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SELECTION OF CORROSION-RESISTANT MATERIAL FOR THE CASING OF NPP PUMP UNITS UNDER CAVITATION DAMAGE CONDITIONS

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The results of the surface condition assessment of a damaged pump unit casing are presented. It was found that the destruction of S355JR steel has a cavitational nature, with a corrosion rate of 15…20 mm/year. Fluid flow modeling indicated the possible formation of crevice cavitation in areas where intensive corrosion traces were detected during operation. The results of metallographic studies on the composition, structure, type, and nature of corrosion are provided, along with the characterization of the corrosion process in the metal of the casing. To select a suitable material for the pump unit casing of a nuclear power plant, the corrosion resistance of several chromium-nickel steels was investigated under conditions as close as possible to actual operating conditions. The highest corrosion resistance was demonstrated by steels containing molybdenum, such as 254 SMO, SAF-2507, and AISI 316Ti, as well as titanium. Steels like AISI 304 also exhibit high resistance to corrosion and erosion; however, under nuclear power plant operating conditions, they may be susceptible to pitting corrosion.

INTRODUCTION

At nuclear power plants, pumps ensure coolant circulation, reactor cooling, and the operation of safety systems. Therefore, protecting pumping equipment from cavitation is a critically important task, as any failure can lead to reduced safety and efficiency of the entire plant. Cavitation erosion is one of the primary causes of damage to hydraulic machine components and liquid transport systems.

Cavitation is the process of bubble formation and subsequent collapse in a liquid [1], occurring due to local pressure fluctuations caused by flow or vibration. When bubbles collapse near a solid surface, they generate high-pressure impulses. Repeated impulses cause plastic deformation of the material, fatigue, and gradual mass loss, described as the process of cavitation erosion. The intensity of such damage is determined by hydrodynamic parameters and the physicochemical properties of the liquid [1]. A distinguishing feature of cavitation erosion is that a material’s resistance to this type of degradation is a unique mechanical characteristic that does not always directly correlate with its bulk properties [2].

The negative effects of cavitation in pumps include:

– Mechanical damage – destruction of impeller blades, cracks, and erosion;

– Hydraulic issues – reduced system performance and increased energy consumption;

– Increased noise and vibration levels – excessive load and bearing wear;

– Higher risk of emergency situations – failure of cooling systems.

Cavitation is a critical issue in pumping systems, leading to reduced efficiency, material damage, and operational failures. Various strategies can be applied to mitigate cavitation, including design improvements, operational adjustments, and the use of advanced materials or technologies.

Optimizing pump design is a fundamental approach to preventing cavitation. This includes using durable materials resistant to cavitation-induced erosion, such as hardened alloys or protective coatings. Additionally, optimizing the impeller blade geometry can help minimize pressure drops and turbulence. Screens or diffusers can also be used to stabilize flow and reduce the likelihood of cavitation by lowering pressure.

Ensuring adequate net positive suction head (NPSH) is crucial for preventing cavitation. Operators must maintain sufficient hydraulic head by controlling liquid temperature, pressure, and flow rate. Excessive suction height should be avoided, as it can cause pressure to drop below the liquid’s vapor pressure, triggering cavitation. Operating pumps within their rated range is essential for avoiding cavitation. Abnormal operation, such as excessively high or low speeds, can also contribute to cavitation formation. Frequency converters can be used to regulate pump speed and maintain optimal operating conditions, reducing the risk of cavitation. Vibration exacerbates cavitation by destabilizing fluid flow and promoting bubble formation. Implementing anti-vibration measures, such as dampers and balancing rotating components, can help mitigate these effects. Proper alignment and maintenance of pump components also contribute to reducing vibration-induced cavitation.

Chemical additives can be introduced into the liquid to reduce bubble formation and stabilize flow. These inhibitors alter the liquid’s properties, such as surface tension or viscosity, to minimize cavitation. Although this method is effective, it requires careful consideration of compatibility with the fluid and system materials.

