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THERMOGRAPHIC MONITORING OF NUCLEAR POWER PLANT'S SPRAY PONDS USING INFRA-RED DATA PROCESSING METHODS

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This paper outlines an approach to monitor nuclear power plant spray ponds using thermographic monitoring. The approach involves measuring temperatures during summer and winter periods to identify potentially dangerous or fault-prone areas and improve the reliability of technical water supply. The automated machine processing procedure for thermograms was developed based on digital image processing. The results demonstrate that the obtained database can effectively help determine losses resulting from critical situations at nuclear power plants.

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INTRODUCTION

The commissioning of new power generation facilities at nuclear power plants (NPPs) is associated with the task of providing cooling water [1]. For the operation of an AP-1000 reactor, about 57 m^3/s of cooling water is required, which is used for cooling the turbine condenser, the spent fuel pool, etc. Natural or artificial water reservoirs, as well as hydrotechnical structures such as cooling towers (dry and wet) and spray ponds, are used to meet the demand for technical water. In Ukraine, spray ponds are predominantly used for most NPPs, since the cooling capacity of spray ponds is sufficient in winter when the demand for electricity increases. Increased attention to emergency water supply systems, reliability of cooling water reservoirs and supply facilities for cooling the reactor's active zone and turbine steam condenser is a guarantee of preventing accidents with severe consequences, similar to those that occurred at the Chernobyl NPP and the Fukushima-1 NPP [2].

The operation of NPPs in Ukraine has been heavily impacted by military aggression of the Russian Federation. Previous discussions regarding terrorist threats to nuclear power plants have been primarily hypothetical, with direct intervention being mostly limited to various cyberattack scenarios [3]. However, the military occupation of the Zaporizhzhia NPP by Russia has occurred, and the shelling of the power infrastructure has created critical loads, which pose a significant risk to the safety of the plant's operation.

In response to significant nuclear accidents, such as Chernobyl and Fukushima, IAEA has revised the safety requirements, especially in the assessment of water supply systems' reliability. To restore the Zaporizhzhia NPP, modern tools will be required to evaluate its performance and facilitate its swift integration into the Ukrainian energy system as soon as possible.

PROBLEM STATEMENT

Reliable operation of spray ponds involves meeting the set of requirements during the acceptance stage, monitoring during operation, and carrying out preventive maintenance and regulatory work. Integrity of underground and surface pipelines, supporting structures, shut-off and regulating valves, nozzles, support grounds, and building structures are among the signs that determine their reliability. Mechanisms of destructive processes are based the fact that the ponds are open and therefore they are subjected to the influence of atmospheric factors: temperature fluctuations, wind, precipitation, and are in a state of constant mass exchange with the environment, including dust, leaves, vegetation, etc. Current instructions require measuring the water and air temperature, water level, wind direction, and visually observing the uniformity of water dispersion from nozzles and the presence of water leakage through enclosing structures.

A visual inspection, which may also involve documenting in the form of videos and photographs and their subsequent comparison over time, is usually an essential component of industrial facility monitoring. Considering that monitoring tools for the condition of NPPs in the IR range are currently being developed [4, 5], it is appropriate to consider approaches for their expanded application to the technical water supply system of NPPs. It should be added that modern trends in digitization encourage a review of monitoring procedures, as the processing of digital data significantly expands the information base while decreasing FTE of resources.

The results presented in this work, are based on materials acquired at the site of the Zaporizhzhia NPP before the occupation by Russian troops as part of testing the methodology of thermographic monitoring. The measurements were carried out using the Fluke Ti 32 thermographic camera with a temperature sensitivity of 0.05 K and a matrix size of 240x320 pixels.

SPECIFICS OF IR RADIOMETRIC STUDIES OF NPP SPRAY PONDS

Verification of the technical water supply system for responsible consumers in the group A at NPPs is crucial to prevent emergency cases of vacuum reduction in turbine condensers, improper cooling of spent nuclear fuel storage pools, etc. We propose an approach for assessing the state of spray ponds based on measurements conducted at the Zaporizhzhia NPP site.

Spray ponds are more effective than cooling ponds in terms of the area of hydraulic structures, although they are less energy-efficient due to the need to provide a pressurized supply of water to nozzles. Meanwhile, cooling ponds are simpler to construct and less energy-intensive [1].

