic structural characteristics of the resin. The relative binding strength of the epoxy resin is 1,379 kg_f/cm^2 (2,000 lb_f/in^2). Since the basic backbone structure exists but epoxy resin contains aromatic structures, the binding strength is about three times stronger than vinyl ester or polyester resins and has greater impact absorption. In addition, epoxy resin is not harmful to the environment and does not generate bubbles when exposed to water, such as polyester or vinyl ester resin.

2.2 Damage Characteristics of Lining

If seawater is highly corrosive but the lining installed inside the pipe is sound, no problem occurs. Aging mechanism, which normally damages lining material inside seawater piping, is as follows.

1) Delamination: A delamination event may occur if the coating material is separated from the base metal of the pipe, and the chemical binding force of the coating material is reduced or the inside of the piping is not kept clean for long periods of time.
2) Membrane permeability: The phenomenon in which the fluid penetrates the resin and comes into contact with the base metal of the pipe, resulting from a reduction in the binding force between the long-drawn resin and the membrane.
3) Erosion: If foreign substances, such as shells and sand, are forced to damage the coating material, the base metal may be exposed to the fluid if left for a long time.
4) Glass transition: The phenomenon of rapid changes in the physical properties of resin as the temperature around the coating increases above the glass transition temperature reduces tensile strength and Young's Modulus and increases the degree of creep.
5) Thermal stress: This means the phenomenon where the coating material is hardened due to seasonal changes, loss of flow, and change of operating temperature.
6) MIC: If cleaning is insufficient before coating the surface of the seasonal pipe, there is a possibility of microbial presence between the pipe and the coating, and vigorous activity of these microorganisms may corrode the base metal and cause the coating material to fall off the surface of the pipe.
7) Water hammer: In case of water hammering inside the pipe, repeated pressure changes and water shocks on the coating surface can cause the hardened coatings to fall off.
8) External Pressure/Vacuum: The external pressure variation is similar to the water hammering phenomenon, and the vacuum inside the pipe can accelerate the stripping of the coating.
9) Seismic: Polymer products tend to be hardened during long-term operation. In these situations, external

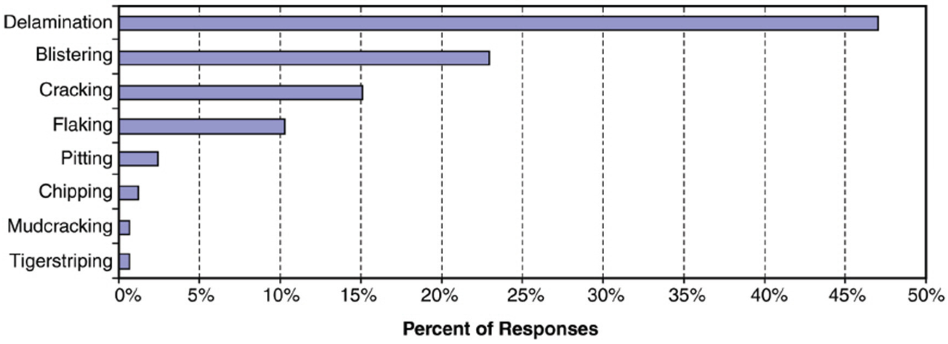

Fig. 1 **EPRI survey results for lining damage.**

forces such as earthquakes may cause cracks in the coating.

10) Manufacturing or installing defect: If there are cracks, defects, and other structural discontinuities in the base of the pipe before the coating, the combination of the resin and the pipe may not be smooth, and the coating damage may be accelerated due to temperature and pressure differences on the inside and outside of the resin.

According to a 2006 U.S. EPRI survey on the causes of lining damage [3], it was found that lining damage by delamination was the most common, followed by blistering, cracking, flaking, etc. Fig. 1 shows the EPRI survey results for lining damage.

