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WET STEAM FLOW IONIZATION AND PROSPECTS TO PRACTICALLY APPLY ELECTRICAL DISCHARGE DEVICES IN TURBO INSTALLATIONS

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This paper considers the experimental studies on steam flow ionization in a supersonic nozzle and possibility of artificial flow ionization influence on unequal-weight processes in the low-pressure cylinder and an increase in turbine efficiency. Results of studies to assess the effect of barrier and corona ionizers on the process of intensifying fine-dispersed wetness in a supersonic nozzle are presented. It is shown that ionization allows intensifying the process condensation of steam in the form of fine wetness, reduce film condensation and coarse-particle wetness concentration, reduce the levels of supercooling and condensation non-stationarity. The range of parameters at which steam ionization is most effective is determined. Advantages and disadvantages of using barrier and corona ionizers are considered. Given are dependencies, and determined are flow dispersion and condensation nuclei concentration at which the process of steam expansion approaches equilibrium. It is shown that the positive effects arising from steam ionization are comparable to the use, in turbines, of metered chemical additions. At the same time, steam ionization has a number of significant advantages. Possible options for implementing the use of ionizers in the law-pressure cylinders of wet steam turbines are considered both at the stage of creating or upgrading turbines and for the existing turbine plants. It is shown that in the future, the use of ionizers will increase the efficiency and economy of turbine stages operating in the two-phase region, and increase the efficiency of turbine units by 1–1.5%.

Keywords*: steam flow, supersonic nozzle, ionization, non-equilibrium processes, wet steam turbine, efficiency.*

Introduction

It is known [1, 2] that the most active condensation nuclei in the phase transition zone, both in natural phenomena and in technical devices, are charged particles (ions and electrons). In the steam turbine, the natural electrification in this zone is too small, and the volume density of charges formed by charged particles is only 10^{-11}–10^{-8} C/m^3. The charge density is sufficient enough to affect the process of volume condensation, and is achieved only after the last stage of the turbine, where the process of steam expansion has already been completed.

Until recently, the absence of real methods of controlling the process of steam volumetric condensation in order to reduce the steam supercooling level and increase turbine efficiency has been a constraint to the development of this area. Unfortunately, some attempts, for example, the use of chemical additions to the feed water, which have been made to control the process of steam condensation in the phase transition zone, have not found industrial application until now.

Therefore, the authors of this article propose a method to intensify the formation of condensation nuclei due to the artificial ionization of steam flow before the phase transition zone, with the ionization carried out using corona or barrier discharges [1].

Experimental Studies

To conduct experimental studies in this direction, a thermodynamic test bench was created at IPMash of the NAS of Ukraine (Fig. 1).

Functionally, the test bench consists of:
– a steam generator;
– an ionizer;
– a supersonic nozzle;
– a measuring system;
– a condenser.

Fig. 1. General view of the test bench

The steam generator provides the necessary steam flow rate of the following specified parameters:

– absolute pressure from 30 to 110 kPa;

– steam flow rate up to 0.0015 kg/s;

– steam temperature up to 200 ^{o}C.

The test bench is shown schematically in Fig. 2.

To create artificial condensation nuclei at the nozzle entry (1), a corona electrode (3) is installed. To measure the current transferred by the steam flow, a grid (6) is installed in the exhaust manifold (2), which serves as an electrical probe.

One of the main elements of the experimental test bench is an axially symmetric convergent-divergent nozzle with the possibility of measuring pressure at 14 points.

The main characteristics of the nozzle and steam parameters during the experiment are the following:

– steam flow rate through the nozzle G_0=0.00115 kg/s;

– nozzle exit section area F=1.418·10^{-5} m^2;

– steam pressure at the nozzle entry p_0=59 kPa;

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

– evaporation heat in the zone of sudden expansion χ=2415.3 kJ/kg;

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

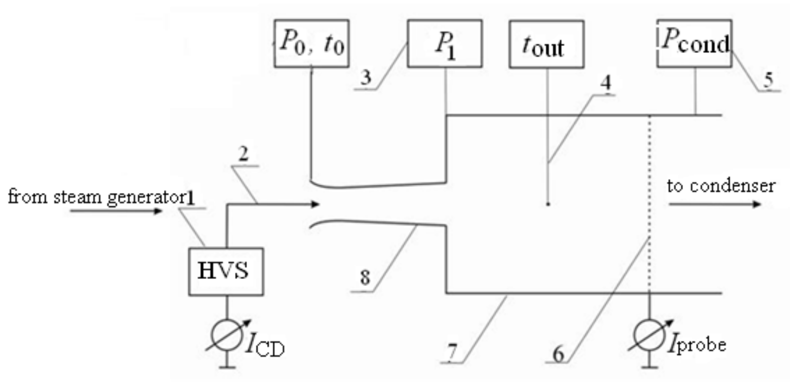


Fig. 2. Simplified test bench layout (corona discharge):
1 – high-voltage source; 2 – corona electrode; 3 – pressure gauge for measuring the pressure at the nozzle exit; 4 – thermocouple; 5 – pressure gauge for measuring the pressure in the exhaust pipe; 6 – grid (electric probe); 7 – exhaust pipe (zone of sudden expansion); 8 – nozzle