Monitoring the condition of spray ponds is necessary for compliance with the operational instructions. Elements that require inspection include underground pipelines, shut-off valves, structures on which nozzles are installed, open pipelines, and building structures. The integrity of each of these elements is a component of the uninterrupted operation of hydrotechnical structures. However, due to the specific features of thermographic monitoring, the mechanisms of resource loss for each of these elements may differ due to the impact of external (natural) and operational factors.

One of the most important problems in verifying the state of the technical water supply system is the development of means, tools, and methods for determining the primary signs that precede damage to underground pipelines. For example, at the Zaporizhzhia NPP site, it is known that pipelines were laid under conditions of unstable groundwater levels. The pipelines are supported by concrete pillars on saturated grounds, and these operating conditions are associated with a range of mechanisms that can significantly accelerate corrosion processes. Rising groundwater levels may cause settlement of supports, leading to bending stresses and simultaneous destruction of the protective polymer layer, and intercrystallite corrosion. High soil moisture is also a significant factor that can accelerate corrosion by increasing the intensity of electrochemical processes. To ensure the integrity of the pipeline, a risk-oriented approach should be adopted instead of a random approach for selective excavation. Identifying sections with anomalous heat exchange characteristics is possible by analyzing a statistical base of measurements of the distribution of surface radiation temperature above the surface of the pipeline installation [6].

The decision-making process regarding the classification of a thermal image section as pre-failure is based on the analysis of the temperature field's dynamics using the temperature contrast method. The temperature contrast method is used for this purpose. This method involves analyzing the distribution of radiation temperature values $T_{i,j}$ using numerical methods with a spatial resolution defined by the distance between the thermal camera and the plane and the dimensions of the device matrix (actually $i \times j$). The pre-failure classification of high-risk areas is determined when the temperature contrast $\Delta T = \dfrac{T_{i+1,j} - T_{i,j}}{T_{i.j}}$ reaches the critical value $\Delta T \geq T_{\lim}$. This approach is applied for screening express analysis. The monitoring method involves measuring at specific time intervals. In the case of monitoring a macro-object, such as spray ponds, weather conditions have a significant impact, which corresponds to the active thermography, where the temperature field of the object under investigation is disturbed by an external influence. In this case, the temperature field $\Delta T_{r(i,j,t)}$ for each pixel over time t is taken into account, and the decision to classify as a high-risk area is made when the threshold value $\Delta T_{i,j,t_2} = \dfrac{T_{i,j,t_2} - T_{i,j,t_1}}{T_{i,j,t_1}}$ is reached.

During the startup acceptance tests, it is necessary to observe the absence of leaks from the reservoir and record any detected defects in a special journal over a period of 2–3 days. As noted in previous works [7, 8], the locations of water filtration are identified through thermographic observations, since moist poured soil has different heat exchange regimes from dry soil.

Fig. 1 shows the distribution of radiation temperature along the spray pond in August. It can be seen that the basin operates under high pressure, and the side surface is unevenly moistened due to the carried droplets beyond the basin's surface. At the same time, areas with different moisture values are clearly distinguished, but the temperature background is sufficiently uniform, indicating the integrity and homogeneity of the state of the side structures.