3. Damage Assessment for a Seawater Piping

3.1 Design and Damage Characteristics

The design characteristics and the damage status were reviewed for analysing the causes of damage in the piping of the component cooling seawater system of a particular nuclear power plant in Korea. Fig. 2 shows a schematic diagram of the area where the damage occurred. Fig. 3 shows the Isometric Drawing of the area. In both figures, the area marked with a circle is the area where the damage occurred, and an orifice is installed in front of the damaged pipe. The pipe is a diameter of 609.6 mm (24 in), a pipe thickness of 9.5 mm, an Archcoat of polyester family, and a coating thickness of about 2 mm. Fig. 4 and Fig. 5 show internal and external photographs of the areas where the damage occurred. As shown in the two figures,

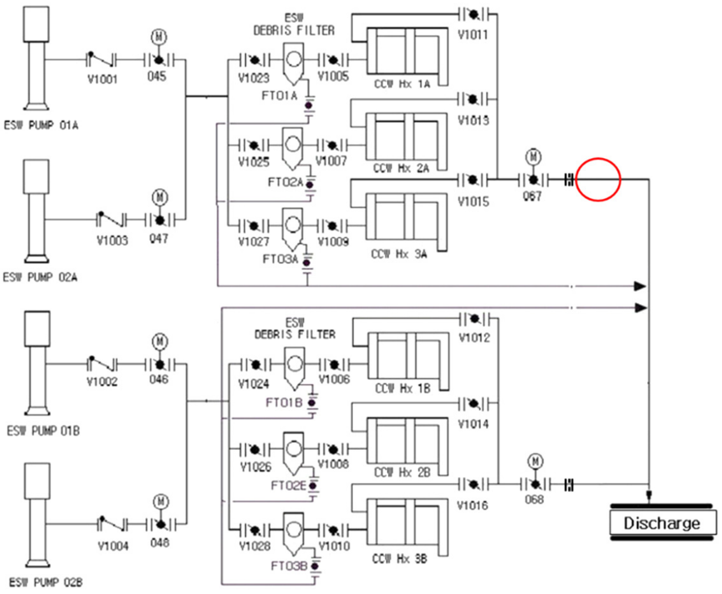

Fig. 2 **System schematic diagram of the seawater system**

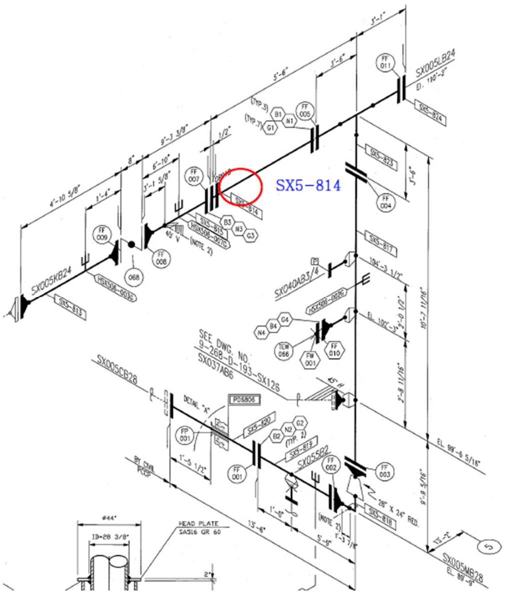

Fig. 3 **Isometric drawing of the damaged pipe.**

Fig. 4 **Damaged inside surface.**

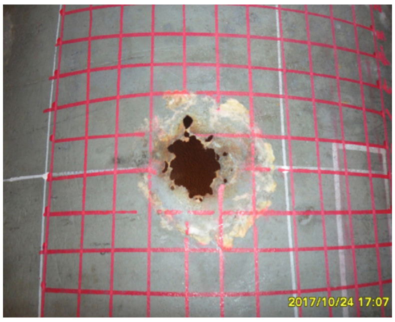

Fig. 5 **Damaged outside surface.**

the lining of the damaged pipe is peeled and the base metal is eroded, indicating that cavitation is the cause of the damage.