The studies of the steam expansion process in the axisymmetric nozzle showed that the nature of the pressure change varies significantly during the process of steam ionization. In this case, under the action of an electric-discharge device, charged particles are formed from neutral steam molecules.

Fig. 3 shows the change in the relative value of the steam pressure along the nozzle.

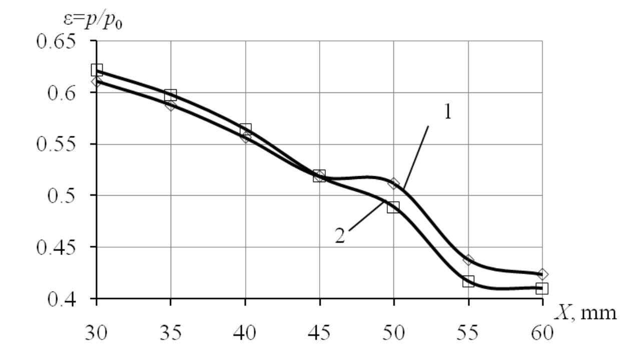


Fig. 3. Relative pressure distribution along the axisymmetric nozzle length:
1 – neutral steam; 2 – charged steam

With the expansion of the neutral steam after the nozzle throat, a decrease in the pressure gradient caused by the spontaneous condensation is observed. With the expansion of the ionized steam, the pressure uniformly decreases along the entire length of the nozzle (Fig. 3, curve 2) and the process approaches equilibrium.

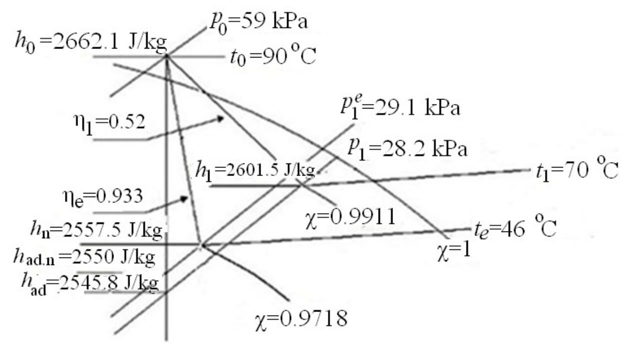


Fig. 4. Steam expansion process in h, S-diagram
(index "e" denotes the steam ionization process)

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. 4). As a result, the amount of the phase transition heat used in the nozzle increases by 44 kJ/kg, which increases the expansion process efficiency from 0.52 to 0.933. The maximum neutral steam wetness at the nozzle exit does not exceed 1.5% (compared with the adiabatic one of 3.5%). In the ionized steam, the wetness can reach a value of 3.4%, which is very close to adiabatic, i.e. the process is approaching equilibrium. The positive effect is achieved through the action of the ionizer, which forms, in the volume of steam,numerous hydrated ions (additional nuclei of heterogeneous condensation), which are a complex of an ion and water molecules linked to it by electrostatic forces. They become "frozen" in the steam flow, and, when falling into the volume of saturated and supersaturated steam, intensify the condensation process, thereby reducing the supercooling process level.

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

To practically implement this approach, it is very important to determine the thermo-gas dynamic steam parameters at which the hydrated ions are stable (tenacious) and are not destroyed both in the zone of slight overheating temperatures (the zone before the phase transition) and in the low pressure zone, i.e. it is necessary to determine the limits of the thermo-dynamic parameters of steam expansion, with the limits ensuring the effectiveness of the ionization process.

It is especially important to know the maximum steam pressure and temperature values at which the ionizer action initiates and intensifies the beginning of the steam condensation process.

These values can be established by means of numerous experiments on the test bench, which allows determining the efficiency of the steam expansion process with and without ionization. However, in addition to the complexity of this approach, there should be mentioned the difficulties involved in determining the steam parameters corresponding to the onset of condensation. In this case, the changes in pressure and temperature in the nozzle, with their values recorded in the experiment, determine the condensation onset point ambiguously, since the process is influenced by such factors as the losses occurring in the nozzle and at its exit, which are difficult to take into account when conducting experiments, and the result is affected by the accuracy of measurements.

