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ANALYSIS OF ENERGY EFFICIENCY AND OPERATIONAL RELIABILITY OF HEAT AND MASS EXCHANGE EQUOPMENT AT POWER PLANTS FOR IMPROVING THEIR PERFORMANCE QUALITY

Energy efficiency and reliable operation are fundamental factors shaping the modern energy sector under the paradigm of sustainable development. Heat and mass exchange equipment constitutes a critical component in the functioning of thermal and nuclear power plants (TPP and NPP), enabling efficient thermal transfer and optimizing the use of available energy resources. This article presents a comprehensive analysis of the energy efficiency and operational reliability of heat and mass exchange devices used in turbine units, focusing on improving the performance and capacity of low-potential complex condensing power units. Through statistical analysis and expert evaluation methods, key reliability indicators of heat exchange equipment in turbine installations were examined. The study highlights the predominance of condensers as essential components in low-potential complexes and investigates common defects affecting their operation, including corrosion, erosion, mechanical wear, and sealing failures. The research applies finite element analysis and automated engineering design techniques to assess the stress-strain states of condenser structures, pinpointing critical zones prone to mechanical failure. Additionally, temperature distribution within the condenser under stationary operating conditions is modeled to optimize thermal performance. The findings underline the significant impact of material degradation and mechanical stresses on the durability and efficiency of heat exchange apparatuses. Consequently, the article offers targeted recommendations for the enhancement of heat and mass exchange equipment. These include the adoption of advanced corrosion-resistant and high-strength materials such as titanium alloys and composites, implementation of automated monitoring and diagnostic systems for real-time condition assessment, and refinement of condenser designs to improve thermal-hydraulic performance and minimize energy losses. The proposed measures aim to elevate the operational reliability, extend the service life, and increase the energy efficiency of power plant heat exchange systems, contributing to reduced operational costs and environmental impact. This work supports the advancement of energy technologies aligned with global trends toward sustainable and efficient power generation.

KEY WORDS: *energy efficiency, reliability, quality, power plant, heat and mass exchange equipment, steam turbine, condenser*

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Problem Statement and Its Connection with Important Scientific and Practical Tasks

Energy efficiency and reliable operation are the key factors in the development of modern energy systems within the framework of the sustainable development concept. Heat and mass transfer equipment at power plants plays an important role in ensuring efficient energy use and reducing operational costs. Improving their energy efficiency and reliability contributes to the optimization of power plant performance and the reduction of environmental impact [1-2].

The economic efficiency of steam turbine units is significantly influenced by the performance of low-potential equipment (LPE) at power plants. A change in the pressure behind the turbine by 1 kPa results in an approximately 1% change in the economic performance of steam turbine units at thermal power plants (TPPs), while for nuclear power plants (NPPs), this change reaches 1.5–2.0%. The greater sensitivity of NPP steam turbine units is due to the fact that turbines with a small thermal drop, particularly saturated steam turbines, exhibit a higher relative change in pressure drop.

The reduction of steam parameters behind the turbine is typically achieved by lowering the pressure below atmospheric levels, which requires the condensation of the exhaust steam. This task is fulfilled by the condenser unit, which, in addition to this primary function, also provides clean condensate for feeding the steam turbine.

Malfunctions in the operation of condenser units, regeneration system equipment, and district water heating apparatuses are among the reasons for the reduced efficiency and reliability of steam turbine unit operations.

Analysis of Recent Studies and Publications

The issue of improving the efficiency of heat and mass transfer energy equipment has been addressed in studies [3–5].

The low-potential complex (LPC) of modern power plants typically includes the following components:

- steam condensing units, which consist of condensate pumps, ejectors with coolers for air removal;

- technical water supply systems, including water sources and cooling devices (such as reservoirs, cooling towers, spray ponds or their combinations), circulation pumps, circulating water filters, and pipeline systems;

- the last stages or sections of the low-pressure turbine cylinders with working wheels and exhaust steam nozzles;

- low-pressure feedwater heaters (LPHs) of the regenerative feedwater heating system.