3.2 Cavitation Evaluation

Visual inspection results show that the cause of the pipe damage in the component cooling seawater system is cavitation due to differential pressure at the front and rear of the orifice. As such, the cavitation evaluation was performed by engineering method. The cavitation evaluation was performed by the Tullis theory described in EPRI Report [4]. Cavitation and flashing are not evaluated as quantitative values, but rather as a method of evaluating the conditions under which the pipe is located by separating the occurrence conditions step by step. The intensity of the generation of the phasic cavitation can be calculated from the following equations (1) through (4) [5].

$$\sigma_i = 0.62 + 4.4C_d + 6.6C_d^2 + 1.3C_d^3 \quad (1)$$

$$\sigma_c = 0.78 + 1.0C_d + 7.9C_d^2 - 3.2C_d^3 \quad (2)$$

$$\sigma_{id} = -0.11 + 6.5C_d - 7.6C_d^2 + 8.6C_d^3 \quad (3)$$

$$\sigma_{ch} = 0.15 + 1.2C_d - 0.31C_d^2 + 3.3C_d^3 \quad (4)$$

where, C_d and β are shown in equations (5) and (6).

$$C_d = 0.019 + 0.083\beta - 0.203\beta^2 + 1.35\beta^3 \quad (5)$$

$$\beta = \frac{d}{D} \quad (6)$$

equations (7) through (10) indicate an adjusted cavitation index, which are compared with the cavitation index (σ) to estimate the intensity of the cavitation occurrence.

$$\sigma_{ad,i} = SSE \cdot PSE \cdot (\sigma_i - 1) + 1 \quad (7)$$

$$\sigma_{ad,c} = SSE \cdot PSE \cdot (\sigma_c - 1) + 1 \quad (8)$$

$$\sigma_{ad,id} = SSE \cdot PSE \cdot (\sigma_{id} - 1) + 1 \quad (9)$$

$$\sigma_{ad,ch} = SSE \cdot PSE \cdot (\sigma_{ch} - 1) + 1 \quad (10)$$

where SSE and PSE represent size scale effect and pressure scale effect. And the cavitation strength is determined by equation (11) through equation (15).

$\sigma_{ad,i} < \sigma$: No Cavitation (11)

$\sigma_{ad,c} < \sigma < \sigma_{ad,i}$: Incipient Cavitation (12)

$\sigma_{ad,id} < \sigma < \sigma_{ad,c}$: Cavitation (13)

$\sigma_{ad,ch} < \sigma < \sigma_{ad,id}$: Incipient Damage (14)

$\sigma < \sigma_{ad,ch}$: Chocking (15)

The actual operating conditions of the pipe are shown in Table 1. The results of the cavitation evaluation are shown in Table 2, and the cavitation index (σ) is smaller than $\sigma_{ad,c}$ and greater than $\sigma_{ad,id}$, and thus is evaluated

Table 1 **Actual operating conditions**

No	Item	Unit	Value	No	Item	Unit	Value
1	Inlet Pressure	Pa(a)	273,626	5	Operating Temperature	℃	40.06
2	Outlet Pressure	Pa(a)	18,750	6	Density	kg/m^3	1,025.4
3	Pressure Difference	Pa(a)	254,876	7	Salinity	ppt	45
4	Vaporization Pressure	Pa(a)	7,409	8	Inlet Velocity	m/s	3.217

Table 2 Cavitation evaluation results

$\sigma_{ad,i}$	$\sigma_{ad,c}$	$\sigma_{ad,id}$	$\sigma_{ad,ch}$	σ	Decision
3.281	2.031	1.340	0.580	1.044	**Incipient Damage**

to be occurring the incipient damage.

3.3 CFD Analysis

Fluid dynamic analysis was conducted to analyse the possibility of cavitation using the ANSYS FLUENT code. The analytical model ranges from the pipe in front of the valve 068 shown in Fig. 3 to the vertical pipe TEW 066 lower 30.34 m (99.526 ft) (elevation). Fig. 6 shows the target model, and Fig. 7 shows the grid system. The composite grid was used. The butterfly valve, orifice, and tee areas with relatively complex features were based on the tetrahedral grid. The rest of the area was based on the prism grid using the sweep mesh technique. The boundary conditions for analysis are same as shown in Table 1.