Advancements in pump technology offer innovative solutions for cavitation prevention. For example, pumps with dual impellers distribute pressure more evenly, reducing the risk of cavitation. Cavitation suppressors, which dissipate energy from bubble collapse, can also be integrated into pump systems to reduce damage.

In conclusion, protecting pumps from cavitation requires a multifaceted approach that combines robust design, operational vigilance, and advanced technologies. By implementing these methods, the longevity and efficiency of pumping systems can be significantly enhanced, minimizing risks associated with cavitation.

1. PROBLEM STATEMENT

The inspection of pump unit operations has identified several key factors accelerating the corrosion of nuclear power plant (NPP) pump casings. These include low material resistance, hydroerosion, cavitation, and exposure to the working environment containing suspended particles and oxygen. Under such conditions, the metal surface undergoes cyclic loading, while the environment significantly reduces the material's fatigue limit.

Variable stresses cause deformation of the protective film that forms on the metal surface, making it susceptible to mechanical loads. The degree of this susceptibility depends on the structure and properties of the metal. Corrosion-resistant alloys exhibit greater resistance to mechanical degradation in microzones compared to less resistant materials, where the protective film loses its integrity.

To select a material with high corrosion-erosion resistance, reference materials were tested for cavitation erosion resistance using the ASTM G32-10 standard. Based on studies by American researchers Knapp and Garcia [2, 3], a comparative analysis of material resistance to cavitation erosion was conducted.

To assess the durability of all materials, the maximum erosion rate parameter was chosen, normalized over a wide range of material densities. The physical representation of this parameter is the linear erosion rate, expressed in micrometers per hour.

The objective of this study is to determine the most resistant structural materials for NPP pump casings under cavitation damage conditions.

2. RESEARCH METHODS

To study the microstructure of the casing material, a metallographic method (light microscopy) was used. This approach allowed for the investigation of the shape, size, and mutual arrangement of crystals, and defects in the crystal structure. Samples of S355JR steel were prepared in the form of cylinders and polyhedra sized 10…20 mm, cast in thermosetting plastics for ease of examination. To reveal the structure, chemical etching was performed using standard etchants (e.g., 5% HNO_3 in ethyl alcohol).

Micrographs were examined using an Optika IM-3 MET microscope at 100x magnification. The samples were compared according to the DSTU standard.

Gravimetric testing was conducted following the methodology developed by UKRNIIXimMash [4]. Samples were mounted on a pin, and to determine the overall corrosion resistance, carbon steel samples of grade Vst-3 were added to the cassette. To prevent electrochemical corrosion due to contact between different metals, the samples were isolated using fluoroplastic tape and rings. The pin was fixed in side holders made of stainless steel, forming a single cassette (Fig. 1). Appearance of the cassette with experimental samples for gravimetric research

Fig. 1. Appearance of the cassette with test samples for gravimetric studies

The metal samples were tested in a flow of cooling water from the nuclear power plant. The cassettes with the experimental samples were mounted on a sludge trap to ensure their exposure to the flow of cooling water. To improve the accuracy of the results and reduce measurement errors, two experimental cassettes with identical samples were manufactured. The samples were exposed to the water flow for 360 h. This setup allows for the assessment of the intensity of corrosion wear of the samples under the selected conditions.

Corrosion-resistant steels (Table 1), which provide high resistance in salt environments and are characterized by high resistance to hydroerosion, were selected for the tests. Zones free from corrosion were also taken from the pump casing, and samples were made from these zones in the form of plates 10 mm thick for further comparison of research results.

Table 1

Chemical composition of steels selected for testing

Steel grade	Content of alloying components, %							PRE*
	C	S	P	Cr	Ni	Mo	N	
254 SMO	0.01	0.010	0.030	20.0	18.0	6.1	0.20	43
SAF-2507	0.02	0.010	0.030	25.0	7.0	4.0	0.27	43
AISI 304	0.08	0.030	0.045	19.0	9.3	–	–	–
AISI 316Ti	0.08	0.030	0.045	18.7	12.0	2.4	–	40
AISI 410	0.08	0.030	0.04	11.5	0.6	–	–	–
S355JR**	≤ 0.24	≤ 0.035	≤ 0.035	–	–	–	≤ 0.012	–
Vst-3	0.15	0.05	0.04	0.03	0.2	–	–	–

* – pitting resistance index
** – steel contains Mn≤ 1.60 and Si ≤ 0.55, as well as Cu ≤ 0.55

The modeling of cavitation conditions was carried out using a high-speed disk electrode VDE-U. The corrosion rate was estimated by analytical methods based on the amount of dissolved iron in the medium.

