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ANALYSIS OF THERMODYNAMIC AND CONDENSATION PROCESSES IN THE LOW-POTENTIAL SECTION OF STEAM TURBINES AND APPROACHES TO IMPROVING THEIR EFFICIENCY

Introduction. *Improving the efficiency of the low-potential section of high-capacity wet steam turbine units, which substantially influences the overall turbine performance, remains a critical engineering challenge. Despite the application of advanced modeling and design methods, there still have been understudied issues.*

Problem Statement. *This study addresses the justified identification of non-conventional methods for reducing additional energy losses that arise specifically in the low-potential section of steam turbines, namely in the final stages of low-pressure cylinders (LPCs), where phase transitions and moisture formation occur. Particular attention has been given to the influence of wet-steam flow electrization on thermodynamic and condensation processes.*

Purpose. *The purpose of this study is the development of a methodology for improving the efficiency and operational reliability of the low-potential section of high-power steam turbine units through targeted control of thermoelectrophysical processes.*

Materials and Methods. *The study has examined electrized and ionized wet steam using a combination of literature analysis and experimental investigations. Experimental studies have been conducted on a thermodynamic test bench at the Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine. Full-scale experiments have been carried out at thermal power plants (TPPs) and combined heat and power plants (CHPPs) in Ukraine and the United States. The analytical framework is based on the classical laws of thermodynamics of complex systems, electrophysics, and turbomachinery theory.*

Results. *Based on computational and experimental investigations, the study has demonstrated positive effects of targeted control of electrophysical influences acting from the final LPC stages through the*

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exhaust system to the condenser. The steam ionization and the application of a constant electric field at the condenser inlet have been proposed respectively, for reducing losses associated with supercooling and for increasing the heat load, improving the uniformity of the velocity field, as well as for neutralizing downstream of the final stage to decrease exhaust pressure and to enhance heat transfer.

Conclusions. The research has shown that improving thermoelectrophysical processes in the low-potential section of steam turbine units can increase their operational efficiency by approximately 1.5—2%.

Keywords: last stages of the steam turbine unit, exhaust pipe, condenser, thermoelectrophysics, electrized and ionized wet steam, dielectric permittivity.

In the current context of electricity generation shortages in Ukraine, even a slight improvement in the efficiency of steam turbine units is highly relevant. This certainly applies to the low-potential part that significantly affects the overall performance of the turbine unit.

In the low-pressure cylinders (LPC) of high-capacity steam turbines, complex thermodynamic processes occur that are associated with phase transitions and moisture formation. These processes lead to steam supercooling, its electrization and ionization. These factors have a substantial impact on the turbine's performance, causing additional energy losses, erosion-corrosion effects, and other negative phenomena that reduce both the efficiency and the reliability of LPC components. However, to date, there are no mathematical models that allow for the incorporation of these effects at the design stage of turbine units or enable the calculation of additional losses. Another issue that arises is the lack of data on changes in the dielectric permittivity of charged wet steam — one of the key parameters characterizing its thermodynamic state.

The performance and reliability of the exhaust pipe and condenser are also critically important for the low-potential section of the turbine.

Currently, there are numerous studies dedicated to enhancing the efficiency of LPC operation. Many focus on optimizing the blade shape of the final turbine stages to reduce supercooling [1—3], using CFD modeling of the wet steam flow with consideration of nonequilibrium condensation, and numerical simulations of two-phase flow with phase transitions and supercooling in turbine sta-

ges [4, 5]. Other studies explore the reduction of erosion processes through steam-drying strategies (lowering humidity and increasing superheat) by introducing turbulent excitations on the suction side [6]. There are also works examining the electrization of wet steam flow and its negative effects [7—9].

There are also studies focused on improving the gas-dynamic performance of the exhaust pipe [10, 11] and increasing the efficiency of condensers [12, 13]. For example, some works explore the potential to equalize the heat load on the condenser tube bundle both across the inlet cross-section and along its depth in the direction of steam flow, thereby enhancing overall heat removal.

However, despite the fact that modern LPCs of wet steam turbines, exhaust pipes, and condensers have reached a fairly high level in terms of efficiency, manufacturability, strength, and durability — thanks to the application of advanced modeling and design methods — many unresolved issues still remain.

From our perspective, achieving new results in improving the performance of the low-potential section of a steam turbine unit is possible only through synergistic approaches that combine thermodynamics, geometry, and electrophysics, as well as through the application of innovative, non-conventional scientific and technological solutions — not only at the design stage but also for existing turbine units.

The authors have considerable experience both in the optimal design of the final stages of LPCs [14] and in studying the effects of electrophysical phenomena — specifically, the electrization and ioni-

zation of wet steam. This work is based on theoretical research, bench-scale experiments, and, most importantly, the results of numerous full-scale tests carried out at thermal power plants (TPPs) and combined heat and power plants (CHPPs) in Ukraine and the United States. These results and conclusions regarding their practical application are presented in detail in [15].

Considering the above, we will focus on identifying ways to improve the efficiency of the low-potential section of high-capacity steam turbine units. This will be based on the analysis of literature sources, the results of full-scale and bench-scale experimental tests, as well as new experimental and computational studies, with particular attention paid to the influence of wet steam flow electrization.

We will examine these processes in detail within the individual components of the turbine unit's low-potential section.

WET STEAM STAGES OF THE LPC

Losses due to steam electrization. As previously mentioned, in the last stages of wet steam turbines, steam electrization occurs, resulting in additional losses associated with its presence [15, 16]. These include, first and foremost, losses caused by charge generation; in an adiabatic steam expansion process, such losses are related to the work performed by steam in an electric field, as well as electro-gas-dynamic flow blockage.

Furthermore, under conditions typical of the final stages of wet steam turbines — characterized by high flow velocities exceeding 300 m/s, humidity levels of 3—10% or higher, temperatures of 300—400 K, and the presence of impurities or droplets ranging from 1 to 10 μm — steam ionization occurs, resulting in additional energy losses. These can become significant at high charge densities and strong electric field strength. Another important aspect is the increased intensity of erosion-corrosion processes.