Therefore, we proposed another, rather simple and original approach to solving this problem, with both a barrier ionizer (BI) and corona discharge (CD) used.

For these purposes, we used optical probes that perceive, in the visible part of the light spectrum, changes in the optical density of the steam flow as a function of wetness according to the probe output current values. In these experiments, the magnitude of the difference in the optical probe current values both in the neutral and charged flux was used to estimate the ionization efficiency. The greater the difference in the values of these currents (the greater the density of the fog), the higher the ionization efficiency.

For these studies, the thermodynamic steam test bench was upgraded (Fig. 1). The diagram of the upgraded section with the BI and optical probe is shown in Fig. 5.

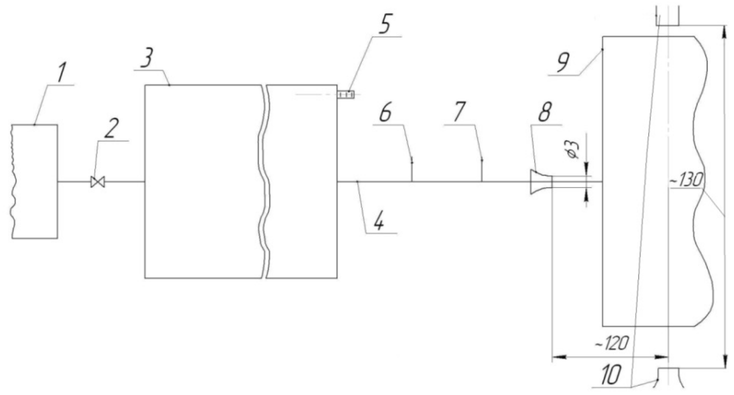


Fig. 5. Diagram of the working section of the steam test bench with the BI and optical probe:
1 – steam inlet chamber; 2 – valve dy6; 3 – BI; 4 – steam line dy6; 5 – BI heater winding terminals; 6 – pressure gauge; 7 – thermocouple; 8 – nozzle; 9 – discharge pipe; 10 – optical probe

During the experiments in all the operating modes of the test bench, the values of the optical probe current of neutral and charged steam flows were recorded at different values of the initial temperature at the nozzle entry.

To perform the mode tests, we adopted a series of pressure values, which are characteristic of a number of the wet-steam stages of turbine low-pressure cylinders, p_0: 112.8; 127.5; 142.2; 156.9; 176.5 kPa. At the highest value of p_0, both a near-critical pressure drop in the subsonic nozzle and reliable operation of the test bench elements were provided. The values of the initial temperatures and ranges of their changes were determined during the experiments.

Figs. 6–8 show the study results obtained in some of test bench operating modes.

As can be seen from Figs. 6–8, at each value of the initial pressure p_0, there is an initial temperature range in which one can observe the effect of ionization on the state of the steam flow at the nozzle exit. This is evidenced by the change in the probe current in the visible part of the light spectrum both in the non-ionized (neutral) and ionized (charged) steam flow at the same initial temperature values. With an increase in the initial temperature, the ionization efficiency decreases. This can be explained as follows.

In the charged steam flow, as mentioned above, hydrated ions appear. As the steam expands and its temperature drops to or close to the saturation temperature, these irons are additional condensation centers. The greater the concentration of such ions, the greater is the steam condensation, and the greater is the fog density due to the greater amount of wetness in the flow. Therefore, its transparency decreases and the probe current decreases. With an increase in the initial steam temperature t_0, i.e. with an increase in steam overheating, the kinetic energy of water steam molecules increases, the number of the steam molecules accumulated in the charged particles decreases, the mass of hydrated ions and their number also decrease. At the same time, the amount of the condensing steam decreases, and the flow transparency increases. Consequently, the difference in current optical probe values in the neutral and charged flow decreases. With a further increase in the initial steam temperature, the kinetic energy of water steam molecules becomes so high that they cannot hold on the charged particles in the zone of the ionizer barrier or corona discharge. In this case, hydrated ions simply do not form, and condensation nuclei are absent. Therefore, to talk about the "survivability" of hydrated ions in this case is inappropriate. In this case, steam does not condense. The flux transparency does not change, so the neutral steam probe current, which has the highest value, is equal to the charged steam probe current. The higher the initial pressures, the higher the initial temperature t_0, with which the probe current of the neutral steam and that of the charged one become equal, i.e. $I_{op}^{n}=I_{op}^{chg}$. So, for example, in the mode with p_0=112.8 kPa, the neutral steam probe current and charged steam probe current become equal at t_0≈145 °C, and in the mode with p_0=176.5 kPa, at t_0≈160 °C (see Figs. 6 and 8). Thus, at the nozzle entry, in the investigated range of initial pressures p_0 112.8÷176.9 kPa, the maximum values of the initial temperatures t_{0max} at which the influence of steam ionization by the barrier ionizer is no longer observed, are in the range ≈150÷160 °C.