The modeling of cavitation occurrence in the medium was carried out using the ANSYS Turbogrid program.

To monitor the corrosion activity of the cooling water in the pump unit, a laboratory electrochemical measurement of corrosion activity was used, which involved obtaining potentiostatic curves. The corrosion activity was determined by the electrochemical method based on the ER-20A potentiostat, which was automatically controlled by a program via a computer. The measurements were conducted in a glass three-electrode cell with separated electrodes and free access to oxygen within the cell. The electrode potential values were measured relative to a saturated silver chloride electrode, E_0 = -0.222 V. A platinum disc was used as the auxiliary electrode, while the working electrode was the steel sample made from the selected pump casing material. To simulate the water flow velocity, a rotating electrode was used.

The corrosion current was determined by analyzing the polarization curves, which establish the relationship between the electrode potential of the steel electrode and the current density of steel dissolution during polarization from an external constant current source.

The corrosion current density is proportional to the corrosion rate of the metal in the studied environment, which was determined by extrapolating the Tafel regions on the obtained polarization curves to the corrosion potential value. The corrosion rate of the metal in the studied solution was determined using the formula:

$$K_m\ [\text{g/m}^2\cdot\text{hr}] = \frac{i\cdot A}{n\cdot 2{,}68\cdot 10^{-2}},$$

where A is the atomic mass of iron; n is the number of electrons involved in the electrochemical reaction; i is the corrosion current density, A/cm².

3. EXPERIMENTAL STUDIES

3.1. DETERMINATION OF THE NATURE OF DAMAGE

A visual inspection of the damage to the pump unit housing revealed through holes of various diameters (Fig. 2,a), a radial crack near the pump screw (Fig. 2,b) and local foci of corrosion of various depths.

The main damage is concentrated in the form of a radial strip in the area of movement of the pump screw. Single point metal defects (1…2 mm in diameter) were found along the periphery of the damage zone, which increase towards the central part. A spongy structure was formed in the middle part of the damage zone, which is characterized by a significant area of damage and depth of destruction. The damaged surface is covered with brown corrosion products that are easily removed and white deposits formed by salts dissolved in water. The study of the electrochemical potential values in the pump housing area confirmed the stability of the voltage, which excludes the possibility of electrochemical corrosion caused by stray currents, and indicates reliable grounding of the equipment.

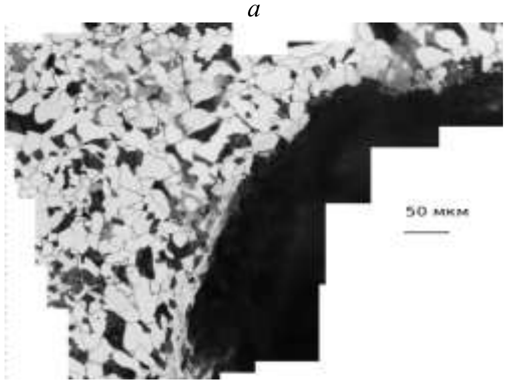
a

b

Fig. 2. Appearance of the pump casing after operation:
a – through holes of different diameters,
b – radial crack near the pump screw

Metallographic studies of samples of damaged S355JR steel showed that due to corrosion, local destruction of the material microstructure occurs (Fig. 3,a). This is accompanied by an increase in the surface area and the formation of individual areas of pearlitic microstructure (Fig. 3,b).

a



b

Fig. 3. Corrosion damage to S355JR steel of the pump casing:
a – corrosion damage to steel on an unetched section of the specimen, magnification, x50;
b – corrosion damage to steel on an etched section of the specimen, magnification, x500

Analysis of corrosion damage revealed that the destruction process occurs mainly in the form of general corrosion with the formation of pores, cavities and pits, the sizes of which significantly exceed the size of the steel grain. Corrosion damage does not have signs of intergranular corrosion, which indicates the absence of a significant influence of grain boundaries on the material degradation process. The main mechanism of destruction is electrochemical corrosion, enhanced by the hydroerosive influence of the working environment.