Unfortunately, existing mathematical models of thermodynamic processes for wet steam expansion do not take electrization into account, and

the associated additional losses are not considered. Let us examine these issues in more detail.

To estimate energy losses due to charge generation (steam electrization) under specified conditions, simplified approaches can be used [17].

For example, in a constant (static) electric field, the power losses can be calculated based on the conduction current created by free charges using the equation:

$$J = \rho_q \cdot \mu \cdot E,$$

where J is the current density (A/m^2); ρ_q is the charge density (C/m^3); μ is the charge mobility, equal to $5 \cdot 10^{-4} \text{ m}^2/(\text{Vc})$, which corresponds to the average velocity of charge carriers under a field strength of 1 V/m (i.e., a drift velocity of 100 m/s). The power loss w_v is then defined by the following relation:

$$w_v = J \cdot E = \rho_q \cdot \mu \cdot E^2. \quad (1)$$

Another approach to estimating losses due to steam ionization involves considering the conductivity of the mixture, denoted as σ . In this case, the formula for evaluating power losses per unit volume is as follows: $w_v = \sigma E^2$, where σ is the electrical conductivity of the medium (S/m).

To estimate the specific energy losses w per unit mass, it is necessary to take into account either the volume or the density of the wet and dry steam mixture, denoted as ρ_{mix} .

$$w = w_v / \rho_{\text{mix}}, \quad (2)$$

Let us now consider energy losses during adiabatic expansion of wet steam in the presence of electric charges. As is known [18], in a thermodynamic system where, in addition to expansion work, other types of work are performed, the combined equation of the first and second laws of thermodynamics, under equilibrium conditions, takes the following form:

$$TdS = dU + pdV - \sum \zeta dx, \quad (3)$$

where T is temperature, S is entropy, U is internal energy, p is pressure, V is volume, ζ is the generalized force, x is the generalized coordinate, and ζdx is the work done on the system. For a dielectric, such as wet steam, considering only the po-

larization caused by the applied external stationary electric field, equation (3) takes the form:

$$TdS = dU + pdV - PdE,$$

where E is the electric field strength, and P is the polarization of the dielectric.

Considering that the polarization of the material is evaluated through the relative dielectric permittivity and the electric field strength

$$P = (\varepsilon - 1)\varepsilon_0 E,$$

where $\varepsilon = f(T)$ is the dielectric permittivity of the medium; $\varepsilon_0 \approx 8,854 \cdot 10^{-12}$ (F/m) is the electric constant.

The dielectric permittivity of the steam is thus the most representative parameter characterizing the thermodynamic state under the influence of the electric field.

The relations for determining the changes in internal energy, heat capacity, enthalpy, and entropy under the influence of the electric field are thoroughly discussed in [13]. It should be noted that all these quantities are related to the volume of the dielectric.

Here, only some of them are presented.

$$\Delta S = S(E, p, T) - S_0(p, T) = \frac{1}{2} \varepsilon_0 \frac{d\varepsilon}{dT} E^2, \quad (4)$$

$$\Delta i = i(E, p, T) - i_0(p, T) = \frac{1}{2} \varepsilon_0 (T \frac{d\varepsilon}{dT} - \varepsilon + 1) E^2, \quad (5)$$

where i is the enthalpy of the steam (kJ/kg).

Essentially, it is the change in enthalpy that characterizes the energy losses due to electrization. In this case, referring to (2),

$$\frac{d\varepsilon}{dT} = \frac{2\Delta S}{\varepsilon_0 E^2}$$

by substituting the last into (3) and solving for ε , we obtain $\varepsilon = 1 + \frac{2(T\Delta S - \Delta i)}{\varepsilon_0 E^2}$.

In the case of adiabatic expansion of steam, through transformations, we obtain a rather simple relation for determining energy losses.

$$\Delta i = -\varepsilon_0 (\varepsilon - 1) E^2. \quad (6)$$

Analyzing the obtained dependencies, it can be stated that for conducting calculation studies it is necessary to have values of dielectric permittivity and electric field strength.

The actual values of the electric field strength and charge density distribution along the flow section of the turbine unit were obtained during field tests [15]. An example of the range of variation of the volume charge density along the wet steam section of the LPC is shown in Fig. 1.

The electric field strength can be determined if the charge density is known, using Poisson's equation:

$$\nabla \cdot E = \varepsilon \cdot \varepsilon_0 / \rho_q, \quad (7)$$

where $\nabla \cdot E$ is the divergence of the electric field vector.

Based on the obtained results, we return to determining the change in dielectric permittivity of the electrized mixture (moist steam).

Unfortunately, there is currently an insufficient amount of research addressing these changes. This is primarily due to the complexity of conducting such experimental studies. Neglecting the influence of an external electric field, we can calculate the dielectric permittivity ε_{mix} of the mixture representing wet steam using the linear mixing rule:

$$\varepsilon_{mix} = (1 - Y)\varepsilon_s + Y\varepsilon_w, \quad (8)$$

where Y is the steam humidity (the mass fraction of water); ε_s is the dielectric permittivity of dry steam; ε_w is the dielectric permittivity of water.

In some cases, for a more accurate description, the logarithmic mixing rule (Lichteneker's rule) can be used:

$$\log \varepsilon_{mix} = (1 - \varphi) \log \varepsilon_s + \varphi \log \varepsilon_w,$$

where φ is the volume fraction of the liquid phase.

Certainly, when determining the dielectric permittivity, temperature parameters, pressure, steam ionization, as well as frequency dependence, should be taken into account [19].

An approximate estimation of the dielectric permittivity of wet steam without considering the influence of the electric field can be made using [20].

