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# INTEGRATED STUDIES OF ELECTROPHYSICAL PROCESSES IN STEAM TURBINES

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*The paper deals with comprehensive research in the field of electrization of wet steam flow in a turbine. The experience of the conducted studies on laboratory stands and full-scale objects (CHP and TPP) in Ukraine and the USA is introduced and generalized. It was shown that in the process of steam electrization, the charge density in the flow can reach very high values (an order of magnitude appears to be higher than in a thundercloud), and this phenomenon mainly has a negative effect on the turbine operation. Statistical data on the charge formation of the steam flow in the low-pressure cylinder of the turbine are presented. Results of the research to establish the main electrophysical factors of influence on the surface strength of the blade, such as electric fields, charge density and their polarity, are presented. The research results showed that such factors as the presence of a positively charged steam flow, constant and variable electric fields, which were most often recorded at operating turbines of CHPs and TPPs, significantly (by two or more times) intensify erosion-corrosion processes on the metal surfaces of the blades, thus reducing their working resource. Thermodynamic processes are studied both under conditions of natural electrification of a high-speed flow, which reduce the efficiency by about 0.3–0.35%, and under the influence of artificially created electric charges, which make it possible to increase the efficiency of the steam expansion process in the turbine by 2 or more percent. Various options of local input of electrical energy for steam ionization in the turbine are considered. At the same time, it is noted that for the practical implementation of these approaches, further careful design improvements and tests on model and full-scale installations are required. Water chemistry regimes are also considered in the context of their influence on the flow charge formation process, as well as on reliability and efficiency indicators of the turbine. Experimentally at an 800 MW turbine plant in the USA, it was shown that a change in the pH of the medium affects the intensity and polarity of the charge formation of the steam flow. The paper introduces the physical features of this phenomenon and notes the importance of these processes influence on the strength characteristics of the blades. Information on new methods and technologies that could lead to an increase in the operational efficiency and reliability of wet steam turbines, such as methods for input and removal of electrical energy into the flow; rational choice of water chemistry regimes; space charge neutralization, etc., is provided. These comprehensive electrophysical studies, considered in conjunction with thermal processes, can be characterized as a new scientific direction in the theory of steam turbines – thermal electrophysics.*

***Keywords**: steam turbine, electrization, statistics, efficiency, strength.*

## Introduction

Steam turbines are heat engines in which thermal energy of steam is converted into mechanical energy. High-temperature high-pressure steam, passing through the flow path of the turbine, expands while maintaining near and supersonic speeds, contacting (being in touch) with the metal structures of the flow path of the low-pressure cylinder (LPC). As a result, the flow of wet steam is electrified. This happens exclusively due to the electrization of the drops contained in the stream flow. The collision of water drops during movement with the working surface of the blade or the walls of the nozzle causes electrization of both the drop itself and the metal surface. Drops of water can take an electric charge when separated from the surface of metal or water as well as when a large drop is crushed while moving in a stream. The high charge density in the flow path of the turbine's LPC is accompanied by electrical discharges and ionization of the steam flow, which can have a noticeable effect on the properties of steam, heat exchange processes and, given the presence of an aggressive electrified working medium, can intensify erosion-corrosion degradation phenomena in metal structures. In fact, in this part of the turbine, the ongoing processes should be considered as thermoelectrophysical, in which the effect of electrization cannot be ignored.

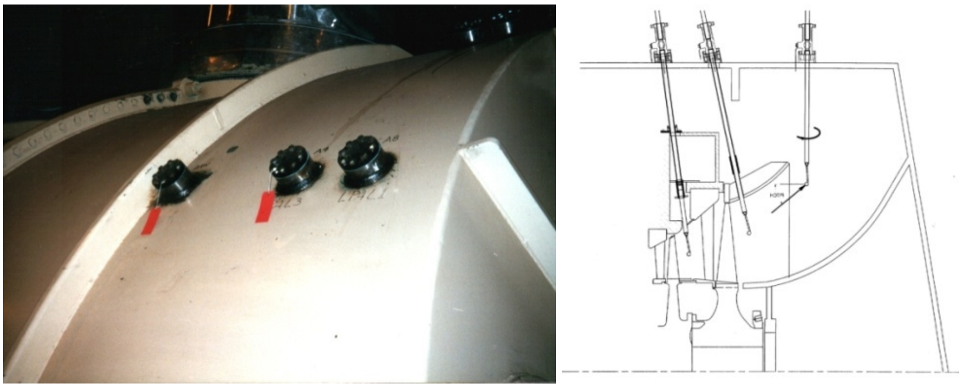
During the operation of wet steam turbine plants, part of their thermal energy, due to the electrization of the wet steam flow, is converted into electrostatic energy of the flow path. The magnitude of these energy losses is small, however, as the studies have shown, the effect of electrization on the performance of the turbine unit is very tangible and is relevant and important from both practical and scientific points of view.