3.2. ANALYSIS OF FLOW PARAMETERS IN A PUMP UNIT

The modeling of cavitation in the medium was carried out using the ANSYS Turbogrid program in 3 stages. At the first stage, the problem was solved in a one-dimensional formulation. The solution contained regions with a negative pressure value. This is completely unphysical, but indicates the presence of a phase transition.

At the second stage, the problem was solved in a two-phase formulation. In this case, the saturated vapor pressure was given as a function of temperature, given that the temperature was taken as one of the parameters for conducting a numerical experiment. A feature of the calculation at the second stage was the adoption of a homogeneous flow model to ensure a stable calculation process.

At the third stage, the modeling was carried out using the calculation results of the second stage as initial values. In this case, an inhomogeneous model was used, which allowed different velocities for the liquid and gas phases.

The velocity distribution in the gap between the blade and the casing (gap 2 mm) is presented in Fig. 4. According to the results of numerical modeling during the operation of the pump unit, the flow velocity in the gap between the impeller blades and the casing can reach up to 38 m/s. The modeling showed that in areas where traces of intense corrosion were found during operation, gap cavitation may occur.

During the numerical experiment, where the gap between the impeller blades and the casing and the water temperature were varied as parameters, it was found that the formation of steam phase in the gap occurs across the entire investigated range.

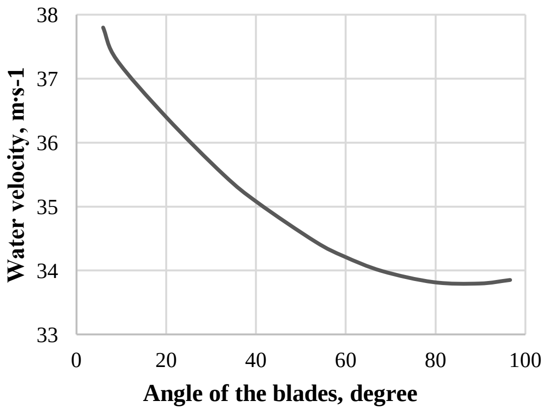


Fig. 4. Velocity distribution in the gap between the blade and the casing

The maximum speed in the gap between the blades and the casing, when the gap is increased from 2 to 4 mm, decreases from 37.5 to 35.7 m/s, while the maximum steam phase fraction on the casing wall decreases from 75 to 56%. Thus, increasing the gap will positively affect the operating conditions of the pump unit in terms of the durability of the flow path parts against corrosion.

3.3. DETERMINATION OF CORROSION AGGRESSIVENESS OF COOLING WATER

The results of corrosion tests in the cooling water of the nuclear power plant are presented in Table 2 and Fig. 5.

According to the results of the field tests, the mass corrosion rate of the shell material (S355JR steel) is between 0.31 and 0.52 g/(m²·h). This material is poorly resistant to corrosion and requires protection. More resistant materials include corrosion-resistant steels 254 SMO, AISI 304, SAF-2507, AISI 316Ti, and titanium.

The calculation of the Langelier Index according to the Building Codes (SNiP) shows that at a temperature of 42 °C, the cooling water of the circulating cycle has a positive value in the range of (1.50–1.52), indicating the scaling regime of the cooling cycle [5].