The results of the study of the influence of steam ionization by the BI on the steam flow parameters made it possible to determine the maximum values of the initial temperatures t_{0max} in all the studied modes at which the influence of ionization is no longer observed, and the neutral steam optical probe current is equal to the current of the charged steam (Fig. 6–8). Naturally, the use of steam ionization at temperatures equal to or greater than t_{0max} does not make sense.

At the same time, with increasing pressure p_0 at the nozzle entry, t_{0max} increases, and the ionization efficiency decreases. The same will be observed when the temperature of the expanding steam in the flow path of wet-steam turbine stages decreases.

The studies resulted in obtaining equal level lines (Fig. 9), which reflect the degree of steam ionization efficiency with changes in pressure and temperature, and determining their boundary values.

It follows from the above that in the investigated range of initial pressures, the influence of steam ionization is most effective at a temperature close to the saturation temperature and its effect is almost absent when t_0 increases up to t_{0max}.

Similar studies, with the same steam operating conditions as for the experiments with the BI, were conducted with the corona ionizer (CI). According to the test results for all the modes, there were obtained optical probe current dependencies, in the visible part of the light spectrum in the neutral and CI-charged steam flow, on its initial temperature at a selected pressure.

The upper limits of the maximum temperature and steam pressure for experiments with the CI were at the same stream parameters at the nozzle entry as in the experiments with the BI.

To determine the lower limit of the steam ionization effect on the flow parameters in the nozzle flow path, it was sufficient to use the results obtained earlier from the studies carried out on the above test bench [3], with the studies performed at various minimum possible values of the initial pressure at the

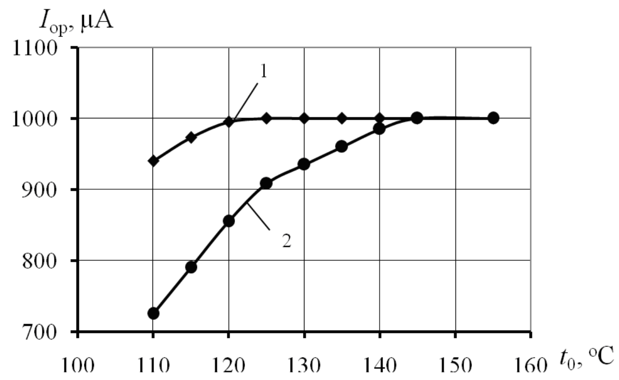


Fig. 6. Dependencies of the optical probe current, in the visible part of the light spectrum in the neutral and BI-charged steam flow, from its initial temperature at an initial pressure of 112.8 kPa:
1 – neutral steam; 2 – charged steam

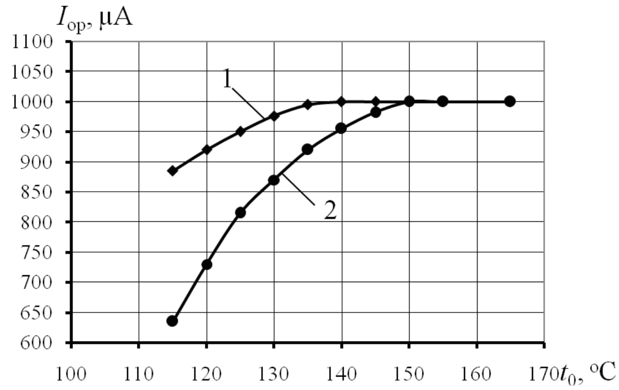


Fig. 7. Dependencies of the optical probe current, in the visible part of the light spectrum in the neutral and BI-charged steam flow, from its initial temperature at an initial pressure of 142.2 kPa:
1 – neutral steam; 2 – charged steam