Considering the assumption that the dielectric permittivity of electrized steam may significantly differ from that of neutral steam, experimental

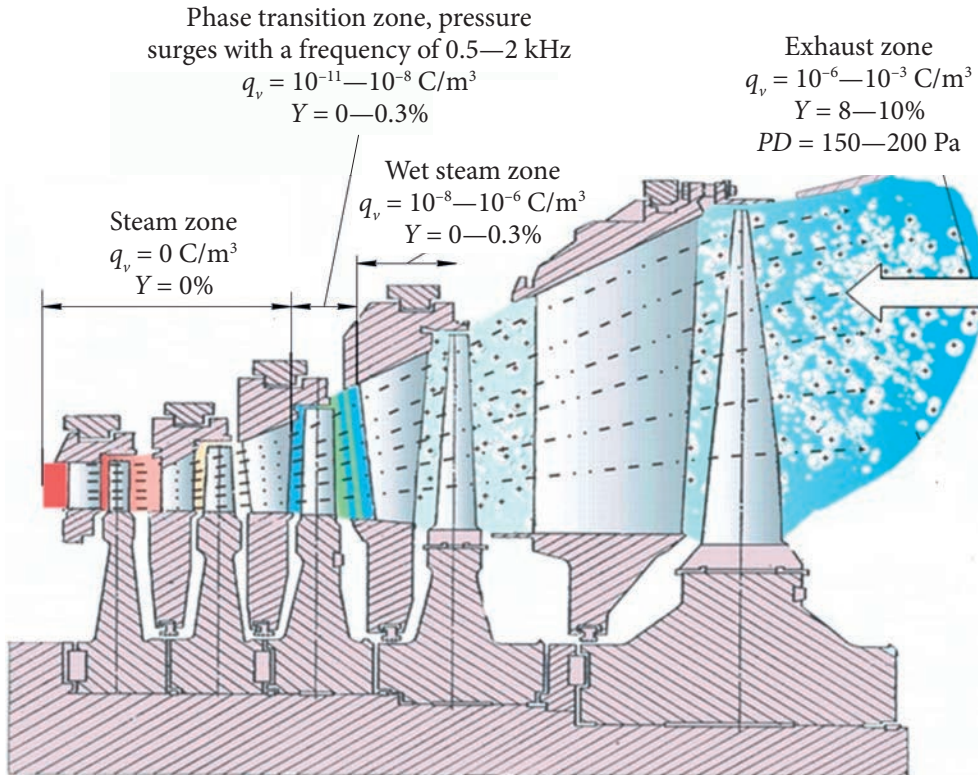


Fig. 1. LPC region containing a space charge

studies were conducted on the change of dielectric permittivity with temperature, flow pressure, and volume charge density. To address this task, a gas-dynamic laboratory setup, manufactured at IPMS of the NAS of Ukraine and previously used in our experimental thermogasdynamic studies, was re-equipped.

For evaluating the dielectric permittivity of the charged steam flow, an inductive method (*L*-method) for determining dielectric properties was chosen, in which the investigated substance is introduced inside an inductive solenoid coil. The schematic of the setup is shown in Fig. 2.

The most significant parameter is the quality factor signal ΔC , presented in relative units, by which the change in dielectric permittivity is determined. The results of one study, as an example, are shown in Fig. 3.

The obtained experimental data have allowed for a preliminary conclusion that there is no signi-

ficant change in the dielectric properties of the steam flow with a volumetric unipolar electric charge having the parameters and spatial structure used in this experiment. More detailed information about the conducted studies is provided in [21].

Subsequently, in order to refine the results obtained in the initial experiments, a new inductance coil with a higher quality factor and lower dielectric losses was manufactured, and the frequency range of the studies was expanded. The results of the conducted experiments also confirmed the insignificant change in dielectric permittivity.

Obviously, to obtain more representative information about the electrophysical properties of the wet steam flow with volume charge in a turbine, it is necessary to create conditions in the experimental setup that allow generating a volume charge with parameters and structure similar to those of a real turbine unit. In particular, this involves a two-component charged dispersed phase, repre-

sented by positively and negatively charged droplets in the steam flow. Unfortunately, at present, it is not possible to simulate such conditions for conducting research.

However, it can be stated that the insignificant change in dielectric permittivity in the wet steam flow and its small values in the range of 1–6% are theoretically explained by the amount of moisture, the steam density — which is quite low — and the charge density that increases and leads to a decrease in the dielectric permittivity.

Let us estimate the losses associated with the electrization of the flow (equations 2 and 6) at the last stages of the K-325-24.5 turbine. The electric field strength and dielectric permittivity are determined using equations 7–8. The steam parameters were obtained through a 2D calculation of the thermogasdynamic characteristics of the turbine's wet steam path under various operating conditions.

At steam parameters $p = 0.03$ MPa; $T = 363$ K; $Y = 1.2\%$, corresponding to the 3rd stage of the wet steam path, the steam density is approximately 0.192 kg/m³. Under these conditions, the dielectric permittivity of the water vapor is approximately 1.01–1.05, while the dielectric permittivity of water is about 78–80 at 300–370 K. Using relation (8), we obtain an estimated dielectric permittivity value $\epsilon \approx 1.94$. To determine the losses due to electrization, the value of the electric field strength is needed. For this, we will use the results of field tests shown in Fig. 1.

The charge density near the phase transition zone (corresponding to the 3rd stage) ranges from 10^{-11} – 10^{-8} C/m³. Accordingly, from equation (7), the electric field strength will not exceed 0.19–2 V/m. Such low values are certainly justified by the very low charge density. Therefore, the energy losses caused by electrization and ionization of the flow, as well as during the adiabatic expansion of the steam in this case, will be very insignificant. They amount in total to approximately $1.15 \cdot 10^{-4}$ kJ/kg.

