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Determination of the Efficiency of Cooling Systems of Nuclear Power Plants of Ukraine in the Conditions of Global Climate Changes

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ABSTRACT

The impact of climate change on the efficiency of nuclear power plants and cooling reservoirs depends, to a certain extent, on the increase in the temperature of cooling reservoirs in the summer months of the year. Nuclear power plants use water throughout their lifetime in cooling systems to dissipate the waste heat generated, including system safety, cooling systems and for power generation. In this work, on the basis of the analysis of monitoring data, the correlation dependences between the temperature indicators of atmospheric air and cooling reservoirs for operating nuclear plants in the conditions of Ukraine are established. In order to obtain the efficiency of the operation of nuclear power plants depending on global climate changes, based on the analysis of the average monthly temperature indicators of the atmospheric air for the period 1881–2020, we made a climatic forecast of the atmospheric air for the territory of Ukraine and established the forecast dependence of the increase in air temperature for the period until 2160. Based on the assessment and forecasting of the influence of climatic factors on the temperature of the cooling water in the specified reservoirs and on the power of the stations, the values of the relative overall efficiency of the reactor at the NPP of Ukraine for the periods 2021–2030, 2031–2040 and 2041–2050 have been established. The obtained data, output power coefficients indicate a gradual decrease in output power in the next decades and in the Ukrainian nuclear energy sector in terms of operating nuclear power plants in the conditions of forecast values of global warming and cooling water temperature. They testify that climate change and global warming are a risk of emergency situations at nuclear power facilities, which requires making strategic decisions regarding adaptations of reactor operation in conditions of global climate change.

Keywords: nuclear power plants, cooling ponds, climate change.

INTRODUCTION

The impact of climate change on cooling reservoirs is expressed in a decrease in their overall cooling efficiency due to an increase in average annual temperatures, as well as in an increase in water temperature and a decrease in the level of the water table in the dry months of the year (Ivanyuta S.P., 2020). As an alternative, the IAEA suggests reuse of process water (closed water circulation systems) or more expensive dry cooling technologies. As for hurricanes, floods and droughts, here the impact can be much more significant, and the methods of protection against them are significantly more expensive. The experience of the first years of the decommissioning of the cooling reservoir of the Chernobyl NPP determined the need to solve problems related to the dangerous radio-ecological consequences that may arise as a result of external extreme natural influences on the cooling reservoir of the NPP. Such extreme phenomena include tornadoes, earthquakes, floods. The urgent task is to ensure environmental safety during the entire life cycle of the water body and to prevent negative consequences from any combination of natural and man-made internal and external influences (Vashchenko V.M., 2016). Also, according to the conclusion of the IAEA, the impact of climate change on nuclear energy is reduced to a certain loss of thermal efficiency, as well as to the heating and drying of cooling reservoirs. Therefore, the future development of the industry will be dominated by alternative options for cooling systems, focused on the assessment and analysis of the consequences of climate change with an emphasis on global warming in the production of nuclear energy and the risks associated with this aspect. Along with the natural changes that occur, countries with nuclear power plants face serious consequences in terms of electricity production. The energy sector depends on sources and their availability of water, regardless of whether the company is fossil fuel-powered or not.

According to the data of the environmental audit of the South Ukrainian nuclear power plant (environmental audit, 2023), about two-thirds of the thermal energy produced in the reactors is discharged through cooling systems into the environment. The PAES project does not provide for permanent flushing of the cooling reservoir, but for the periodic discharge of surface water from the Tashlytsky reservoir into the South Bug River, and in 2007 – into the Oleksandriv reservoir. The design heat release of the reactor compartment of one PANP power unit entering the cooling system is (Rutberg M., 2012):