One of the main tasks of the research presented in this paper was to assess the level of electrization of the steam flow at the operating turbines of TPPs and CHPs and to determine the post-factor effects of the charged flow on the performance of the power plant.

**Static indicators of electrization**

Comprehensive studies carried out by the employees of IPMach NAS of Ukraine and Sonoma Research Company (USA) at various TPPs and CHPs in Ukraine and the USA have shown that in the process of electrization of steam, the charge density in the flow can reach very high values [1].

In 1992, the employees of IPMach NAS of Ukraine during research on the steam turbine T-37/50-8,8 (TPP-2 "Eskhar") for the first time discovered the presence of charges in the steam flow of the turbine. The measured charge density behind the last stage of the turbine turned out to be higher than in a thundercloud by an order of magnitude and amounted to $10^{-3}$ C/m$^3$ at an electric field strength of up to $2\times10^5$ V/m. The fact of the existence of an electromagnetic field in the turbine branch pipe was also established and its spectral composition was measured.



a b

***Fig. 1. Traversing the steam flow with electric probes:***
a – installation of special valves; b – movable probes

In 1997, in the USA, on a steam turbine of 800 MW at the Navajo TPP (Arizona), the steam flow was traversed in the flow path of the turbine with movable electric probes (Fig. 1).

It was found that before the last stage, the charge density was $10^{-8}$–$10^{-6}$ C/m$^3$, and after the last stage – $10^{-4}$ C/m$^3$.

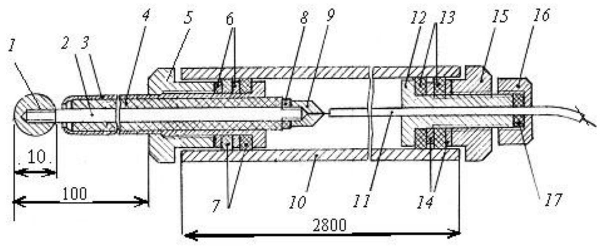



***Fig. 2. Electric probe:***
1 – receiver element (sphere); 2 – electrode; 3 – framework; 4 – insulator; 5 – puck; 6 – washer; 7 – rubber ring; 8 – puck; 9 – puck; 10 – bar; 11– cable; 12 – sleeve; 13 –rubber ring; 14 – washer; 15 – puck; 16 – puck; 17 – rubber ring

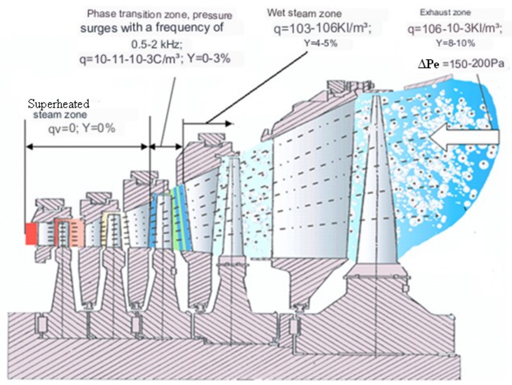



***Fig. 3. Change of steam flow parameters in the LPC flow path:***
$Y$ – steam humidity; $q_v$ – the volumetric charge density; $\Delta P_e$ – counterpressure created by the space charge

Similar studies using the developed tools in the form of electrical probes (Fig. 2) were also carried out on other turbines for various purposes (cogeneration and condensing) and capacities (50; 100; 200; 300; 320; 400; 800 MW).