Before the last stage's working blade, where $p = 0.011$ MPa; $T = 321$ K; $Y = 6.4\%$, the steam density is approximately 0.0795 kg/m³. The charge den-

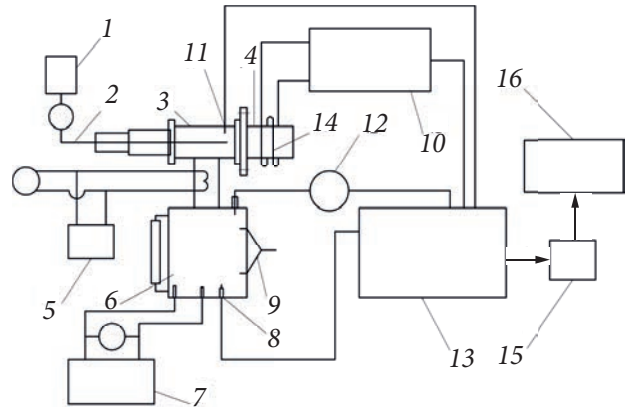


Fig. 2. Schematic diagram of a steam system with vapor ionization by corona discharge: 1 — high-voltage power supply; 2 — high-voltage input; 3 — boiler ionization chamber; 4 — nozzle section of the ionization chamber; 5 — steam superheater; 6 — boiler; 7 — power source for boiler heaters; 8 — boiler water temperature sensor; 9 — boiler water level alarm sensors; 10 — Q-meter (quality factor meter); 11 — pre-nozzle temperature sensor; 12 — boiler pressure gauge; 13 — analog input module; 14 — inductance coil at the nozzle outlet (L-cell); 15 — interface converter; 16 — personal computer

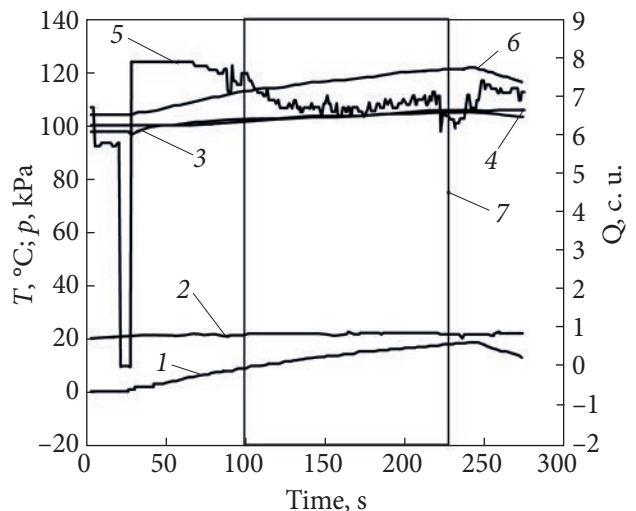


Fig. 3. Graph of experimental parameters: 1 — nozzle pressure drop; 2 — laboratory temperature; 3 — pre-nozzle temperature; 4 — boiler temperature; 5 — quality factor; 6 — boiler pressure; 7 — highlighted region indicating the presence of space charge

sity ranges from 10^{-8} — 10^{-6} C/m³, and the maximum energy losses will not exceed $1.42 \cdot 10^{-3}$ kJ/kg.

Such values are very insignificant compared to the enthalpy drop in the turbine (approximately 200 kJ/kg at the last stage) and play a minor role in the overall energy balance of the low-pressure section of the turbine unit, as they account for less than 0.1%. However, it should be emphasized that in this case, the operation of a specific turbine unit at nominal conditions was considered. Changes in operating conditions can certainly lead to variations in the energy losses associated with steam electrization at the last stages.

This is especially important for turbines at nuclear power plants, where the steam moisture content at the last stage can reach 14—15%, as well as for turbine operation under off-design regimes, where losses related to flow electrization can be significantly higher. It should also be noted that increasing the charge density and the electric field strength leads to a dramatic rise in the losses, reaching from one to two orders of magnitude.

Losses Due to Supercooling. At the final stages of wet steam turbines, additional losses due to supercooling, which can be quite significant may also occur.

The process of steam expansion in the turbine flow path from the saturation line to the Wilson zone differs significantly from the expansion process of superheated steam. Expansion of steam in the two-phase region is always non-equilibrium in nature and is accompanied by supercooling, when due to a deficiency of condensation nuclei, the actual steam wetness appears to be lower than that indicated by the thermodynamic diagram. In other words, the expansion of supercooled steam occurs either without the formation of the liquid phase or with lower wetness. As a result, the latent heat of vaporization is either reduced or absent. The temperature of the supercooled steam is lower than that under equilibrium expansion, and therefore the work performed is also lower at the same pressure drop.

The difference between the actual temperature T and the saturation temperature T_s at the same

pressure p_i is referred to as supercooling — ΔT . The degree of supercooling depending on the rate of expansion and the nucleation rate J can be determined using classical approaches outlined in [22]. For a quantitative assessment of the reduction of the available enthalpy drop by Δh and the losses due to steam supercooling, an engineering method described in detail in [23] was developed.

Using this method, an assessment of supercooling losses was carried out for the LPC of the K-300-24.5 and K-325-24.5 turbines. The results showed that the most critical issues occur at the 3rd and 4th stages of the LPC. We will focus on the K-325-24.5 turbine, for which the calculations of losses due to flow electrization were presented earlier. In this case, the steam exiting the 2nd stage is slightly superheated, while after the nozzles of the 3rd stage it is already supercooled: $p = 43.12$ kPa, $X = 0.996$. Supercooling persists after the rotor blades of the 3rd stage, with steam parameters: $p = 32.3$ kPa, $X = 0.988$. A condensation jump occurs in the guide vanes of the 4th stage, with pressure after the nozzle $p = 22.83$ kPa, $X = 0.974$ (the Wilson zone is reached). A slight supercooling is also observed at the 5th stage. Supercooling losses at two stages account for approximately 6%, and including the condensation jump — about 7%. The total power loss for this turbine in nominal mode is 720 kW per LPC flow path, or 2160 kW for three flows (since this LPC is a three-flow design), resulting in a turbine power loss of 0.72%. For another turbine modification, these losses amount to 1.13%.

If the Wilson zone shifts toward the last stage under off-design operating conditions, the absolute energy losses will increase significantly.