Among the LPC components, the steam turbine condensers hold primary importance, since the main function of the LPC is to create and maintain the required exhaust steam pressure in the turbine.

As the pressure and temperature of the exhaust steam decrease, the amount of heat transferred to the cold sink is reduced. According to thermodynamic principles, under constant fresh steam parameters, this results in an increase in turbine output (due to a higher thermal drop across the turbine) and an overall improvement in cycle efficiency.

Available literature provides limited information on the reliability of thermal power equipment, with most studies focusing on primary equipment such as steam generators and turbines, and paying less attention to auxiliary systems, particularly the heat exchangers of turbine units. However, this group of auxiliary equipment significantly influences the performance of both thermal and nuclear power plants [6–10].

The objective of this study is to analyze the energy efficiency and operational reliability of heat and mass transfer equipment in thermal and nuclear power plants, using the low-potential complex (LPC) equipment as an example, and to provide recommendations for improving their performance quality.

Presentation of the Main Material

The concept of "reliability" encompasses a wide range of indicators, including: faultlessness, durability, maintainability, controllability, operational manufacturability, preservation, mean time between failures, and others. Each of these specific indicators typically characterizes one or several aspects of the overall reliability of the equipment or its specific technical and economic characteristics. According to the accepted methodology for assessing the quality level of energy heat exchange equipment, the reliability of turbine unit heat exchangers is generally considered from the perspective of durability, which is treated as the main indicator of overall equipment reliability.

The most common consequences of failures include underproduction of energy, reduced equipment availability factor, decreased efficiency, and, as a result, increased specific fuel consumption. In certain cases, equipment failure may lead to the shutdown of the entire unit (block).

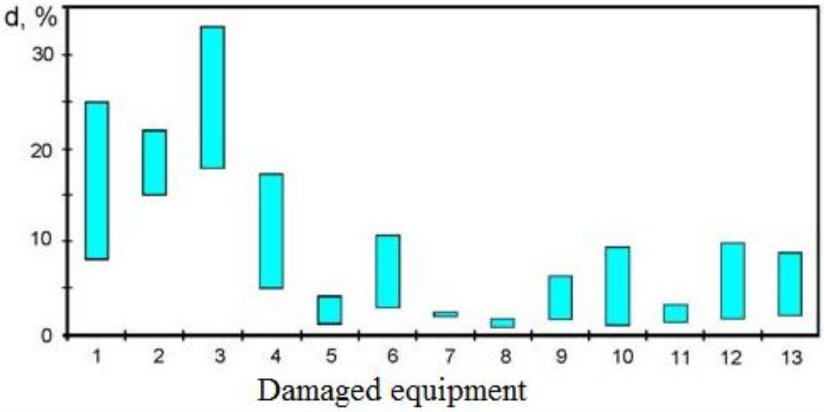

Fig. 1 – Distribution of failures of auxiliary equipment of turbine units: 1 – condensers, 2 – feed electric pumps, 3 – feed turbine pumps, 4 – high-pressure heaters, 5 – low-pressure heaters, 6 – gland heaters, 7 – ejectors, 9 – circulation pumps, 12 – valves, 13 – pipelines

Here is the failure share of each component that led to turbine shutdowns:

$$O = (z_{iT}/z_{io})\cdot 100\%,$$

where z_{iT} is the number of failures of the i-th component that led to turbine shutdowns;

z_{iO} is the total number of failures of the i-th component.

Figure 2 shows the share of failures of each component that resulted in turbine shutdowns.