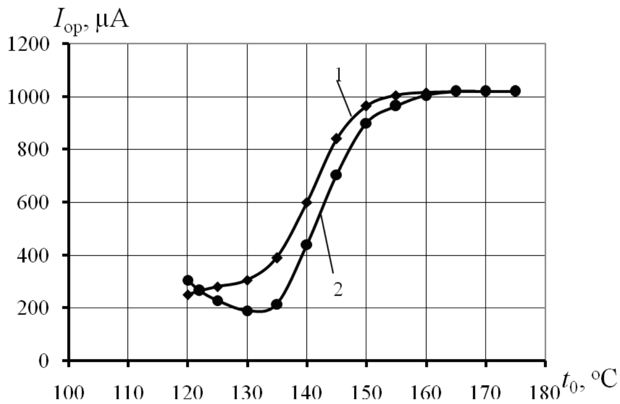


Fig. 8. Dependencies of the optical probe current, in the visible part of the light spectrum in the neutral and BI-charged steam flow, from its initial temperature at an initial pressure of 176.5 kPa:
1 – neutral steam; 2 – charged steam

nozzle entry. In those experiments, the ionization efficiency was determined by the magnitude of the relative pressure decrease in the nozzle exit section. In this case, the steam initial temperature was chosen so that the steam superheating was maintained for all the accepted values of pressure at the nozzle entry in the range of 30–72 kPa. The results of the study are presented in Fig. 10 in the form of the relative pressure change dependence on the steam pressure at the nozzle entry during ionization. At a maximum pressure of p_0=72 kPa, the change in Δp is 8–8.2%, and at the pressure p_0=30 kPa, the effect of ionization is practically absent.

The result of the experiment previously presented with p_0=59 kPa (Fig. 3) is also plotted in Fig. 10, and is located in the zone of effective steam ionization (point A).

Thus, when turbine stages operate in wet steam, where the steam density is low (pressure $p_0 \leq 30$ kPa), the use of an ionizer to reduce losses from steam supercooling may be ineffective.

The studies performed allowed us to determine the region of the most effective steam ionization in the *h,S*-diagram (Fig. 11), which is especially important for the practical implementation of this method.

As a result of the research conducted, it was shown that the BI- and CI- based steam ionization is effective in the zone of rational flow parameters found.

It was found that if ionization occurs in the field of the barrier discharge, then a quasi-neutral wet steam is formed. This gives reason to believe that such a discharge will not have a significant effect on the electro-corrosive processes in the flow path. At the same time, the efficiency of influence on the wet steam flow parameters often exceeds the values obtained during a corona discharge.

As regards the corona ionizer, then, as shown by the special studies conducted at IPMash of the NAS of Ukraine, with a negative polarity of the flow, ionization also does not have a significant effect on the deterioration of the metal surface strength.

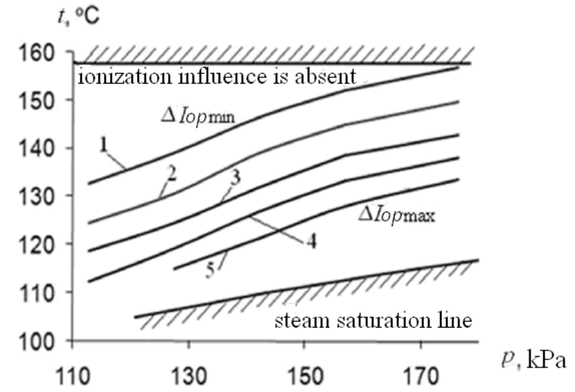


Fig. 9. Steam ionization efficiency depending on changes in pressure and temperature:
1 – ΔI_{op} = 50 µA; 2 – ΔI_{op} = 100 µA; 3 – ΔI_{op} = 150 µA; 4 – ΔI_{op} = 200 µA; 5 – ΔI_{op} = 250 Ma

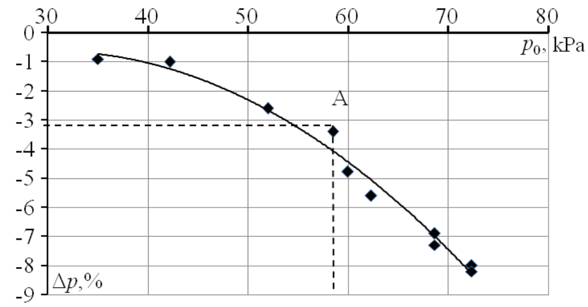


Fig. 10. Relative pressure change at the nozzle exit against the initial pressure

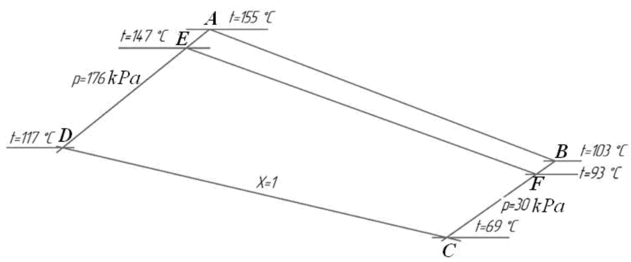


Fig. 11. Area in the water steam h,S-diagram, including the parameters at which steam ionization is most effective:
ABCD – with ionization by BI;
EFCD – with ionization by CI

Determination of Flow Dispersion

To practically implement the approach considered, it is equally important to have information on the flow dispersion arising as a result of steam ionization, since it is known that the presence of large-sized droplets in the flow leads to a decrease in profitability and reliability.