To determine the potential for reducing losses due to supercooling, experimental studies on artificial ionization of wet steam flow were conducted on a specially designed thermodynamic test bench at the IEMS of the NAS of Ukraine. A planar convergent-divergent supersonic nozzle was used in the experiments. As a result of steam flow ionization, the steam dryness at the nozzle outlet decreased from 0.991 to 0.9718. The maximum

moisture content of neutral steam at the nozzle exit did not exceed 1.5% (compared to 3.5% under adiabatic conditions), while in ionized steam it reached 3.4%. This indicates that the expansion process approached equilibrium conditions. Moreover, the bench tests have allowed for determining the range of pressures and temperatures at which ionization is effective.

According to the results of full-scale studies [15], a completely different picture is observed beyond the last stage. It is at this location that the charge density and electric field intensity increase sharply.

At the same time, numerical experiments showed that the energy consumption for artificial steam ionization amounts to only 0.03–0.15% of the energy released during condensation on ions, and the change in dielectric permittivity is negligible.

Thus, we have considered the additional energy losses arising from steam electrization and supercooling. In the examples presented, supercooling losses are more significant. In such cases, artificial steam ionization may be used to improve the efficiency of turbine stages operating in the two-phase region. Detailed information on the research results is provided in [15]. Preliminary estimates based on literature analysis indicate the potential for increasing the efficiency of the turbine unit by 1.5–2%. It should be noted that compared to other methods with similar purposes, such as the use of chemical additives, this approach is equally effective while requiring significantly lower energy input.

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THE LAST STAGE AND THE TURBINE EXHAUST SECTION

Numerical studies conducted in Ukraine and the United States on turbines for various purposes (heating and power generation) and with capacities ranging from 50 to 800 MW have shown that the charge density at the last stage can reach values from 10^{-6} to 10^{-3} (Fig. 1).

In fact, the steam turbine in the area of the last stage plus the exhaust duct can be regarded as an electrostatic generator [15] or a magnetron with a flow of charged particles. Once, for example, a positively charged droplet detaches from a turbine blade carrying a negative charge, the droplet experiences a Coulomb force proportional to the magnitude of its charge. This force acts opposite to the droplet's motion, resulting in a deceleration of the flow (Fig. 1). As a consequence, the mechanical energy of the flow and droplet motion is converted into the energy of the electric field. Ultimately, this leads to an increase in energy losses due to a rise in the static pressure behind the last stage.

During the experiment, a noticeable influence of space charge on the steam flow pattern in the exhaust compartment was also identified. Under certain operating conditions, when the charge density in the flow reached its maximum, oscillations of the liquid levels in the tubes of the manometric panel of ± 5 mm were observed. Numerous full scale tests have shown that the volumetric charge density and electric field intensity are highly non uniform in both the axial and radial directions, and that the electric fields and currents generated by electrization are pulsating in nature. These phenomena, in turn, induce additional flow pulsations that not only reduce turbine efficiency but also increase the vibrational-dynamic loads on the last stage blades.

To quantitatively assess the effect of space charge on steam flow, an experiment was conducted on a T-37/50-8.8 turbine operating in district heating mode. It was found that beyond the last stage of the turbine, the charge density of the steam flow was approximately $6 \cdot 10^{-4}$ C/m³, and the electric field intensity reached $2 \cdot 10^5$ V/m. Under these conditions, the energy of the electric field impedes the steam flow (Fig. 1), increases the pressure behind the last stage, and raises the turbine unit's power output by 140 kW, i.e., by 0.4%.

Therefore, to reduce energy losses and improve reliability in this part of the turbine, appropriate measures must be taken to control the modes of electrostatic generation — for example, by neutralizing the flow charges. The designs of neutrali-

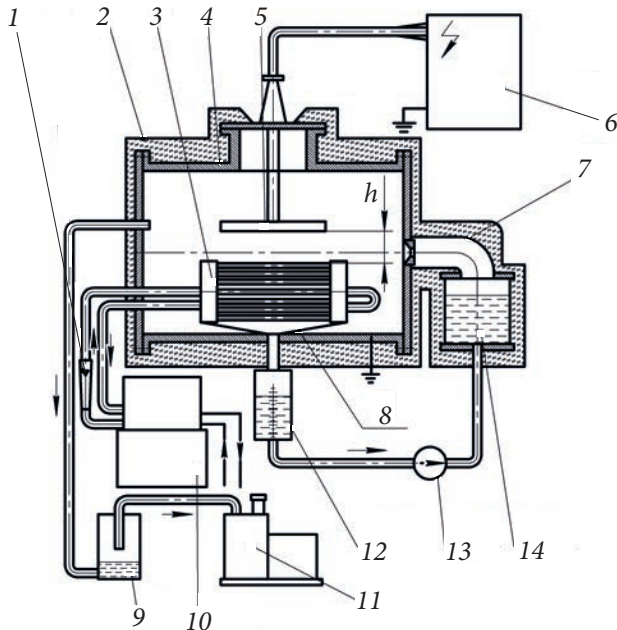


Fig. 4. Schematic diagram of the experimental setup of the heat exchange unit: 1 — flow meter; 2 — thermal insulation; 3 — heat exchanger-condenser; 4 — vacuum chamber; 5 — electrode; 6 — high-voltage power supply; 7 — steam pipeline; 8 — condensate collection tray; 9 — separator; 10 — thermostat; 11 — vacuum pump; 12 — measuring cylinder; 13 — circulation pump; 14 — electric steam boiler

zers are presented in [15], and this approach has been implemented by us at thermal power plant turbines (TPPs and CHPPs).

One of the consequences of steam electrization may be the occurrence of electromagnetic emissions (EME) of wet steam in the area of the last stages and in the exhaust duct. The most probable sources of EME are pulsed currents that arise during the charging and discharging of water droplets, as well as during the fragmentation and coalescence of charged droplets. Experimental studies conducted in the early 1990s confirmed the presence of EME in the exhaust duct of the wet steam turbine T-37/50-8.8 [15].