Summarizing the results of all studies in this area, it is possible to sum up that the distribution of the charge density in the flow path and in the condenser of wet steam turbines (Fig. 3) is represented:

– at the beginning of the phase transition zone $10^{-11}$–$10^{-8}$ C/m$^3$;

– before the last stage $10^{-8}$–$10^{-6}$ C/m$^3$;

– after the last stage $10^{-6}$–$10^{-3}$ C/m$^3$;

– in the condenser area $10^{-9}$–$10^{-7}$ C/m$^3$.

The established fact of electrization of a wet steam flow in a turbine predetermined the need for research on the influence of these phenomena on the reliability and efficiency of turbines.

**Strength indicators**

In this regard, the results obtained experimentally for the first time on the establishment of a significant effect of an aggressive electrified steam medium on the surface strength of working blades are very important.

To carry out the above-mentioned studies, a wet steam stand was created using artificial ionization of steam (Fig. 4), as well as a mechanoelectric stand for the effect of electric fields on metal samples (Fig. 5). The tests were carried out in different thermodynamic and electrical regimes. These studies are detailed in papers [2, 3].

It is shown that such factors as the presence of a positively charged steam flow, constant and alternating electric fields, which were most often recorded during experimental studies on operating turbines of TPPs, significantly (by two or more times) intensify erosion-corrosion processes on the metal surfaces of the blades, thus reducing their working resource. In this case, the change in the surface strength of the material during electrization of the flow occurs mainly due to an increase (by 5–10 times) of the absorption of hydrogen into the metal and a change in its surface energy under the influence of electric fields, due to a change in the density of electrons.

The results of the studies on the effect on the surface density of the blades, depending on the polarity of the flow, are shown in Fig. 6.

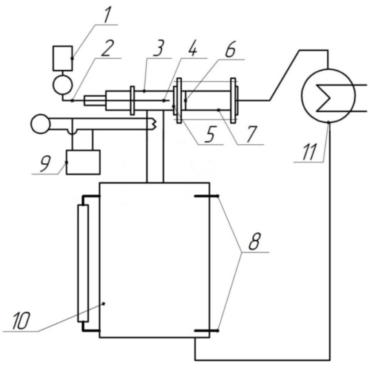



***Fig. 4. Conventional scheme of the basic elements of a steam installation with steam ionization by corona discharge:***
1 – high-voltage source; 2 – high-voltage input; 3 – ionization steam chamber; 4 – coronating electrode; 5 – nozzle; 6 – steel sample attachment module; 7 – sample processing chamber; 8 – water level sensors; 9 – steam superheater; 10 – boiler; 11 – capacitor

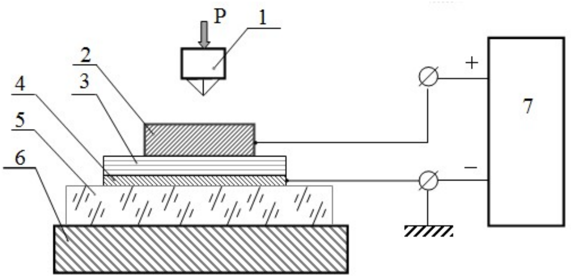



***Fig. 5. Scheme of measuring the microhardness of the sample surface in the electric field:***
1 – indenter; 2 – sample; 3 – fiberglass; 4 – foil; 5 – insulator; 6 – object table of a microhardness meter; 7 – voltage source

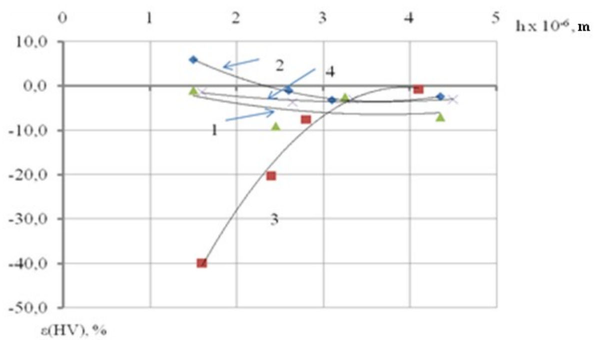



***Fig. 6. A summary graph of the relative change in microhardness due to the depth of the surface of samples processed in wet steam in the following modes:***
1 – neutral wet steam; 2 – negatively charged wet steam; 3 – positively charged wet steam; 4 – quasi-neutral steam (electrization in the barrier discharge)

Fig. 6 shows that the impact of a positively charged flow (as opposed to a negative one) reduces the strength properties of the surface layer of the blade material by 30–50%. Moreover, it is necessary to pay attention to the fact that (as numerous field studies have shown) in the zone of the last turbine stages, the polarity of the steam, as a rule, has a positive sign, and therefore has the greatest degradation rate.