Standard k-ε model was applied as a governing equation for numerical analysis. The transport equation for the turbulent kinetic energy (k) and the turbulent displacement rate (ϵ) used in the Standard k-ε model is as shown in equations (16) and (17) [6].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon + Y_M + S_k \quad (16)$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_k \quad (17)$$

Schnerr & Sauer model was used for the cavitation evaluation. In cavitation modeling, the mass transfer between liquid and vapor is calculated by the steam transport equation (18).

$$\frac{\partial}{\partial t}(\alpha\rho_q) + \nabla\cdot(\alpha\rho_v\vec{V}_v) = R_e - R_c \quad (18)$$

where α is the volume fraction of steam, R_v is the density of steam, $\vec{V}_v$ is the flow rate of steam. R_e and R_c mean the mass transfer rate under evaporation and condensation conditions, respectively, and is evaluated as equations (19) and (20), where r_B is the radius of bubbles, P_v is saturated steam pressure, and ρ_l means the density of the liquid.

$$R_e = \frac{\rho_v\rho_l}{\rho}\alpha(1-\alpha)\frac{3}{r_B}\sqrt{\frac{2}{3}\frac{(P_v - P)}{\rho_l}} \qquad when\ \ P_v \geq P \quad (19)$$

$$R_c = \frac{\rho_v\rho_l}{\rho}\alpha(1-\alpha)\frac{3}{r_B}\sqrt{\frac{2}{3}\frac{(P - P_v)}{\rho_l}} \qquad when\ \ P_v \leq P \quad (20)$$

Fig. 8 shows the steam generation area derived from CFD analysis, and Fig. 9 and Fig. 10 illustrate the dis-

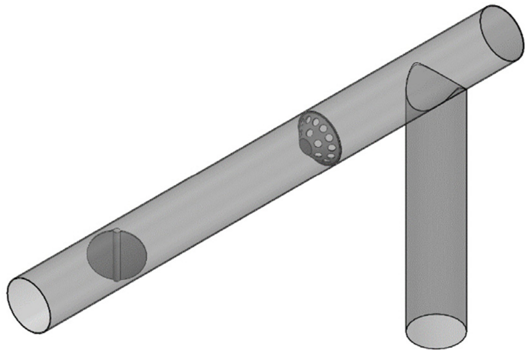

Fig. 6 Target model.

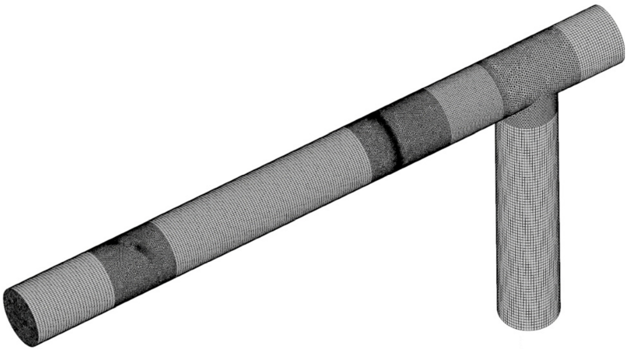

Fig. 7 Grid composition.

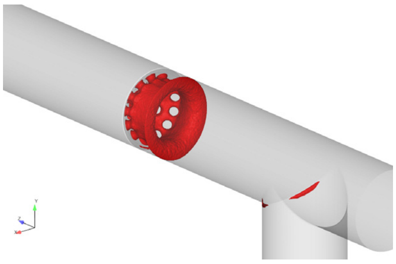

Fig. 8 Steam generation area.