Table 2

Results of corrosion field tests at a water velocity of 0.5 m/s. Test period 300 h

Material	Sample surface area S, m^2	Loss of mass of samples, g	Weight loss per unit surface area, g/m^2	Corrosion rate, g/(m^2·h)
S355JR	0.0051	0.9745	189.81	0.5272
AISI316Ti	0.0045	0.0039	0.87	0.0024
AISI 304	0.0020	0.0061	3.00	0.0083
Titanium	0.0045	0.0015	0.33	0.0009
254 SMO	0.0030	0.0006	0.20	0.0006
SAF-2507	0.0034	0.0025	0.74	0.0021
Vst-3	0.0028	0.2926	104.78	0.2911

Analysis of the obtained data (see Fig. 5) indicates that S355JR steel shows significantly increased weight losses on rotating samples. Alloyed steels, such as stainless steels, exhibit much lower wear. As the sample rotation speed increases, the corrosion-erosion wear noticeably increases.

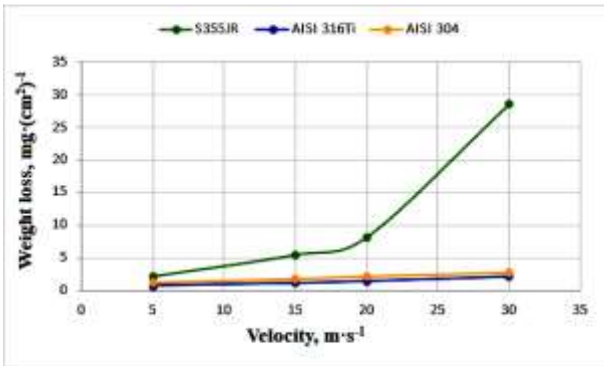


Fig. 5. Mass loss of samples during corrosion-erosion wear tests

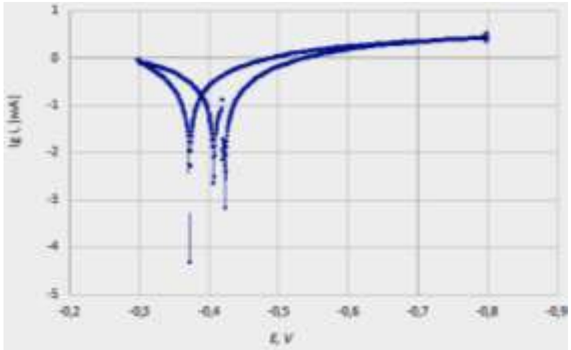
For AISI 316Ti stainless steel, this dependence is linear (see Fig. 5). For S355JR steel, a change in speed from 5 to 20 m/s increases the weight loss of the sample by approximately 2.0–2.4 times. With a further increase in speed, the weight loss of the sample increases sharply at a speed of 30 m/s, increasing by approximately 14 times. For AISI 304 steel, the weight loss of the samples is significantly lower. At a speed close to 30 m/s, the weight loss of the AISI 316Ti steel sample is 15 times less. This can be explained by the presence of a denser and stronger oxide film in stainless steel, which protects the metal well from the external environment and has increased resistance to mechanical effects of the liquid.

Analysis of cyclic voltammograms (Fig. 6) of S355JR steel in NPP cooling water at a temperature of 40 °C at different water velocities of 1.5 and 3.5 m/s shows that the corrosion rate of this steel increases from 1.2 to 1.7 g/(m^2·h). In addition, the electrode potential of the steel becomes more negative with increasing water velocity, which confirms the activation of S355JR steel.

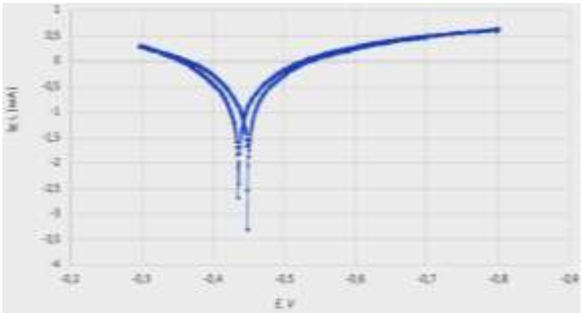
Analysis of cyclic voltammograms of AISI 304 and AISI 316Ti steels in NPP cooling water at a temperature of 40 °C at a water velocity of 3.5 m/s shows that the corrosion rate of these steels is approximately – 0.1 g/(m^2·h). Under these conditions, these steels are in a passive state. Thus, these steels will be stable under these conditions. It should be noted that on AISI 304 steel, current fluctuations are observed in the potential range from -0.3 to 0.3 V, which confirms the instability of the protective films. Thus, under these conditions, AISI 316Ti steel will be more stable.