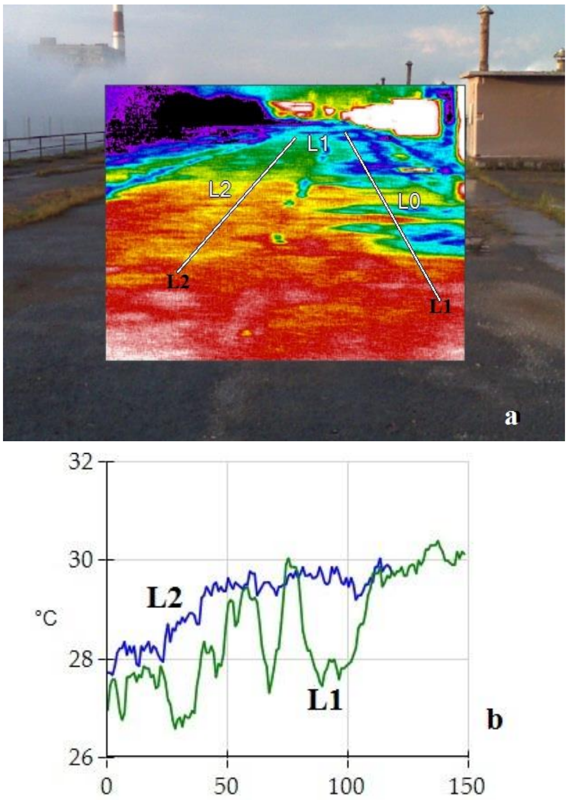

Fig. 1. Is the view of the NPP spray pond in the summer in the combined visible and infrared bands (a); shows radiation temperature distribution along the selected lines (b)

At the same time, we can see from Fig. 2 that the water temperature distribution is uneven over the surface, which is clearly visible in the IR mode. With this in mind, let’s proceed to compare the recommendations of the operating instructions with the capabilities of the proposed method.

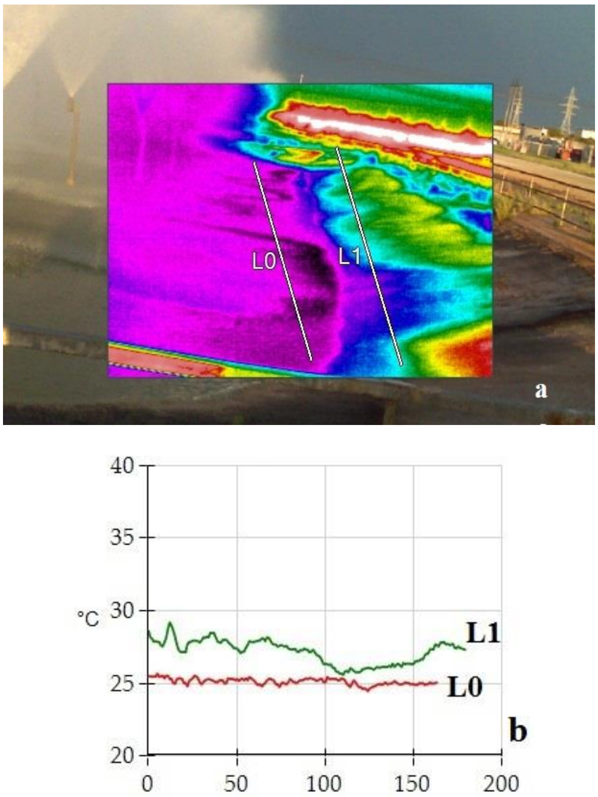

Fig. 2. Thermogram of the side part of the spray pond (a); distribution of radiation temperatures along the profiles as indicated on a (b)

According to the State Building Code B.2.5-74:2013 (Ukraine), the density of the reservoir should ensure the retention of water with a flow rate per surface of no more than 3 l/m^2. The thermograms in Figs. 1 and 2 visually demonstrate differences in radiative temperature depending on surface moisture. Although the excessive moisture in this case occurred due to water ejection from the pond nozzle, it can be expected that hidden moisture will also result in a temperature manifestation of the leakage point.

Given the current conditions where decisions are made to stop nuclear power blocks, it is expected that blocks will also need to be restarted suddenly, particularly in the winter. The operating rules stipulate that the spray pond should not be activated earlier than 12 h before the turbine rotation, and it is recommended to open the valves on idle drains for system warming up. These measures are taken to prevent water freezing in pipelines, nozzles, channels, and wells. The type of pool nozzle in the winter period is shown in Fig. 3. Operational control requires an understanding of the uniformity of system heating, which can be achieved by using thermographic monitoring.

As seen from Fig. 3, temperature decreases with increasing distance from the pipeline inlet. Therefore, the uneven distribution of temperature should be taken into account during operations such as pond startup. Considering the transition to quasi-steady state operation of the nuclear power plant, such operations will need to be performed in a rather unpredictable schedule, thus increasing the urgency for additional operational visual/automatic monitoring using thermographic techniques.