Let us elaborate on the definition of flow dispersion.

It is known that the sizes of the droplets formed in the process of condensation depend on the concentration of nuclei and the wetness diagram at the end of the expansion process

$$r_{dr} = \sqrt[3]{\frac{3G \cdot Y}{4\pi \cdot n \cdot \rho}},$$

where r_{dr} is the radius of the droplets, m; G – is the steam rate through the channel, kg/s; Y is the steam pressure diagram ; n is the number of the droplets formed in the steam flow per second, 1/s; ρ is the steam density, kg/m^3.

Since each nucleus can contain no more than one elementary charge [2], the number of droplets at the end of the expansion process is equal to the number of condensation nuclei, and can be determined by the magnitude of the electric current transferred by the steam flow,

$$n_e = \frac{I}{e},$$

where n_e is the number of the condensation nuclei transferred by the steam flow, c^{-1}; I is the current transferred by the steam flow, A; e is the elementary electric charge ($1.6 \cdot 10^{-19}$ C).

By varying the concentration of the condensation nuclei before the phase transition zone through a change in the magnitude of the current, it is possible to change the size of the droplets at the end of the expansion process. Fig. 12 shows the dependence of the droplet diameter at the end of the expansion process on the concentration of nuclei condensation and the degree of steam wetness.

As applied to the conditions of our experiment (Fig. 4), for example, when the corona discharge was used to create condensation nuclei in a steam flow, at a wetness of 3.5% and the concentration of the nuclei (charges) of condensation 10^{14}–10^{15} kg^{-1} required for equilibrium expansion [1], the droplet size was ~0.4–0.8 µm (Fig. 12). The value of the corona discharge (CD) current I_{CD} to provide the necessary concentration of condensation nuclei depends on the flow rate of the steam flowing through the field of the corona discharge G and the specific current of the corona discharge J.

$$I_{CD} = J \cdot G,$$

where $J = \frac{(n_e \cdot e)}{G}$.

Since part of the charged particles arising in the zone of the corona discharge accumulates on grounded surfaces, when determining the required value of the corona discharge current, the utilization factor of the corona discharge η_{CD} should be taken into account

$$I_0 = \frac{(J \cdot G)}{\eta_{CD}}, \quad \eta_{CD} = \frac{I_f}{I_{CD}},$$

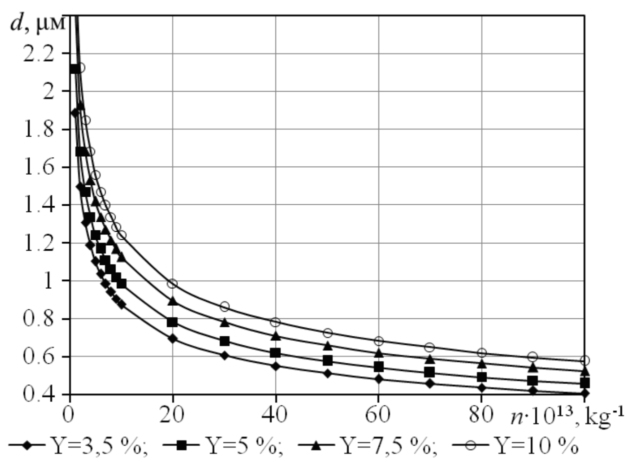


Fig. 12. Droplet diameter change in a wet stream flow

where I_f is the value of the current transferred by the steam flow.

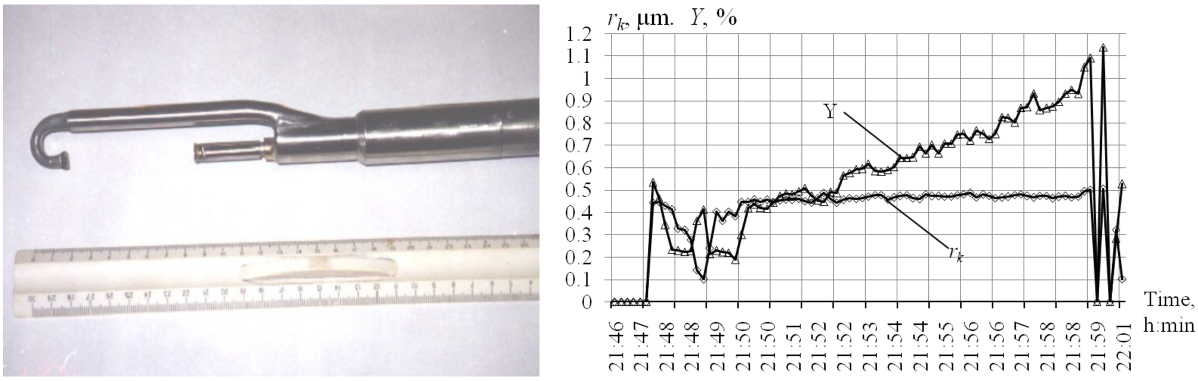
The results of our laboratory studies show that the efficiency of using the corona discharge current can be $\eta_{CD} \geq 0.01$. With this value of η_{CD}, the specific corona discharge current should be ~$3.2 \cdot 10^{-3}$ A/(kg/s), which coincides with the value of the specific current that was used in our experiment (Fig. 4).