Since scale deposits will form in the system, areas with varying aeration will appear. As a result, studies on the corrosion behavior of these steels in narrow gaps – crevices – were conducted. According to the obtained results, the mechanism of corrosion initiation and progression, activated by pitting or crevice corrosion, is identical and is determined by the operation of a powerful galvanic element – anode (bottom of the pit) – cathode (passive surface that has not been activated).

Based on this, an accelerated electrochemical method for assessing the corrosion resistance of structural materials was used [6]. The essence of the method lies in a specially developed electrode [6], which determines the potential of the activated metal in the crevice. By studying the anodic behavior of AISI 304 and AISI 316Ti steels in cooling water at nuclear power plants at a temperature of 40 °C, it was found that AISI 410 steel corrodes even at a free corrosion potential of $\Delta\varphi = \varphi_{(RP)} - \varphi_{(free.cor.)} < 0.05$ V.



a



b

Fig. 6. Voltamperogram of S355JR steel in the cooling water of the nuclear power plant at a temperature of 40 °C at a water flow velocity: a – 1.5 m/s; b – 3.5 m/s

Ulcerative degradation also affects AISI 304 steel in the crevice. Upon investigation, only AISI 316Ti steel shows sufficient resistance to activation in the crevice. The main electrochemical parameters for metal activation in the crevice are provided in Table 3.

Table 3

Activation parameters of metals in the gap

Potentials, V	Material		
	AISI 316Ti	AISI 304	AISI 410
Free corrosion potential $\varphi_{(free.cor.)}$	0.04	-0.015	0.015
Pitting formation potential $\varphi_{(pf)}$	1.1	1.0	0.2
Repassivation potential $\varphi_{(RP)}$	0.42	0.25	-0.15
Activation potential in the gap $\varphi_{(akt.p)}$	0.37	0.25	0.05
Repassivation potential in the gap $\varphi_{(rp.p)}$	0.37	-0.11	-0.05
$\Delta\varphi = \varphi_{(RP)} - \varphi_{(free.cor.)}$	0.34	-0.09	-0.20

As can be seen from the data (see Table 3), the potential for the onset of ulcerative corrosion in the bulk is 0.2, 1.0, and 1.1 V (depending on the degree of alloying), and the potentials for stopping pitting activity are -0.15, 0.25, and 0.42 V, respectively. These potentials, referred to as the repassivation potentials of the metal in the crevice, indicate a greater susceptibility to corrosion degradation in the crevice than in the bulk.

The process of active metal degradation in the crevice continues until the repassivation potential is reached. Below this potential, the metal no longer corrodes, both in the bulk and in the crevice. The difference between the repassivation potential in the crevice and the free corrosion potential serves as the basis for selecting corrosion-resistant materials. Thus, AISI 316Ti steel is more resistant to pitting corrosion than AISI 304 steel in cooling water at nuclear power plants.

4. DISCUSSION OF RESULTS

The selection of steels resistant to corrosion-erosion *co*nditions was based on corrosion tests, which showed high corrosion resistance in the cooling water of the pump unit.

The most resistant materials are corrosion-resistant steels such as 254 SMO, AISI 304, SAF-2507, AISI 316Ti, and titanium. The corrosion-erosion destruction rate of steel S355JR is catastrophic, with losses of 10…12 mm/year. The analysis of ASTM G32-10 test data also shows that AISI 304, AISI 316Ti, SAF-2507 (Ferralium Duplex S32550), and titanium have the highest resistance to erosion among the tested materials [2, 3]. Thus, these structural materials or their analogs will be the most suitable materials for manufacturing the pump unit casing due to their high corrosion-erosion resistance. These materials will ensure high cavitation resistance under real operating conditions. Steels such as AISI 304 also demonstrate high resistance to corrosion and erosion; however, under the operating conditions of a nuclear power plant, they may be sensitive to pitting corrosion.