During research at the "Eskhar" TPP [1] it was found that alternating electromagnetic fields arise in a low-pressure cylinder in the wet steam electrization zone. The influence of alternating electric fields with frequencies of 20, 200, 2500, 20000 Hz and a voltage of 10 V on the surface microhardness ε(HV) of a prismatic sample made of 15Kh11MF steel was also studied. Microhardness was determined at three different indenter loads: 10, 20, and 100 gf. The results of measurements in the form of graphs are given in Fig. 7.

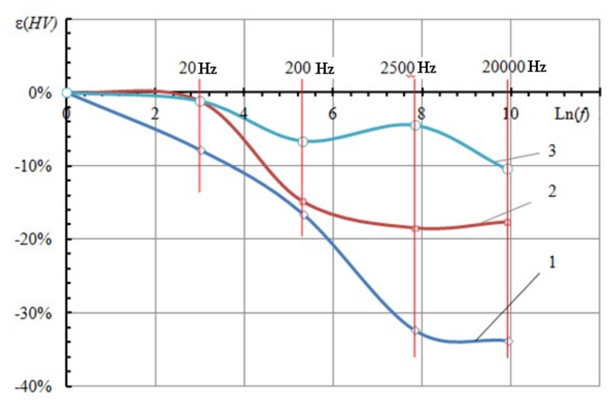



***Fig. 7. Relative change in the microhardness of the surface of a sample made of 15Kh11MF steel depending on the frequency of an alternating electric field with a voltage of 10 V:***
1 – ε(HV 0.01); 2 – ε(HV 0.02); 3 – ε(HV 0.1)

The graphs show that variable electric fields in the range from 200 Hz to 20.000 Hz have a significant effect on the plastic deformation of the surface layer of the 15Kh11MF blade steel. The greatest relative decrease in microhardness is observed at an indenter load of 10 g (HV 0.01) up to 30% and at an indenter load of 20 g (HV 0.02) up to 18%. The obtained results show that electromagnetic fields also have a negative effect on the metal resistance.

A comprehensive analysis of the influence of the flow charges and its magnetic fields on the blades surface strength showed that with a high charge density, the operational life of the blades can be reduced by 50 percent or more.

**Efficiency indicator**

When considering the degree of influence of natural electrization of the flow on the turbine efficiency, it was taken into account that this phenomenon could be effective as a factor of additional formation of condensation nuclei in supercooled steam. However, this assumption was not confirmed when considering the real processes occurring in the turbine. This can be explained by the fact that in the initial phase transition zone when supercooling usually reaches a maximum level, the number of naturally forming charges, as it was experimentally confirmed (Fig. 3), is insignificant, and they practically do not affect heat and mass transfer processes. In the zone of the last stages, on the contrary, the level of hypothermia is already minimal, and the charge density is maximum, which significantly reduces the possible effect of reducing hypothermia from electrization. Moreover, an additional negative factor such as electrostatic forces of flow deceleration ($\Delta P_e$, Fig. 3) is imposed on this process in this zone. Thus, taking into account all possible processes occurring during the flow of a charged stream (electrostatic forces of deceleration of the flow in the exhaust part, an increase in the non-stationarity of the flow due to the uneven distribution of charges and electric fields in the flow path, the electrostatic force of a drop directed to the grounded sections of the flow path, etc.), it is possible to estimate the amount of heat energy losses in the turbine LPC from the effect of electrization, which approximately are 0.3–0.35%.