Thus, in the case of the ionization of steam with a specific current providing a charge concentration of 10^{14}–10^{15} kg^{-1} for the conditions close to the equilibrium state, the size of the droplets should not exceed 1 µm.

Numerous experiments show that the energy consumption for steam ionization is 0.03–0.15% of the energy released during the condensation on ions.

The obtained theoretical results of the formation of fine-dispersed wetness, when the flow was exposed to a corona discharge, were confirmed in the process of specially conducted full-scale tests (Fig. 13).

Fig. 13, b shows that artificial ionization initially leads to an increase in wetness and droplet size (up to a certain limit d=0.8 µm), with subsequent dispersion stabilization. A further increase in wetness occurs due to an increase in the number of condensation centers with a fixed droplet size.



a b

Fig. 13. Flow traversing after the last stage with an optical probe:
a – optical probe for measuring wetness and droplet sizes "MEI-CKTI";
b – time-dependent change in dispersion and wetness with the change of flow charge state

The above studies show that artificial ionization of steam leads to an increase in wetness and a decrease in the level of supercooling, and the mainly fine wetness formed in this process cannot significantly affect the erosion of rotor blades and the efficiency of the flow.

Let us proceed to the assessment of effectiveness and possible ways to practically implement the approach propose.

To begin with, consider the known method of octadecylamine (ODA) addition to the feed water, which makes it possible to intensify the fragmentation of droplets by reducing the surface tension of the liquid phase. At the same time, initially, on the ODA molecules, heterogeneous condensation develops, and then there occurs the effect of active fragmentation of droplets into additional centers, which, integrally, through the intensification of condensation, gives the effect of reducing the degree of supercooling. Full-scale tests with the use of ODA were carried with 12 MW turbines, at G. Dimitrov TPP and KA-70-30 NPP in Reinsberg. A short-term increase in efficiency of more than 2% was registered [4]. The effect was achieved by reducing the degree of supercooling and increasing the specific volume of steam; reducing film condensation and coarse particle wetness concentration; reducing losses from condensation non-stationarity; reducing profile losses and the losses for accelerating coarse droplets, etc. However, this technology is not widespread now, as it turned out to be expensive because of the need to continuously use reagents. In addition, with the long-term use of ODA, the products of reagents have a negative effect on the reliability and economy of the turbine: there occurs the hydrophobization of the heat exchange surfaces of the whole boiler-turbine tract, with the hydrophobization reducing the intensity of heat exchange; pulse tubes of monitoring and protection devices get clogged; during the final treatment of surfaces, hidden holes appear, etc.

We propose, in essence, an equivalent approach using ionized steam, and not chemical additions, to intensify the condensation process. At the same time, unlike the process with ODA, the activation of the process of heterogeneous condensation occurs on the ions, and the fragmentation of large droplets in the stream into small ones, under the action of an electric field. Taking into account that positive effects, such as reducing losses from supercooling, droplet size, etc., are comparable with those of ODA, and in some cases exceed these parameters, it can be expected that with steam ionization, the efficiency of turbine stages working in a two-phase area will be the same.

The greatest effect with the use of barrier or corona discharge ionizers can be achieved if, at the stage of turbine creation or modernization, the location of the ionizing device is taken into account, with the location depending on the process thermo-gas dynamic parameters that determine the initial zone of the phase transition in the flow path.

This problem is more difficult to solve for the existing turbines.

Currently, this approach can be used for the existing turbines of geothermal installations with steam inlet temperatures of 80–150 ° C and pressure of 180–200 kPa.

Possible uses of ionizers are shown in Fig. 14.