CONCLUSIONS

1. S355JR steel does not provide sufficient resistance to cavitation and corrosion under operating conditions in nuclear power plants. The use of stainless chromium-nickel steels with molybdenum (254 SMO, SAF-2507, AISI 316Ti) or titanium will significantly increase the service life of the pump unit casing.

2. Numerical modeling showed that the flow velocity in the gap between the impeller blades and the casing can reach 38 m/s, and in areas of intensive corrosion, crevice cavitation occurs. The steam phase forms throughout the entire range of the study. Increasing the gap from 2 to 4 mm reduces the maximum velocity from 37.5 to 35.7 m/s and the steam phase on the casing wall from 75 to 56%, which improves the material's resistance to corrosion.

3. It has been shown that AISI 304 steel can only be used in moderately corrosive conditions and when there are no high cavitation loads.

4. Optimizing the shape of the impeller blades and the pump casing helps reduce turbulence and low-pressure zones, minimizing the risk of cavitation damage.

5. Maintaining optimal levels of pressure, temperature, and cooling water purity will help reduce corrosion intensity. The use of filters and degassing systems will decrease the impact of suspended particles and oxygen.

REFERENCES

1. А.Ф. Луговський, Н.В. Чухраєв. *Ультразвукова кавітація в сучасних технологіях.* К.: Видавничо-поліграфічний центр «Київський університет», 2007, 244 с.

2. Garcia Ramon. *Comprehensive Cavitation Damage for Water and Various Liquid Metals*: PhD dissertation: Nuclear Engineering, University of Michigan, USA, 1966, 399 p.

3. *Development of a Cavitation Erosion Resistant Advanced Material System:* Project Report for the Modular Advanced Composite Hull form Technology Project / Applied Thermal Sciences Inc; Kendrick L.H., & Caccese V. Sanford, Meand, 2005, 76 p.

4. *Керівний технічний матеріал: РТМ 26-01-21-68. Методи корозійних випробувань металевих матеріалів. Основні вимоги. Оцінка результатів*. Всесоюзний науково-дослідний і конструкторський інститут хімічного машинобудування. М., 1969.

5. W-index. Water index calculations. Version 5.0 for Excel [Електронний ресурс] / Marvin Silbert and associates. 23 Glenelia Avenue, Toronto, Ontario, Canada, 2006.

6. С.В. Нестеренко, В.А. Качанов. Працездатність і схильність до корозійного руйнування пластинчастих теплообмінників // *Комунальне господарство міст.* 2013, №110, с. 141-146.

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ВИБІР КОРОЗІЙНО-СТІЙКОГО МАТЕРІАЛУ КОРПУСУ НАСОСНИХ АГРЕГАТІВ АЕС В УМОВАХ КАВІТАЦІЙНОГО ПОШКОДЖЕННЯ

С.В. Нестеренко, О.В. Саввова, О.І. Фесенко, М.С. Бічев

Наведено результати оцінки стану поверхні пошкодженого корпусу насосного агрегату. Встановлено, що руйнування сталі S355JR має кавітаційний характер зі швидкістю корозії 15…20 мм/рік. Моделювання потоку рідини показало можливе утворення щілинної кавітації у місцях, де під час експлуатації були виявлені сліди інтенсивної корозії. Наведено результати металографічних досліджень складу, структури, виду і природи корозії, а також характеристику корозійного процесу в металі корпусу. Для вибору відповідного матеріалу для корпусу насосного агрегату атомної електростанції було досліджено корозійну стійкість кількох хромонікелевих сталей в умовах, максимально наближених до реальних умов експлуатації. Найвищу корозійну стійкість показали сталі, що містять молібден, такі як 254 SMO, SAF-2507, AISI 316Ti, а також титан. Такі сталі, як AISI 304, також демонструють високу стійкість до корозії та ерозії, однак в умовах експлуатації атомної електростанції вони можуть бути чутливі до точкової корозії.