The majority of tube damage (44.6%) is associated with corrosion-erosion deterioration occurring during long-term operation. Wear on the external surface of the tubes is primarily caused by droplet-impact erosion, while erosion on the internal surface is linked to poor quality of circulating water, which often carries a significant amount of abrasive particles in suspension. These particles lead to internal surface wear, especially near the tube sheets at the tube inlet areas. The main causes of corrosion damage in condenser tubes are the presence of oxygen in the working fluids, which leads to various types of corrosion, including general corrosion, dezincification of brass, stress corrosion cracking, and others.

The second most common type of damage (39.3%) is associated with the loss of tightness in the tubes or rolled joints. In many cases, it is difficult to determine the specific cause of depressurization, primarily because the damaged tubes are located deep within the tube bundle, making visual inspection impossible. However, in the few cases where damaged tubes were cut out and examined, it was found that depressurization resulted from both corrosion-induced tube wear and frictional wear in the regions where tubes pass through intermediate baffles. The main cause of this wear is tube vibration, which may also lead to loosening of the rolled joints and eventually to their loss of tightness.

As seen in Figures 1–2, among the auxiliary heat exchange equipment of turbine units, the condenser accounts for high values in terms of failure share, recovery time, and impact level on the operation of the steam turbine unit.

Below is the distribution of failure characteristics of condensers that typically caused emergency shutdowns of the turbine unit as a whole.

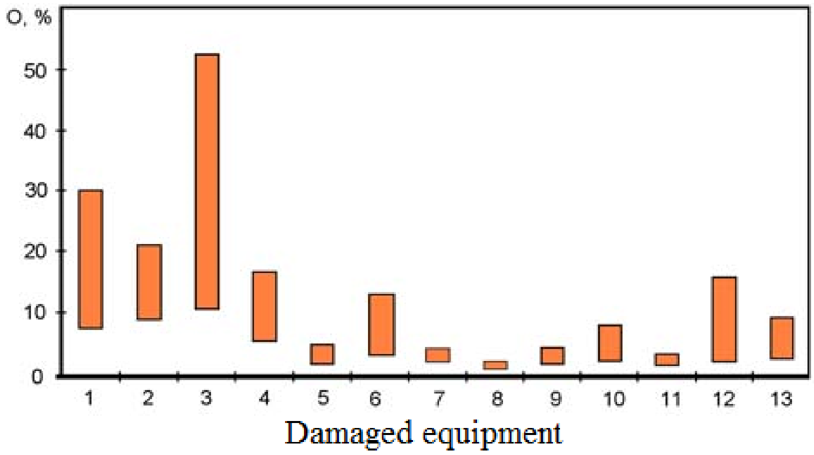

Fig. 2 – Share of auxiliary equipment failures causing turbine shutdowns (according to Fig. 1)

Table 1.

Distribution of condenser failure types, %

Increasing the hardness of the condensate	58,1
Vacuum drop	33,7
Siphon break	7,0
Other	1,2

Let us consider the distribution of specific defects that caused failures in the operation of condensers. The majority of these are tube damages (60.9%).

Table 2.

Distribution of failures due to defects of condenser elements, %

Condenser tube damage	60,9%
Damage to fittings, drains, etc..	7,6%
Clogging of tubes and tube sheets	6,5%
Leaks in the casing	4,3%
Leakage of repair plugs of plugged tubes	2,2%
Other	18,5%

Corrosion-erosion processes are often exacerbated by the poor quality of the heat exchanger tubes, which is due to metallurgical and manufacturing defects, a factor frequently identified during failure investigations.

The failure statistics for condensers are consistent with findings for other shell-and-tube heat exchangers used in steam turbine units. For all types of such equipment, the main factors contributing to reduced service life are corrosion damage and erosion-mechanical wear of the tubes.

The conclusions obtained are supported by reliability studies of heat exchange equipment in turbine units, which were carried out using expert evaluation methods.