- minimum – 2.9×10^6 W,
- maximum – 23.4×10^6 W,
- average working – 17.4×10^6 W

To date, there are numerous models of the relationship between the use of water for cooling and electricity production, but most of them are characterized by the need for a large amount of natural or calculated statistical data (Rutberg M.J., 2011). Recently, a general system-level model (S-GEM) was developed for water use in power plants of various types (Klett M.G., 2007). The basis of the input parameters in the model was chosen so that each parameter has a clear physical meaning that can be related to the operating conditions of the plant and the performance indicators. The system-level model (S-GEM) presented in the paper can be applied to problems of the relationship between water withdrawal and water consumption intensity (the ratio of the volume of water withdrawn or consumed to the net electrical energy produced). The heat load of the cooling system is represented here by a Senkey diagram through the balance relationships, and the net power generation ratio is used to determine the efficiency of the nuclear power plant. The possibility of this is presented in (Myhre R., 2002).

Thus, applying this approach and the obtained equation, we can obtain the coefficient of consumption of fresh water in the system. This approach can be used in the evaluation and forecasting of the water balance in the technological system of reactors, as well as for open cooling ponds (Climate Change Impact, 2020).

A series of studies (National Energy Technology Laboratory, 2010; DiPietro P., 2009; Zhai H., 2010) published by NETL were devoted to detailed process models of state-of-the-art power plants to compare various aspects of plant performance, including water use. Recent works by Zhai (Zhai H., 2011; Energy Information Administration, 2010) apply IECM to estimate the impact of carbon sequestration on water use. However, due to the great detail of these models, it is difficult to apply them to create and estimate the water use of regional power plants or to assess the potential consequences of the introduction of new technologies.

Based on the analysis of monitoring data, to establish correlational dependences between the temperature indicators of atmospheric air and cooling reservoirs for operating nuclear plants in the conditions of Ukraine.

METHODS

The spent heat at a nuclear power plant that is removed depends on a number of factors, including the power of the plant, efficiency, size, and the type of technology used. There are seven different types of cooling systems in the world (Zhai H., 2011), but for the conditions of Ukraine, emphasis should be placed on three technologies used at nuclear power plants, direct-flow cooling systems with and without a tower, wet closed loop cooling system.

Nuclear power plants use water throughout their lifetime in cooling systems to dissipate the waste heat generated, including system safety, cooling systems and for power generation, as well as used in facility industrial services such as demineralized loop feed water, sanitary water, firefighting, irrigation (IAEA, 2012).

The lower the temperature of the cooling water, the better the performance of the plant, as the margin for increasing the temperature of the water in the reverse direction increases, thus reducing water consumption. Failures for a power plant with a thermal efficiency of 33% are about 14% lower than for a plant with the same capacity with an efficiency of 36% (IAEA, 2012). This means that a higher efficiency in the technological process can be achieved if the temperature of the suitable water is lower.

The amount of water required for cooling the station can be found using the equation (ECOFYS Netherlands B.V., 2014).

For a closed cooling system:

$$Q^F = \frac{KW \times h \times 3{,}6 \times (\frac{1-\eta_{total}}{\eta_{electrical}}) \times (1-\alpha) \times (1-\beta) \times \omega \times EZ}{AS \times c \times v} \quad (1)$$

For an open cooling system:

$$Q^F = \frac{KW \times h \times 3{,}6 \times (\frac{1-\eta_{total}}{\eta_{electrical}}) \times (1-\alpha)}{AS \times c \times v} \quad (2)$$

where: Q^F – need for cooling water (m^3);
KW – installed power (kW);
h – working hours (hours);
3.6 – coefficient for conversion of kWh (MJ);
η_{total} – overall efficiency (%);
$\eta_{electrical}$ – electrical efficiency (%);
α – fraction of spent heat not removed by cooling water (%);
β – share of spent heat released into the air (%);
ω – correction factor that takes into account the influence of air changes (temperature and humidity during the yar usually fluctuate between 0.7 – 1.25);
v – water density in (t/m^3);
c – specific isobaric heat capacity of water in (MJ/t K);
AS – permissible increase in cooling water temperature (K);
EZ – compression ratio, which is usually 1–4 according to (Savchenko D.V., 2021).