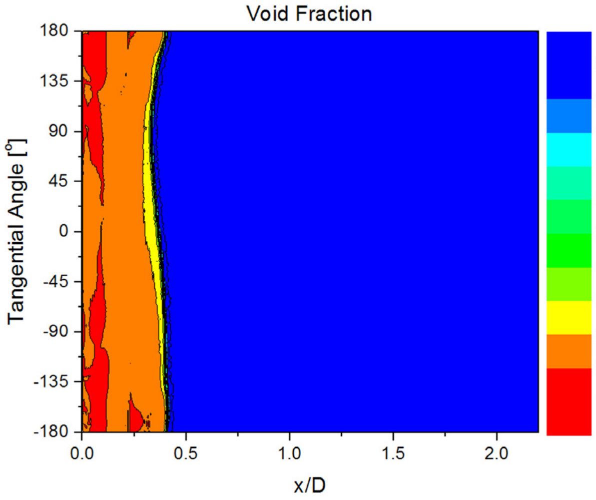

Fig. 9 Void fraction contour in vertical section

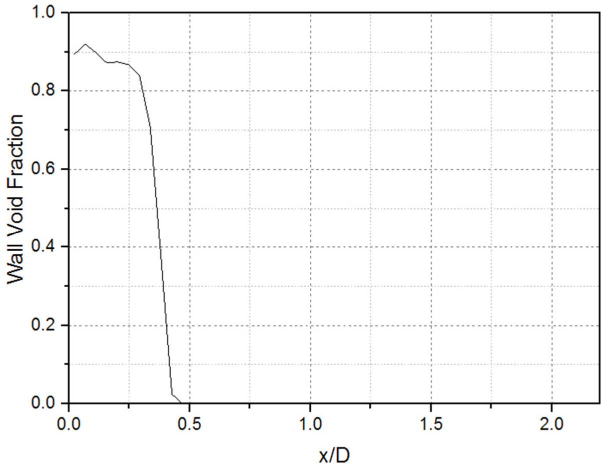

Fig. 10 Void fraction profile in vertical section

tribution of void fractions in vertical sections of piping in contour and void fraction profile. It was assessed that cavitation occurred as it was assumed to be dissipated after air bubbles were generated near the pipe wall up to an area of approximately 0.5D at the rear of the orifice. This corresponds to the pipe damage areas shown in Fig. 2 and Fig. 3.

4. Conclusions

The cause of piping damage was analysed by engineering evaluation and CFD analysis for the damage of the lining occurred in the rear piping of the orifice installed at the rear of the heat exchanger of the component cooling seawater system of a particular nuclear power plant in Korea. In the engineering evaluation using the Tullis theory, it was evaluated as an incipient damage, and CFD analysis also interpreted cavitation as a result of the rapid disappearance of bubbles over a 0.5D distance after bubbles were generated at the immediate rear of the orifice. In the case of seawater piping, if the internally lined polymer material can absorb water shock by cavitation, there is no damage to the piping. However, a polyester-based Archcoat lining material installed inside the piping was found to be failed to withstand the impact from cavitation due to its high hardness and hardening of materials due to its long-term use. This corresponds to the flaking damage in Fig. 1.

To prevent or mitigate such damage, it is necessary to find ways to prevent rapid pressure reduction by securing horizontal part length at the rear of the orifice, reducing cavitation through change of orifice hole size or type, and optimizing operation range with no cavitation.

References

1. T. Eckert, Service Water Piping Guideline, EPRI 1010059, Final Report (2005).
2. K. M. Hwang, *Proc. The CSSK Spring Meeting & Corrosion Technology Seminar*, pp. 19 - 20, Changwon Exhibition Convention Center, Changwon (2019).
3. T. Eckert, Plant Support Engineering: Aging and Degradation Survey for Nuclear Service Level I Coating, EPRI 1013465, Final Report (2006).
4. J. P. Tullis, Hydraulics of Pipeline – Pumps, Valves, Cavitation, Transients, JOHN WILEY & SONS (1989).
5. R. Mahini, A Method to Predict Cavitation and the Extent of Damage in Power Plant Piping, EPRI TR-103198-T1, Final Report (1993).
6. Y. A. Cengel and J. M. Cimbala, Fluid Dynamics, McGraw-Hill (2005).