The dynamics of the growth of natural charge formation in the flow path of the LPC, as previously noted, occurs in the direction opposite to the required dynamics of the formation of additional condensation centers, which contributes to a decrease in the level of steam supercooling. Therefore, the second line shown in the paper is an artificial ionization of steam that was developed taking into account the accumulated experience and the vision of the disadvantages of natural electrization. The problem of rational control of the processes of charge formation and ionization of steam for this case was formed and solved in the following formulation - increasing the efficiency of the process of the steam flow expanding in a turbine should be carried out by activating (or deactivating) it by local input (or output) into the working medium of electrical and electromagnetic energy. Numerous stand and partially full-scale tests have shown the high efficiency of the proposed method of artificial ionization of the steam flow. As the calculations and results of experimental tests have shown, the efficiency of wet steam turbines in this case can be increased by two or more percent due to a decrease in the level of overcooling and non-stationary condensation, a decrease in film condensation and concentration of large dispersed moisture, etc.

In particular, the results of experimental studies on a thermodynamic steam stand (Fig. 8) are shown below.

During the experiment to determine the effect of ionization on the efficiency of the expansion process, a corona electric discharge device was used in compliance with the following main characteristics of the nozzle and steam parameters:

– steam consumption through the nozzle $G_0$=0.00115 kg/s;

– the area of the outlet section of the nozzle $F$=1.418×10$^{-5}$ m$^2$;

– steam pressure in front of the nozzle $p_0$=59 kPa;

– pressure in the zone of sudden expansion $p_k$=5.99 kPa;

– heat of steamization in the zone of sudden expansion $\chi$=2415.3 kJ/kg;

– the specific current of the corona discharge in the experiment is $J$=3.2×10$^{-3}$ A/(kg/s).

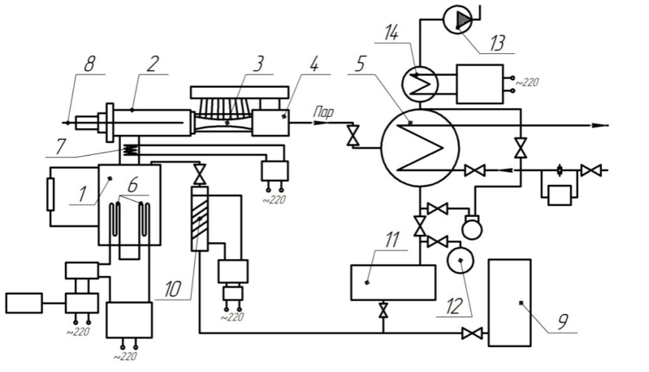



***Fig. 8. Schematic diagram of the experimental steam stand:***
1 – steam boiler; 2 – steam intake chamber; 3 – nozzle; 4 – exhaust pipe; 5 – main capacitor; 6 – heating elements of the steam boiler; 7 – superheater; 8 – ionizer; 9 – replenishment tank; 10 – feed water heater; 11 – condensate collector; 12 – compressor; 13 – vacuum pump; 14 – supporting capacitor

Studies of the steam expansion process in an axisymmetric nozzle have shown that the nature of the pressure changes significantly in the process of steam ionization. In this case, under the action of an electric discharge device, charged particles are formed from neutral steam molecules. It intensifies the condensation process and the pressure jump observed during natural expansion which is almost completely leveled during ionization. As a result, the losses in the nozzle associated with the jump of condensation and supercooling of the steam are reduced.

When the steam flow is ionized, the degree of steam dryness at the nozzle exit decreases from 0.991 to 0.9718, and the enthalpy decreases from 2601.5 to 2557.5 kJ/kg (Fig. 9). As a result, the amount of phase transition heat used in the nozzle increases by 44 kJ/kg, which increases the efficiency of the expansion process from 0.52 to 0.933. The maximum moisture of neutral steam at the outlet from the nozzle does not exceed 1.5% (at adiabatic one – 3.5%). In ionized steam, the moisture can reach 3.4%, which is very close to adiabatic, i.e. the process is approaching equilibrium.

It should be noted that such a process and an increase in efficiency correspond only to this nozzle. Nevertheless, it can be argued that due to the more complete use of the heat of condensation during the ionization of steam, the tendency in increasing efficiency should remain for any process of steam expansion, including those in real turbines.