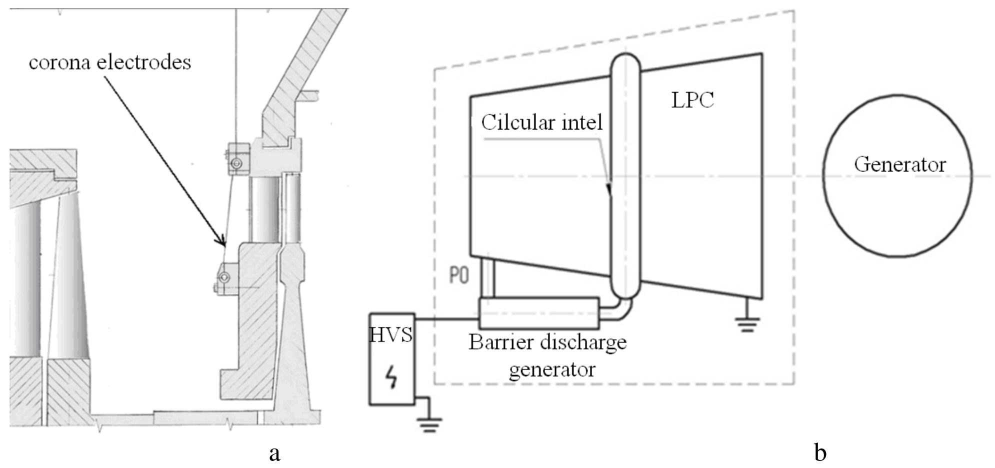


Рис. 14. Layout of steam flow ionizers in the turbine flow path :
a – before the first stage of the low-pressure cylinder;
b – scheme of the external supply of ionized steam to the flow path

Conclusions

The developed approach allows us to intensify the process condensation of steam in the form of fine wetness (droplet size does not exceed 0.4–1 μm), reduce film condensation and coarse particle wetness concentration, reduce the level of supercooling and condensation non-stationarity in the flow path.

The concentration of nuclei condensation at which the steam expansion process tends to equilibrium, is 10^{14}–10^{15} kg^{-1}.

Upon the ionization of steam by the BI, quasi-neutral wet steam is formed. This steam does not cause electrocorrosion in the turbine flow path and does not adversely affect the surface strength of the blades. The BI is more effective in creating condensation nuclei, and the "survivalability" of condensation nuclei, when it is used, is higher than with the use of the CI.

Because of the lower concentration of charges during the ionization by the CI, its effect on the steam flow state ceases somewhat earlier, i.e. at lower values of the maximum steam temperature at the nozzle entry t_{0max}. However, the use of the CI requires less material costs and is simpler in technical and technological support, which must be taken into account when preparing the steam ionization system in the turbine flow paths.

The numerical studies performed showed that steam ionization allows increasing the efficiency of turbine units by 1–1.5%, for example, the power of the K-300-23.5 turbine can be increased by ~3–4 MW with an ionization cost of ~8 kW.

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Іонізація вологопарового потоку та перспективи практичного застосування електророзрядних пристроїв в турбоустановках

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Розглядаються експериментальні дослідження з іонізації парового потоку в надзвуковому соплі і можливості впливу штучної іонізації потоку на нерівноважні процеси в в циліндрах низького тиску (ЦНТ) і підвищення коефіцієнта корисної дії (ККД) турбіни. Наведено результати досліджень з оцінки впливу бар'єрного та коронного іонізаторів на процес інтенсифікації дрібнодисперсної вологи в надзвуковому соплі. Показано, що іонізація дозволяє інтенсифікувати процесну конденсацію пари у вигляді дрібнодисперсної вологи, зменшити плівкову конденсацію і концентрацію великодисперсної вологи, знизити рівень переохолодження та конденсаційної нестаціонарності. Визначено область параметрів, за яких іонізація пари найбільш ефективна. Розглянуто переваги та недоліки використання бар'єрного та коронного іонізаторів. Наведено залежності та визначено дисперсність потоку і концентрацію зародків конденсації, за яких процес розширення пари наближається до рівноважного. Показано, що під час іонізації пари виникають позитивні ефекти, які можна порівняти із застосуванням в турбінах дозованих хімічних добавок. Водночас іонізація пари має ряд істотних переваг. Розглянуто можливі варіанти реалізації використання іонізаторів в ЦНТ вологопарових турбін як на стадії створення або модернізації турбін, так і для діючих турбоустановок. Показано, що в перспективі застосування іонізаторів дозволить підвищити ефективність і економічність турбінних ступенів, які працюють в двофазній області, і збільшити ККД турбоагрегатів на 1–1,5 %.

Ключові слова: *паровий потік, надзвукове сопло, іонізація, нерівноважні процеси, вологопарова турбіна, ефективність, ККД.*

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