Most experts identify design factors (e.g., suboptimal steam supply system in low-pressure heaters, high hydraulic resistance of the desuperheater, limited access to desuperheaters, etc.) and technological factors (e.g., poor welds, leakage in fittings, etc.) as the primary causes of malfunctions and failures in heat exchangers. One significant cause of overall reliability reduction is the low quality of tubing, especially those made from non-ferrous alloys, used for heat transfer surfaces. According to all experts, installation defects account for the smallest share. Operational violations occupy an intermediate position in this ranking.

Failures in heat exchangers related to the condition of the tube bundle are mainly caused by erosion-corrosion wear (approximately 70% of cases) and tube vibration (around 25% of cases).

The types of damage caused by vibration include:

- tube fractures near the tube sheets,
- wear of tubes in intermediate baffles,
- mutual tube abrasion across large spans, bends, and other areas.

These data are primarily qualitative, but they allow us to identify the key factors contributing to the reduced reliability of turbine heat exchangers. The quantitative assessments are statistical averages based on a large number of individual cases.

Currently, computer-aided design and calculation systems are widely used in engineering practice. Simulations and studies conducted using these tools allow engineers to avoid costly and time-consuming development cycles of the “design–manufacture–test” type. In the field of automated engineering calculations, finite element-based software packages are especially popular. These tools enable the solution of a wide range of industrial problems, including stationary and transient 3D solid mechanics, mechanics of deformable bodies, structural mechanics (including contact interaction), fluid and gas mechanics, heat transfer, and more.

Figures 3–4 show the results of the stress–strain analysis of power plant condensers, aimed at identifying critical stress concentration zones in the structures. Figure 5 presents the temperature distribution within the condenser.

Enhancing heat transfer during steam condensation will reduce the temperature differential (undercooling) of the cooling water and the pressure in the condenser. As a result, this will increase the overall energy efficiency of the power unit, taking into account the power shortfall caused by the limiting vacuum level in the condenser.

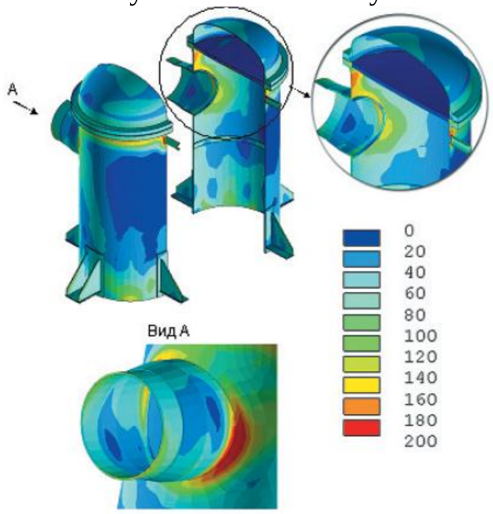

Fig. 3 – Distribution of equivalent stresses (MPa) in steady-state mode

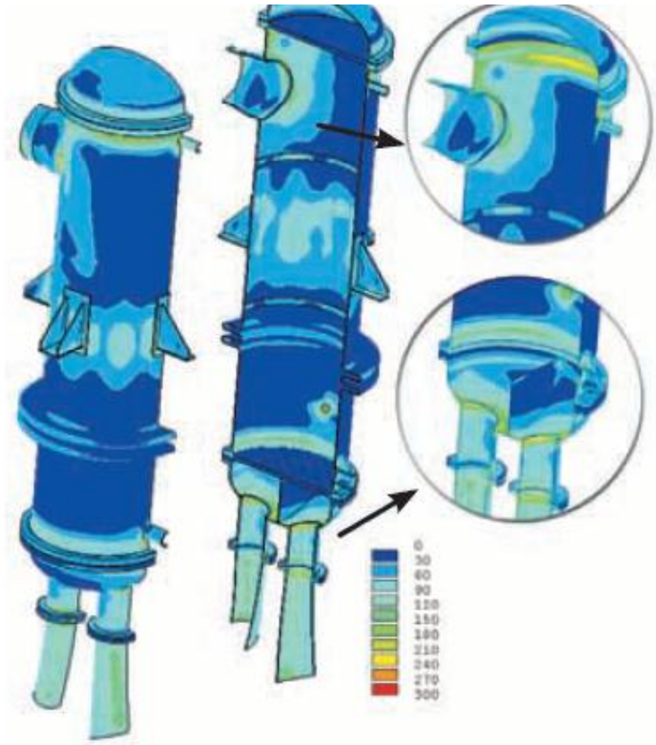

Fig. 4 – Distribution of equivalent stresses in steady-state operation mode of the condenser (linear elastic analysis)