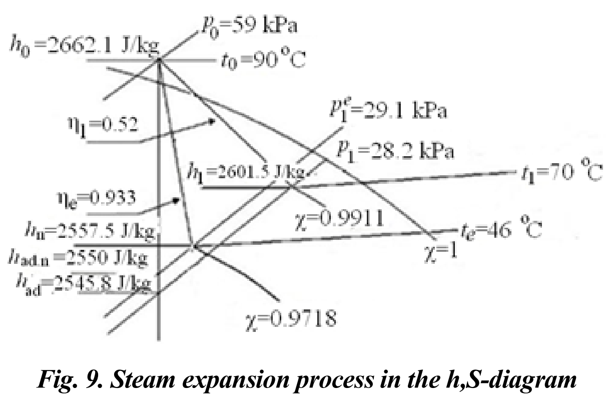



***Fig. 9. Steam expansion process in the h,S-diagram***
(the index "e" denotes the process during the steam ionization)

Nevertheless, the question arises: is it possible to reduce the amount of supercooling due to artificial ionization under natural conditions. As a confirmation of this possibility, a full-scale experiment was carried out on the T-250/300-240 turbine in the area of the last stage. To control the ionization of the flow, a volume charge neutralizer was used by applying a high voltage in the so-called active mode. The experiment showed that the ionization of the steam flow behind the last stage reduces the supercooling process, which is fixed by an increase in temperature by almost 1 ºC.

In the process of study, various options for the local input of electrical energy for steam ionization in the turbine were developed and proposed [4] (Figs. 10, 11).

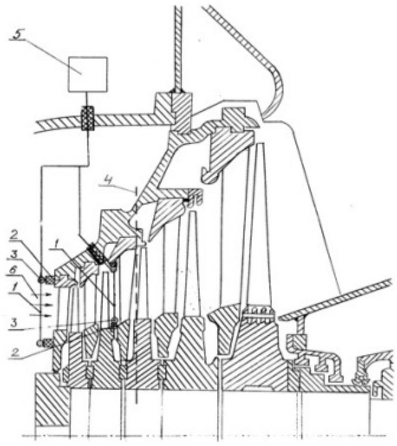


***Fig. 10. Placement of discharge electrodes for ionization of the steam flow in the turbine flow path:***
1 – discharge electrodes; 2 – insulators; 3 – collector;
4 – zone of the condensation beginning;
5 – high-voltage source; 6 – steam flow

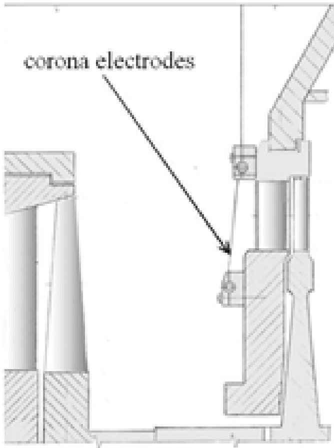



***Fig. 11. Placement of steam flow ionizers in the turbine flow path in front of the first stage of the LPC***

Previous studies on "survivability" during the transportation of ionized steam when using a barrier discharge [5] showed the promising lineup (Fig. 12), but further elaboration and detailing of this proposal is required. In this case, the generation of steam charges is carried out outside the flow path.

To reduce the negative impact of electrostatic flow braking forces in the last stage zone, the local energy removal is provided using charge neutralizers [6, 7], which have been successfully tested at CHP and TPP (Fig. 13).

Structurally, the neutralizer can be made in the form of two half-ring electrodes (Fig. 13.), installed, for example, on support insulators on the outer wall of the exhaust diffuser.

The result of the neutralization of the flow after the last stage due to such removal of electrical energy reduces the back pressure $\Delta P_e$, reduces the flow pulsations arising from electrostatic processes, thereby increasing the efficiency and reliability of the turbine unit.

The level of efficiency of power units due to the control of thermal processes by activating and deactivating electric charges in the steam flow can be increased by 2 percent or more.

The method of artificial ionization of the steam flow proposed in the paper and its possible use for wet steam turbines is scientifically justified. The method effectiveness is confirmed by the results of numerous studies and might be a good basis for its further practical refinement and design improvement of promising steam turbines.