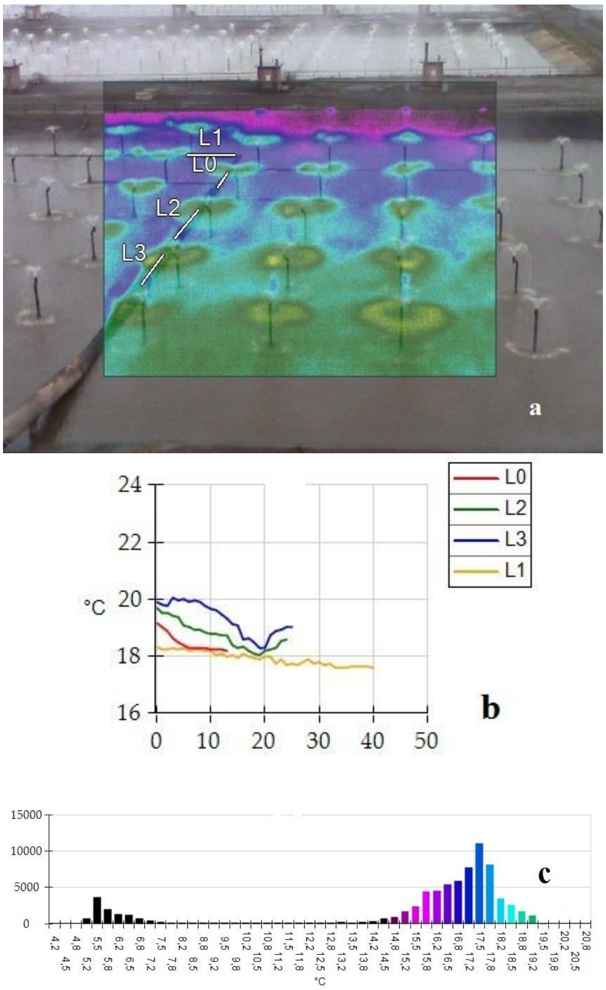

Fig. 3. Temperature distribution around the nozzles of the NPP spray pond (a); temperature profiles along separate sections of ponds structures (b); temperature distribution histogram (c)

In the same aspect, attention is drawn to the recommendation regarding the peculiarities of commissioning in the winter period. In particular, the requirement to prevent water from entering inactive pipelines due to gaps in the valves, as well as the requirement to insulate the pool bottom and walls with heat-insulating materials.

The thermogram makes it possible to determine the degree of inhomogeneity of the thermal field around the pond’s sides. It is also possible to determine local areas of potential freezing. Results of [9] highlight the need to take into account the direction and strength of the wind, because it predicts both the intensity of cooling and water loss:

$$\frac{\partial u}{\partial t} = -\frac{C_d A_d P_A (u - u')V}{m},$$
$$\frac{\partial v}{\partial t} = -\frac{C_d A_d P_A (v - v')V}{m} - g, \qquad (1)$$

where u – is the speed of the droplet in the horizontal projection; v is the speed of the droplet in the vertical projection; t – time; C_d – the coefficient determined by the Reynolds number; A_d is the cross-sectional area of the droplet; P_A is the air density; v', u' are the components of the air speed; V is the absolute speed of the droplet relative to the air; m – the mass of the droplet, and g is the acceleration of gravity.

The heat exchange mode is defined by the expression [10]:

$$\frac{\partial T}{\partial t}=-\frac{1}{\frac{4}{3}C_p\rho\pi r^3}\left[4\pi r^2 h_d\left(C_{WA}-C_\infty\right)\lambda+\right. \tag{2}$$

$$\left.+4\pi r^2 h_d\left(T-T_{A,\infty}\right)\right],$$

where T is the temperature of the droplet; C_p is the specific heat capacity of water; ρ is the density of water; C_{WA} is the concentration of water in air at the given temperature; λ – the energy of moisture evaporation; h_c is the heat exchange coefficient, and $T_{A,\infty}$ is the temperature of air at which the droplet is immersed in water.

It is important to recognize that the pond area experiences turbulence resulting in localized regions of more significant cooling. This issue can lead to increased operational costs and the occurrence of destructive processes, such as local freezing. This phenomenon is associated with the problem of maintaining the surface temperature above 3 °C during the winter months, while also monitoring the formation of ice and increasing the water level if necessary.