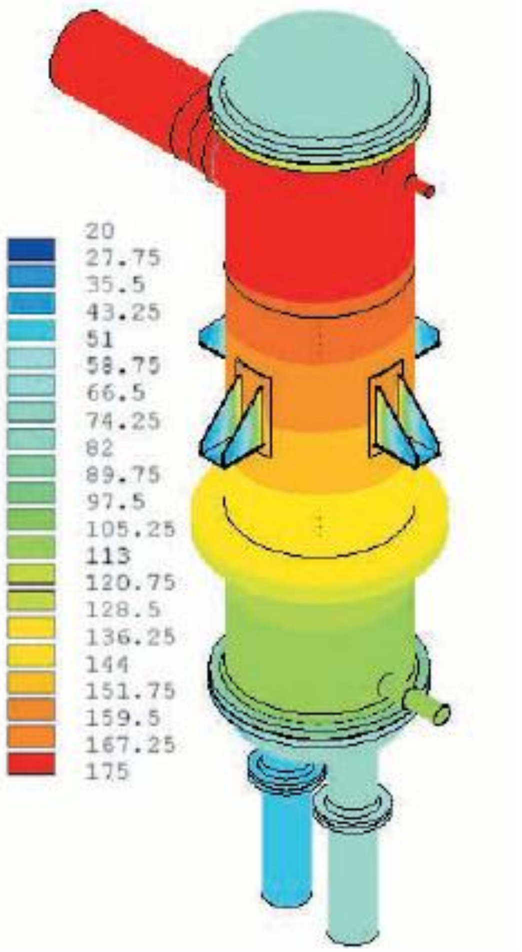

Fig. 5 – Steady-state temperature distribution (ºC) across condenser components in the main operating mode

Recommendations for Improving Heat and Mass Transfer Equipment

The analysis of reliability data for heat exchangers demonstrates the necessity of improvement both at the design stage of new equipment and during operation through the modernization of existing units. The main directions for enhancing heat exchangers should include:

- Increasing the corrosion and erosion resistance of tube systems;

- Improving the vibration reliability of the equipment;

- Enhancing the design of heat exchangers, particularly steam supply systems;

- Improving the quality of tubes used in heat exchangers;

Enhancing the overall quality of assembly and manufacturing, especially for equipment operating under sub-atmospheric pressure, with special attention to air infiltration into the apparatus.

For optimizing heat exchanger element designs, finned and microstructured surfaces can be employed to enhance heat transfer. Thermal resistance can be reduced through the use of multilayer heat exchanger constructions. Geometrical optimization of tube bundles helps achieve uniform thermal load distribution.

The application of high-strength and corrosion-resistant materials—such as titanium, stainless steel, and composites—represents an innovative approach. For example, nanocoatings may be used to reduce fouling of surfaces and improve thermal conductivity. Materials with high resistance to thermomechanical loads are also being introduced.

Heat exchange efficiency can be further improved by using two-phase coolants to enhance the heat transfer coefficient, and by implementing heat transfer intensification technologies such as flow turbulence enhancement or ultrasonic cleaning of surfaces.

Energy loss minimization can be achieved through the optimization of steam condensation modes.

Digital diagnostic systems are increasingly implemented for improved monitoring and control of heat and mass transfer equipment. For example, intelligent sensor systems can detect fouling, corrosion, and leaks. Automation of thermal process control also contributes to improved operational efficiency of the units.