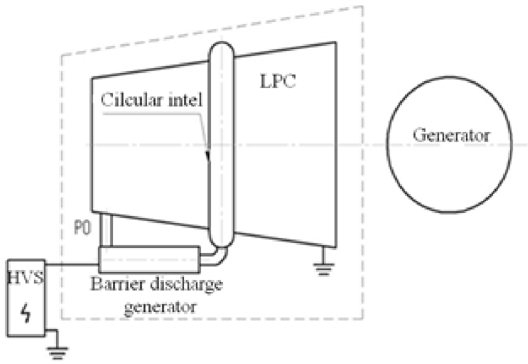



***Fig. 12. Scheme of the external supply of ionized steam to the flow path***

***Fig. 13. General view of the turbine exhaust converter***

**Water chemistry regimes and charge formation**

The possibilities of controlling thermal processes in the turbine by correcting the water chemistry regimes, more precisely the pH of the medium, is also explored and studied in the paper. Unfortunately, the results of all specially conducted laboratory and field tests in this direction have shown that a change in the pH of the medium has practically no effect on the intensification of the formation of process moisture in the flow path, and hence on the steam expansion process in the turbine and its efficiency.

At the same time, during an experiment at an 800 MW turbine unit in the USA, the fact of the influence of the pH of the medium on the intensity and polarity of the charge formation of the steam flow was established (Fig. 14).

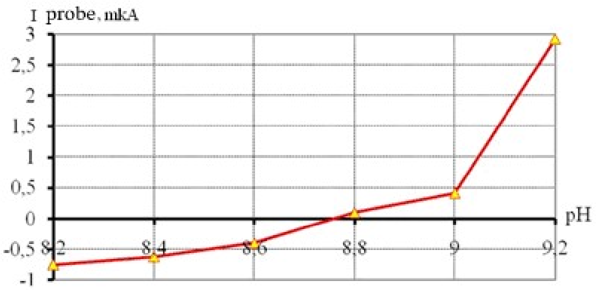



*Fig. 14. Probe current dependence on the pH of the feed water (turbine 800 MW) [6]*

It can be seen that an increase in pH from 8.2 to 8.8 causes a decrease in the probe current to zero, and with a further increase in pH to 9.2, the probe current changes polarity to the opposite and increases sharply. Based on the results of the experiments, it can be concluded that by changing the pH of the feed water, it is possible to control the process of charge formation in the wet steam flow of the turbine.

These processes, in our opinion, are not associated with process moisture, but are the result of film condensation on the blade surface, i.e. factor that has a greater impact on reliability rather than on efficiency. In this case, a change in the properties (amino content of the medium) leads to a change in the forces of the surface tension of the water (film) condensate, which in turn contributes to both a change in the dispersion of droplets breaking off the metal and the degree of their electrification and polarity, i.e. parameters that significantly affect the surface strength of the blade.

Understanding of these processes opens up broad prospects for the development of recommendations for reducing the erosion-corrosion degradation of turbine structural elements. In particular, it is recommended to choose the amine content of feed water in terms of the minimum charge density in the flow (or with negative polarity), and to carry out the corresponding control using an electric probe (Fig. 15).

The technical implementation of the system for suppressing electrization by water chemistry regimes correction can be performed on the basis of an automated system using a steam flow electrization sensor. Studies have shown that such measures lead to a significant extension of the service life of working blades.

The information obtained in the result of these comprehensive studies on electrophysical phenomena in the turbine, including the effect of electrified steam on the surface strength of the blades was the background for the development of new methods and technologies that increase the operational efficiency and reliability of wet steam turbines.