The emission spectrum generated in the exhaust duct covers a wide range — from hundreds of hertz to several gigahertz. The total radiation power can reach a significant value and depends on the operating

conditions and the power of the turbine unit. The electromagnetic radiation is absorbed by the ionized steam-droplet flow and by the condensate film on the surfaces of the condenser, which can lead to an increase in temperature and a deterioration in the condenser's performance.

Neutralization of electric charges in the steam flow beyond the last stage, as presented in [15], not only contributes to improving turbine efficiency but also significantly reduces the negative impact of EMI on heat exchange processes in the condenser.

IMPROVING THE EFFICIENCY OF THE CONDENSER OPERATION

Let us consider in detail one of the possible approaches to enhancing the efficiency of condensation and heat exchange processes in steam turbine condensers, namely — the use of electric fields.

Bench Testing. To study the influence of the electric field on a model steam flow, a bench setup was created, representing a cylindrical chamber with a useful volume of 0.35 m³ (Fig. 4). Inside the chamber, a tubular single-pass heat exchanger was installed, on which steam condensed. Above the condenser's heat exchanger, an active electrode was positioned to generate a corona discharge within a steady high-voltage electric field.

The effect of the electric field on the steam condensation process was determined by measuring changes in the amount of condensate obtained or the amount of heat transferred to the cooling water circulating through the condenser's tube bundle. The voltage on the active electrode was maintained close to the breakdown level.

The study demonstrated that the thermal load on internally underloaded tubes can significantly increase under the influence of a steady high-voltage electric field. As Fig. 5 shows, when the corona discharge system is activated, there is a redistribution of thermal loads, making their distribution more uniform. The total heat removal capacity Q_v of the heat exchanger increases by a factor of 1.4 compared to the baseline, and the vacuum is deepened by 1 kPa.

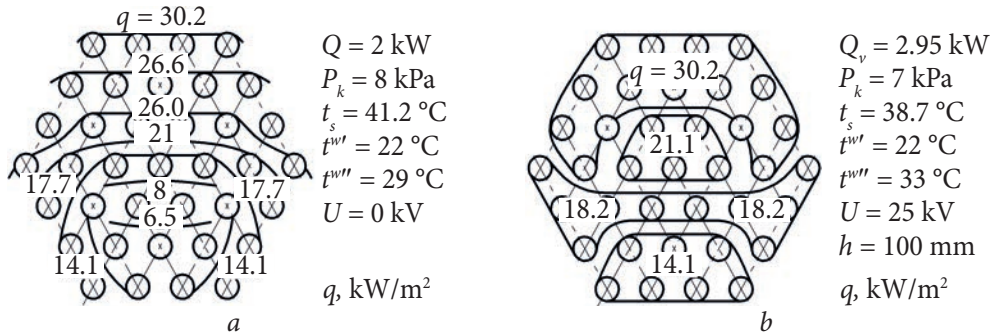


Fig. 5. Distribution of heat loads q across the zones of the tube bundle: *a* — in the presence of a constant electric field; *b* — without discharge; Q, Q_v — heat load on the condenser before and after applying a constant electric field. P_k, P_{kv} — pressure in the chamber; t_s — steam temperature in the chamber; t_w^v, t_w^m — inlet and outlet temperatures of the cooling water, respectively; h — distance between the electrode and the tube bundle; U — voltage on the electrode (subscript v denotes the corona discharge is applied)

The results of the aforementioned tests clearly demonstrate the feasibility of applying steady high-voltage electric fields to increase the thermal loads on the tube bundles in steam turbine condensers. As for the additional electrical power consumption, it is minimal, accounting for only 0.1–0.3% of the increase in the condenser's thermal capacity.

Let us consider the main physical factors arising under the influence of corona discharge on the steam flow, which enhance the heat exchange efficiency of the model condenser. The most significant intensifying effect of the electric field on wet steam under conditions of low pressure and corona discharge is the acceleration of steam movement in the direction from the active electrode towards the condensate tubes. This phenomenon occurs due to the entrainment of steam mass (enhanced diffusion) by ions moving in this direction, as well as the deepening of the vacuum in the condensation intensification zone and the displacement of air from the condensation region.

Furthermore, in a non-uniform electric field, the water vapor molecules — being electric dipoles — are subjected to a force that tends to move them toward regions of higher electric field intensity, i.e., toward the active electrode. This leads to disruption of the continuity or thinning of the con-

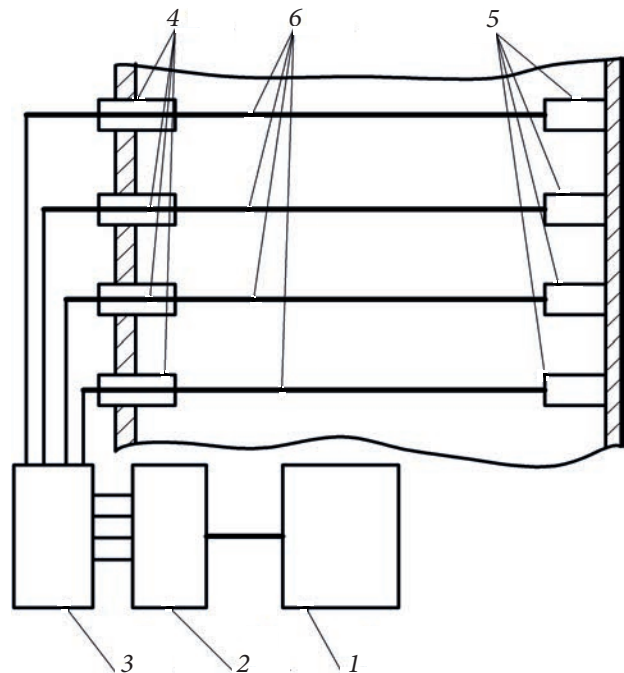


Fig. 6. Connection diagram of corona electrodes: 1 — high-voltage power supply; 2 — distribution device; 3 — corona electrode operation monitoring device; 4 — current conductors; 5 — suspension insulators; 6 — corona electrodes

densate film, which constitutes the primary thermal resistance to heat transfer from the steam to the circulating cooling water.