Condenser operation optimization is essential to reduce thermal pollution of the environment. Measures in this area include technologies for condensate reuse to minimize water losses and the use of environmentally friendly cleaning methods for heat exchange surfaces. These efforts help reduce environmental impact and improve the reliability of condensation unit equipment in thermal power plants.

Modernization of heat and mass transfer equipment in the condenser units of power plants contributes to increased efficiency of power blocks, reduced operational costs, and minimized environmental impact. The implementation of advanced materials, automated control systems, and design optimization leads to high standards of energy efficiency and operational reliability.

Conclusions

Modern power plants face challenges related to improving energy efficiency and operational reliability of their equipment. Heat and mass transfer devices play a key role in energy systems by ensuring efficient heat exchange and optimizing energy use. Their improvement is critically important for reducing operational costs, increasing productivity, and minimizing environmental impact.

There are clear opportunities to improve efficiency and a pressing need to enhance heat exchangers both at the design stage of new equipment and through the modernization of existing systems in operational environments.

The design improvements of heat exchange equipment should aim to intensify heat transfer while maintaining high operational reliability. This can be achieved through the application of enhanced heat transfer surfaces, such as finned and profiled tubes, as well as the use of other heat transfer intensification methods.

Enhancing thermal efficiency is also supported by improving the aerodynamics of tube bundles, which creates conditions for uniform washing of the heat exchange surfaces by the coolant, avoiding stagnant zones or hard-to-reach areas. Additionally, the elimination or consideration of coolant flow through intermediate gaps between baffles and outside the tube bundle helps further improve performance.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of the manuscript. In addition, the authors fully complied with ethical standards, including plagiarism, data falsification, and double publication

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АНАЛІЗ ЕНЕРГОЕФЕКТИВНОСТІ ТА ЕКСПЛУАТАЦІЙНОЇ НАДІЙНОСТІ ТЕПЛОМАСООБМІННОГО ОБЛАДНАННЯ ЕЛЕКТРОСТАНЦІЙ ДЛЯ ПІДВИЩЕННЯ ЯКОСТІ ЇХ РОБОТИ

Енергоефективність та безпечна експлуатація є одними з головних факторів, що характеризують сучасну енергетику в рамках концепції сталого розвитку. Тепломасообмінні апарати відіграють ключову роль у роботі енергосистем, забезпечуючи ефективний теплообмін та оптимізацію використання енергії на електростанціях. У статті аналізується енергоефективність та експлуатаційна надійність тепломасообмінного обладнання ТЕС і АЕС для підвищення якості їх роботи на прикладі устаткування низькопотенційного комплексу конденсаційного енергоблоку. За допомогою статистичних даних та метода експертних оцінок досліджено показники надійності теплообмінного обладнання турбоустановок. Приводяться дані відмов конденсаторів як основного устаткування низькопотенційного комплексу, а також розглядаються дефекти, які викликають ці відмови. Методом кінцевих елементів шляхом автоматизованого інженерного розрахунку досліджено напружено-деформований стан конденсаторів електростанцій для визначення небезпечних зон конструкцій і розподілу температур у конденсаторі при стаціонарному режимі роботи як основному. На базі проведеного аналізу надані рекомендації щодо удосконалення тепломасообмінних апаратів електростанцій, в тому числі приділена увага впровадженню новітніх матеріалів, автоматизованих систем контролю та оптимізація конструкції.

КЛЮЧОВІ СЛОВА: *енергоефективність, надійність, якість, електростанція, тепломасообмінне обладнання, парова турбіна, конденсатор*

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Конфлікт інтересів

Автори заявляють, що конфлікту інтересів щодо публікації рукопису немає. Крім того, автори повністю дотримувались етичних норм, включаючи плагіат, фальсифікацію даних та подвійну публікацію.

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