This equation allows for the estimation of the effect of the increase in water temperature and relates the waste heat at the plant to the demand for cooling water based on the efficiency data and the generated electricity, and for closed cooling systems, the fraction of the waste heat released to the air is determined. In the denominator is the compression ratio, which is a factor that takes into account the increase in fresh water consumption to avoid an increase in salinity due to evaporation during the cooling process. The limitation on return water heating is taken into account by the «AS» factor.

Evaporation costs largely depend on air humidity and temperature, and the relationship between these factors can be described by the Mohseni equation (Savchenko D.V., 2021):

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \quad (3)$$

where: T_s – water temperature (°C);
T_a – air temperature (°C);
μ – calculated minimum flow temperature (°C);
α – maximum flow temperature (°C);
γ – steepest slope function (degrees);
β – air temperature at the inflection point (°C).

According to (Savchenko D.V., 2021), the relationship between air and water temperature is a linear regression model. To obtain the temperature of the inflection point and the steepest slope of the function, the temperatures of the places and water bodies that will be investigated must be collected.

We used the OriginPro software environment to study the cooling reservoirs of nuclear power plants in Ukraine, which is an industry standard for collecting and visualizing data obtained during various experiments, in particular experiments conducted in physical laboratories (Mohseni O., 1998).

RESULTS AND DISCUSSION

In order to obtain the coefficients of Equation 3, correlation dependences were constructed for NPP cooling reservoirs, which are presented in Figures 1–4.

Constructed correlation dependencies make it possible to identify the parameters that will be used in Equation 3 for forecasting and analysis (Table 1).

Having obtained the values of the parameters of the equation, we obtain the parameters for calculating the need for cooling water for NPPs of Ukraine (Table 2).

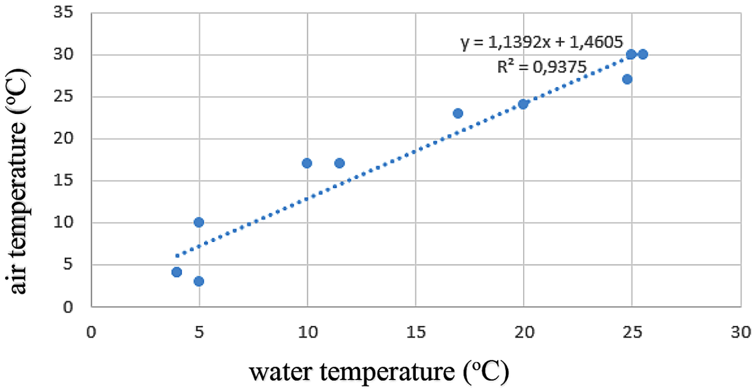

Fig. 1. Correlation between the water temperature in the Kakhov reservoir and the air temperature

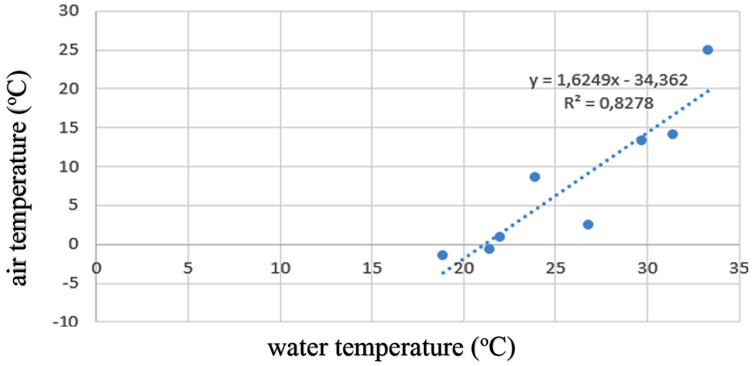

Fig. 2. Correlation between water temperature in the Tashlitsky Reservoir and air temperature