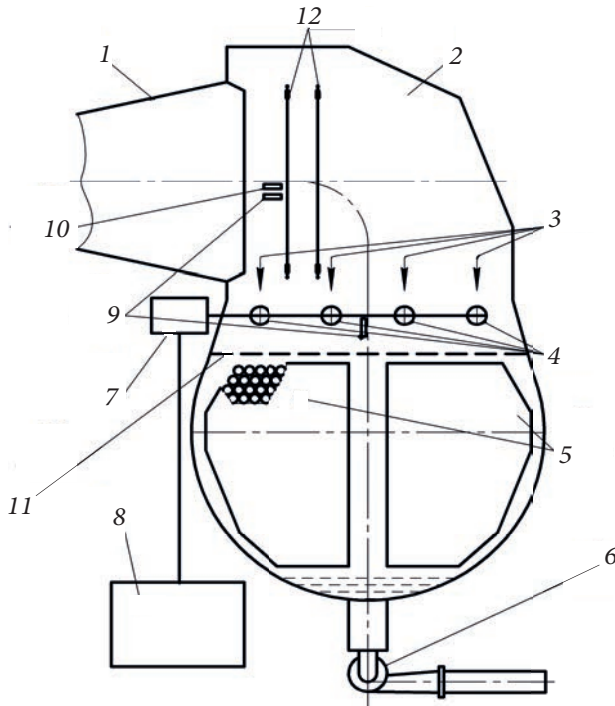


Fig. 7. Schematic diagram of the high-voltage electrode system, neutralizers, and pressure sensors in the exhaust pipe of the T-37/50-8.8 turbine unit: 1 — turbine; 2 — exhaust pipe; 3 — direction of steam flow; 4 — groups of high-voltage electrodes; 5 — tube bundles of the condenser heat exchanger; 6 — condensate pump; 7 — switching device; 8 — high-voltage power supply; 9 — static pressure sensors; 10 — total pressure sensor; 11 — plane of pressure sensor placement at the condenser inlet; 12 — charge neutralizers

Field Testing. In the course of full-scale studies, it was necessary to create a high-voltage electric field directly above the condenser in order to influence the steam-water flow in the exhaust section of the turbine. The most convenient way to generate such a field is by using electrodes mounted on suspension insulators.

Initially, the authors attempted to use rod-type electrodes for this purpose. However, tests of this design revealed that due to low leakage resistance, it was impossible to raise the voltage on the corona electrodes to significant levels.

Experiments conducted specifically on a laboratory setup made it possible to identify a corona

electrode design that meets all technological and operational requirements — a twisted electrode.

This electrode consists of a stainless steel cable. Due to the fact that the cable is made of thin twisted wires, its surface creates a sufficient electric field gradient to sustain corona discharge when voltage is applied. Moreover, this type of electrode demonstrates high reliability. During one year of operation inside the duct, there were no breaks in the electrode and no signs of electrical erosion were observed (Fig. 6).

The operational safety of the corona system is ensured in full accordance with standard high-voltage equipment safety requirements.

Subsequently, full-scale experiments were conducted to investigate the effect of a high-voltage electric field on the intensification of condensation and the flow kinetics of the steam-water mixture relative to the condenser surface. Neutralizers were installed in the turbine duct after the last stage, corona electrodes were mounted above the condenser, and sensors for static and total pressure (Prandtl–Pitot tubes), as well as temperature sensors at the outlet of the last stage and at the exit of the duct, were placed (Fig. 7).

All measurements were performed after the turbogenerator had reached a steady-state gas-dynamic regime. The control valves remained in a fixed position. Pressure measurements were conducted with the corona discharge both activated and deactivated. Only gas-dynamic parameters were recorded during the experiment.

When the corona discharge was switched on, the pressure pulsation amplitude at the inlet cross-section of the condenser decreased on the water differential manometers from 10 mm H₂O to 2 mm H₂O, i.e., from 100 Pa to 20 Pa. At the same time, the power output increased by approximately 100 kW, which corresponds to a 0.3%.

Based on the dynamic pressure measurements, velocity profiles at the condenser inlet were determined and plotted for the cases with and without the application of a steady electric field (Fig. 8). A comparison of these cases shows that when the steady electric field is activated, the velocity dist-

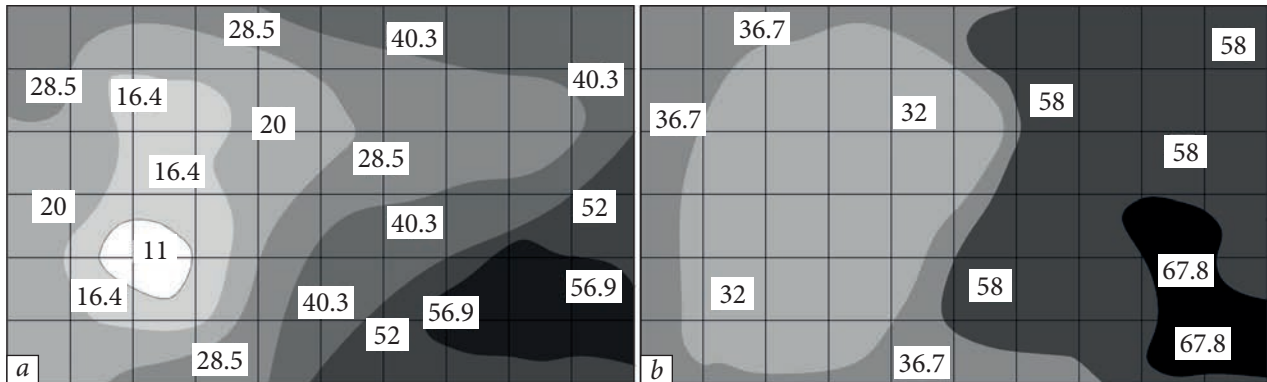


Fig. 8. Steam flow velocity distribution, m/s: *a* — in the cross-section of the exhaust pipe at the condenser inlet without electric field; *b* — in the inlet cross-section of the condenser with the electric field applied

tribution becomes significantly more uniform, the average velocity increases, which leads to reduced losses in the exhaust duct and to an increase in the thermal load on the condenser.