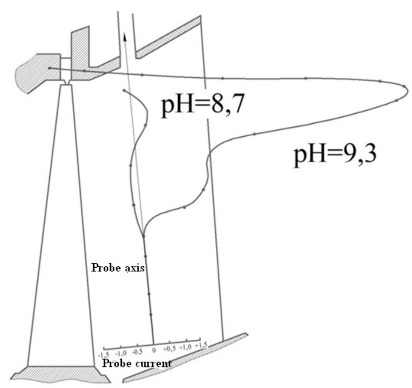



*Fig. 15. Results of measurements of charges behind the last stage of the turbine 800 MW (USA) depending on pH*

On this basis, in addition to the above-mentioned methods for the rational choice of water chemistry and neutralization of the space charge, the following approaches were also developed: a method for diagnosing erosive-dangerous coarse moisture using an electric probe [1, 5]; ways to reduce the erosion-corrosion degradation of the metal from the impact of an electrified medium by evaporation, in which the control of moisture removal from the surface of the blades is carried out by an electric probe [8].

**Conclusion**

Taking into account the conducted studies on the selection of rational thermodynamic parameters at which steam ionization is effective, this technology can be successfully implemented in geothermal installations for turbines with the following steam parameters: inlet temperature 80–150 °C and pressure 180–200 kPa.

Considered options for the possible practical implementation of ionization of the steam flow, of course, require careful design work and tests on model and full-scale installations.

The given results of the study determine the general approach for solving the problem of reducing the damaging effect of charged droplets on the surface of metal part. It is necessary to organize the neutralization of the ion flow before contact with metal surfaces, or to create radical reduction of droplet moisture contacting the surfaces of the flow part, which will increase the service life of the blades by approximately 2 times.

The research on electrophysical phenomena in wet steam turbines given in the paper is relevant and important information for specialists in the energy sector. These comprehensive studies, along with thermal processes, can be characterized as a new scientific direction in the theory of steam turbines – thermal electrophysics.

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## Комплексні дослідження електрофізичних процесів у парових турбінах

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*У статті розглядаються комплексні дослідження в галузі електризації вологопарового потоку в турбіні. Представлено аналіз, узагальнено досвід проведених досліджень на лабораторних стендах і натурних об'єктах (ТЕЦ і ТЕС) України, США. Показано, що в процесі електризації пари щільність зарядів у потоці може досягати дуже високих значень (на порядок вищих, ніж у грозовій хмарі), доведено, що це явище негативно впливає на роботу турбіни. Наведено статистичні дані зарядоутворення парового потоку в циліндрі низького тиску турбіни. Представлено результати дослідження зі встановлення таких основних електрофізичних чинників впливу на поверхневу міцність лопатки, як електричні поля, густина зарядів і їхня полярність. Спираючись* *на це підкреслено, що такі фактори, як наявність позитивно зарядженого потоку пари, постійних і змінних електричних полів, що найчастіше реєструвалися на діючих турбінах ТЕС і ТЕЦ, значно (у два і більше разів) інтенсифікують ерозійно-корозійні процеси на металевих поверхнях лопаток, знижуючи тим самим їхній робочий ресурс. Термодинамічні процеси вивчаються як в умовах природної електризації високошвидкісного потоку, що знижують показники ефективності приблизно на 0,3-0,35%, так і під час впливу штучно створених електричних зарядів, які дають змогу підвищити ефективність процесу розширення пари в турбіні на 2 і більше відсотки. Розглядаються різні варіанти локального введення електричної енергії для іонізації пари в турбіні. При цьому наголошується, що для практичної реалізації цих пропозицій у подальшому потрібні ретельне конструкторське доопрацювання і випробування на модельних і натурних установках. Досліджуються також водно-хімічні режими у контексті їхнього впливу на процес зарядоутворення потоку, показники надійності й економічності турбіни. Експериментально на турбоустановці 800 МВт у США було показано, що зміна pH середовища впливає на інтенсивність і полярність зарядоутворення потоку пари. У статті увагу приділено фізичним особливостям цього явища і наголошено на важливості й впливі цих процесів на характеристики міцності лопаток. Наводиться інформація про такі нові методи і технології, що забезпечують збільшення експлуатаційної ефективності й надійності вологопарових турбін, як способи введення і відведення електричної енергії в потік; раціональний вибір водно-хімічних режимів; нейтралізація об'ємного заряду та ін. Комплексні електрофізичні дослідження, що розглядаються разом із тепловими процесами, можна охарактеризувати як новий науковий напрям у теорії парових турбін – теплоелектрофізика.*

***Ключові слова**: парова турбіна, електризація, статистика, ефективність, міцність.*

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