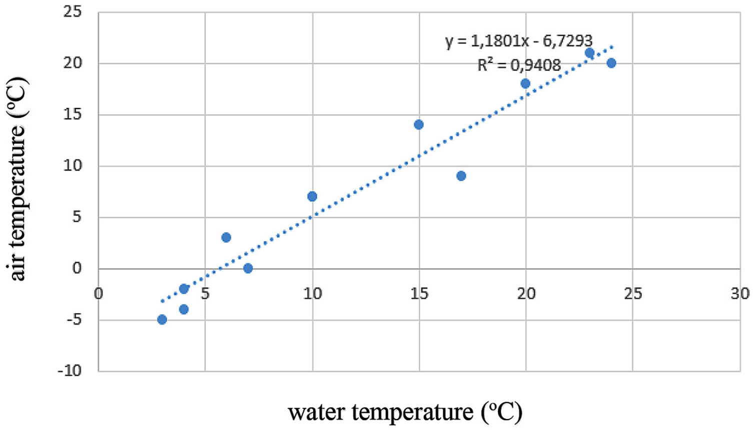

Fig. 3. Correlation between water temperature in the Netyshyn Reservoir and air temperature

Taking into account the design terms for the decommissioning of nuclear reactors at the NPPs of Ukraine, it was sufficient to consider the period up to 2050 to assess and forecast the impact of climatic factors on the temperature of the cooling water in the specified reservoirs and on the power of the stations. The maximum allowable water intake, the maximum allowable increase in return water temperature, and the overall reactor efficiency were taken as practical limitations for modeling.

Accordingly, the maximum production of electricity at the stations occurs in winter, when the temperature of the cooling water is low, while in the summer, at high temperatures, the electricity production capacity is lower (the coefficient of energy capacity, according to forecasts at the end of the 2041–2050 period, will be 0.38–0.4.

Taking into account the expected increase in demand for electricity in the future, it is necessary to take into account climate changes for the operation of the energy sector. In order to

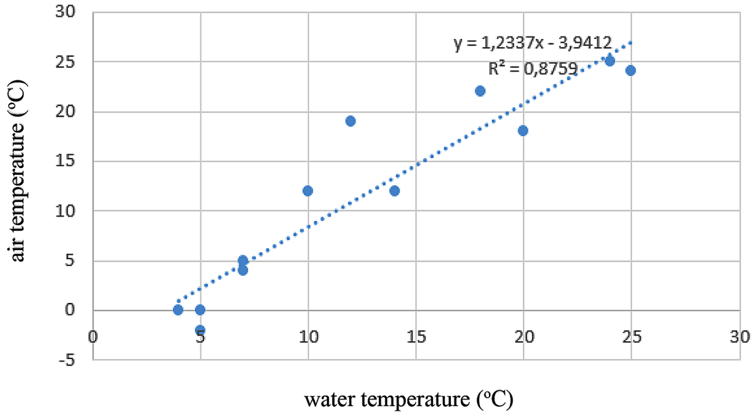

Fig. 4. Correlation dependence between the water temperature in the Styr River and the air temperature near the RANPP

Table 1. Prediction and evaluation parameters according to Equation 2

Object	Kakhov reservoir (ZAEP)	Tashlitsky Reservoir (PAES)	Netyshinke Reservoir (KHAEP)	Styr River (RAEP)
Incline (m)	1.1392	1.6249	1.1801	1.2337
γ = (4×m /$\alpha-\mu$)	0.198	0.382	0.2247	0.2234
β – (°C).	15.5	8	7.5	12
α – (°C)	26	33	24	25
μ – (°C)	3	14	3	3

Table 2. Parameter values for calculating the need for cooling water for NPPs of Ukraine

KW	AS = 10 K
h = 24×30 = 720	EZ = 3
η_{total} = 0.75–0.85	ω = 0.975
$\eta_{electrical}$ = 0.33	(1 − β)= 0.013696, α = 0.01

mitigate the consequences of climate change in the future, the country should already make strategic decisions regarding the transition to «clean energy», in particular to renewable energy sources, as well as to technological solutions for reactors of the future generation.