Since the exhaust duct in this turbine installation is not equipped with a diffuser, pressure recovery cannot be achieved; therefore, the experiments have indicated only a slight reduction in flow losses within the duct. According to the calculations, the application of high-voltage electric fields in this turbine configuration reduces the relative loss coefficient by approximately 2.5–4%. At the same time, this approach enables a reduction in the non-uniformity of the velocity field and a decrease in the number of stagnant zones at the condenser inlet. A reduction of 1 °C in the mean temperature head, defined as the difference between the steam temperature and the outlet water temperature, has also been observed.

We can conclude that the above full-scale experimental results clearly demonstrate the feasibility of improving the performance efficiency of the exhaust duct and the condenser through rational control of electrophysical processes.

CONCLUSIONS

Based on a comprehensive analysis of the literature and the results of extensive numerical simulations, laboratory experiments, and full-scale stu-

dies conducted by the authors, innovation non-conditional research and engineering approaches have been proposed to improve the efficiency of the low-potential section of steam turbine units through targeted control of electrophysical effects in the flow path of the low-pressure cylinder (LPC), including the last stage, the exhaust duct, and the condenser.

Using the developed model for calculating the thermodynamic characteristics of the expansion process of naturally electrized wet steam, additional energy losses in the adiabatic expansion process, as well as losses associated with steam ionization, have been quantified. In these calculations, variations in the dielectric permittivity of wet steam have been taken into account based on the results of full-scale experimental measurements of electric charge density and electric field intensity distributions along the LPC flow path.

For the first time, variations in the dielectric permittivity of ionized wet steam have been investigated. Experimental results have shown that these variations are relatively small (1–6%) compared with those of neutral steam, which has been attributed to the low moisture content, steam density, and charge density. Under the examined conditions, additional losses associated with steam electrization have not exceeded 0.1%.

It has been established that losses caused by steam subcooling are significantly higher, reaching

2—7%, and can result in power losses of approximately 0.7—1.2% in turbines of the K-300-24.5 type. To mitigate these losses, the application of flow ionization of wet steam has been substantiated and proposed. These findings have confirmed the feasibility and effectiveness of artificial ionization when required.

Positive effects of targeted control of electro-physical processes from the outlet of the last stage to the condenser have also been demonstrated. In particular, flow neutralization after the last stage has resulted in pressure reduction, an increase in the thermal head, and a power gain in the range of 0.25—0.4%. In the exhaust duct, flow neutrali-

zation has significantly improved operational reliability by reducing flow pulsations and mitigating the adverse effects of electromagnetic interference. Furthermore, the application of a steady electric field at the condenser inlet has enhanced condenser performance, primarily through an increase in thermal load and improved velocity field uniformity.

Overall, the results have demonstrated that optimization of thermo-electro-physical processes in the LPC flow path, the exhaust section, and the condenser opens up the possibility of increasing the efficiency of steam turbine units by 1.5—2% while significantly reducing fuel consumption.

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АНАЛІЗ ТЕРМОДИНАМІЧНИХ ТА КОНДЕНСАЦІЙНИХ ПРОЦЕСІВ В НИЗКОПОТЕНЦІЙНІЙ ЧАСТИНІ ПАРОВИХ ТУРБІН ТА ЗАСОБИ ПІДВИЩЕННЯ ЇХ ЕФЕКТИВНОСТІ

Вступ. Питання підвищення ефективності роботи низькопотенційної частини потужних вологопарових турбоустановок, від якої суттєво залежить якість роботи турбоустановки загалом, є актуальним. Незважаючи на використання новітніх методів їх моделювання та проектування, дотепер залишається низка невирішених питань.

Проблематика. Обґрунтоване визначення нетрадиційних засобів зниження додаткових втрат енергії, які виникають тільки у низькопотенційній частині турбіни: на останніх ступенях циліндрів низького тиску (ЦНТ) і пов'язані з фазовим переходом та появою вологи (зарядоутворення і переохолодження пари), а також у вихлопному патрубку й конденсаторі, акцентуючи увагу на вплив електризації потоку вологої пари.

Мета. Розробка методики підвищення ефективності та надійності роботи низькопотенційної частини потужних паротурбінних установок на основі цілеспрямованого керування теплоелектрофізичними процесами.

Матеріали й методи. Електризована та іонізована волога пара. Проведено аналіз літературних джерел, експериментальні дослідження на термодинамічному стенді ІЕМС НАН України, результати натурних експериментів, проведених на ТЕС і ТЕЦ України та США. Застосовано аналітичні методи, які базуються на класичних законах термодинаміки складних систем, електрофізики й теорії турбомашин.

Результати. На основі розрахункових та експериментальних досліджень показано позитивні наслідки цільового керування електрофізичними впливами від останніх ступенів ЦНТ до конденсатору. Запропоновано використання іонізації потоку вологої пари для зменшення втрат від переохолодження й постійного електричного поля на вході в конденсатор для збільшення теплового навантаження і зниження нерівномірності поля швидкостей, а також нейтралізацію потоку за останнім ступенем для зниження тиску і збільшення теплоперепаду.

Висновки. Вдосконалення теплоелектрофізичних процесів у низькопотенційній частині паротурбінної установки дозволить підвищити її ефективність роботи на 1,5—2%.

Ключові слова: останні ступені паротурбінної установки, патрубок, конденсатор, теплоелектрофізика, електризована та іонізована волога пара, діелектрична проникність.