Monitoring the operation of the system with an area of approximately 10,000 m^2 is primarily done through visual observation as it is challenging to identify areas of local temperature decrease even with automated temperature collection from a distributed network of thermometers. The example of this challenge can be seen in Fig. 3, which shows a thermogram indicating differences in water temperature of about 3 K. In this regard, it is necessary to apply automated digital control technologies. The use of thermographic monitoring for a large-scale object such as spray ponds, it should not only be considered as an auxiliary tool for maintenance personnel, but also integrated into automated systems using image processing tools [11–14]. To determine potentially dangerous areas, it is advisable to determine the temperature interval within which to monitor the intensity of the IR radiation flow. For this, a segmentation procedure must be performed on the thermogram.

The following methodology was selected for processing IR images:

The temperature gradient field was calculated for the IR image, which was represented as a two-dimensional temperature matrix.

Considering that significant digital noise is inherent in real IR images, the calculated gradient also contains artifacts of this noise. A digital filter was applied to the Euclidean norm of the gradient to reduce the noise.

The final clustering was performed using the k-means method.

Fig. 4 shows the results of the intermediate stages of machine processing of the images in Fig. 3

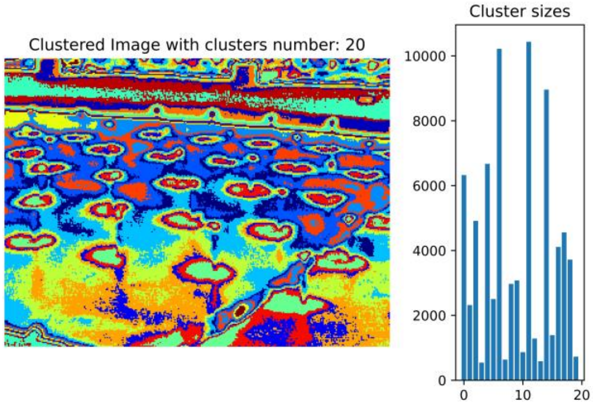

Fig. 4. Images of spray pond areas after machining

As can be seen from Fig. 4, the obtained histogram makes it possible to estimate the intensity in a certain interval of the radiation temperature. The paper [15] presents an additional algorithm for identifying potentially dangerous areas. To implement this method, stationary thermographic cameras should be installed. It is advisable to mount them in a case made of metal-polymer material [16, 17] for protection of electronics from electromagnetic interference and environmental factors. Another approach to obtaining a radiation-protective polymer material is the modification of elastomeric plastics. They are used as a structural material for seals in mechatronics and electronics. In work [18], the experience of using a UV laser for the manufacture of precision molds in plastic products is given. The resulting histograms will be processed using the Shannon entropy expression.

$$H_k=-\sum_{l=0}^{L}\frac{n_l}{N}\ln\frac{n_l}{N}, \tag{3}$$

where n_l – the number of pixels that registered the intensity of IR radiation l; N the total number of pixels.

This approach is gaining popularity for processing thermographic data [19].

CONCLUSIONS

The application of remote thermographic monitoring for spray ponds creates opportunities for more effective implementation of operational instructions for hydrotechnical structures and ensures reliability and safety of nuclear power plants operation. The resulting amount of information obtained through remote thermographic monitoring should serve as the basis for creating reference databases, which can be used to determine damage caused by natural disasters, terrorist acts, and military actions of the aggressor. In order to effectively implement the method of remote thermographic monitoring, digital image processing tools should be used in addition to standard software.

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ТЕРМОГРАФІЧНИЙ МОНІТОРИНГ ЗА СТАНОМ БРИЗКАЛЬНИХ БАСЕЙНІВ АЕС НА ОСНОВІ МЕТОДІВ ОБРОБКИ ІЧ РАДІОМЕТРИЧНИХ ДАНИХ

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Обґрунтовується підхід до впровадження термографічного моніторингу за станом бризкальних басейнів АЕС, заснований на проведенні вимірювань у літній та зимовий періоди року з метою фіксації потенційно аварійних ділянок та підвищення рівня надійності забезпечення технічною водою. Розроблена процедура автоматизованої машинної обробки термограм на основі обробки цифрових зображень. Зроблено висновок про доцільність застосування одержаних баз даних до визначення збитків від критичних ситуацій на АЕС.