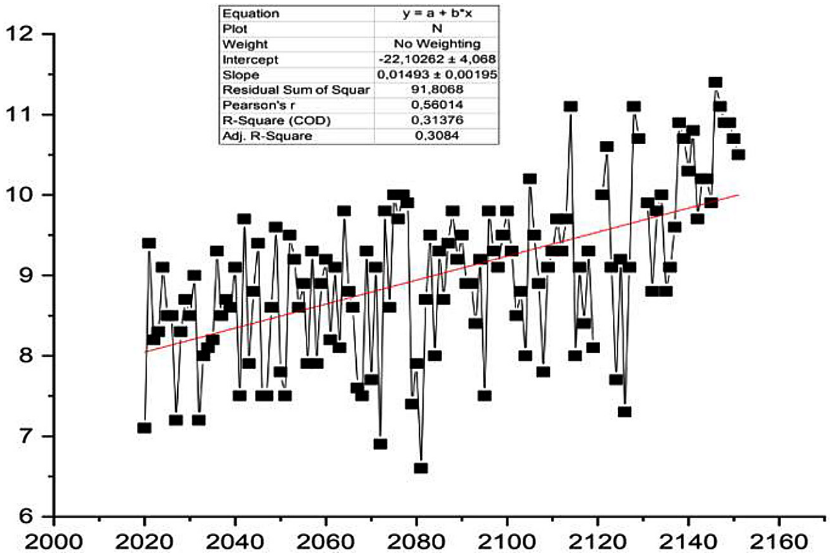

Fig. 5. Modeling of forecast data of the average annual temperature of atmospheric air until 2160

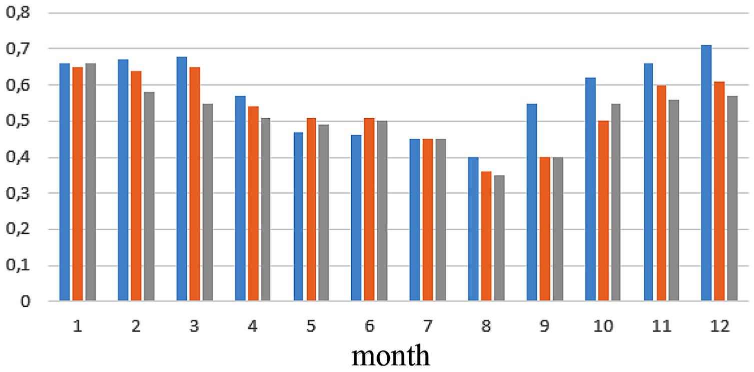

Fig. 6. Value of coefficients of output capacities in the next decades and in the Ukrainian nuclear energy sector, taking into account global climate changes

CONCLUSIONS

Nuclear power plants of Ukraine require a fairly large amount of water due to the process of cooling waste and dissipating heat. The efficiency of the installation and the output power depend on the availability of water and its temperature. Thermal pollution is one of the serious negative factors affecting the main vital resources during the operation of nuclear power plants.

Analysis of the impact of global climate change on the presence of cooling through open reservoirs showed that an increase in the temperature of the cooling water leads to a decrease in the efficiency of the reactors, with a subsequent increase in the risk of an emergency situation at the station. For management decisions regarding the necessary options for adaptations in the conditions of climate change, in order to reduce the probability of emergency situations at the facility, it is necessary to have predictive estimates of the efficiency of the stations from the temperature of water bodies in the conditions of a gradual increase in temperature indicators.

The output power coefficients of the next decades in the Ukrainian nuclear energy sector in terms of operating NPPs show that climate change and global warming are a risk of emergency situations at nuclear energy facilities, which requires making strategic decisions regarding the transition to «clean» energy and new reactors generations.

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