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ANALYSIS OF THE INFLUENCE OF STEAM ELECTRIFICATION ON THE WORKING PROCESSES OF A WET STEAM TURBINE

Andrii V. Nechaiev
nechaev@ipmach.kharkov.ua
ORCID: 0000-0001-6586-4713

Anatolii O. Tarelin
tarelin@ipmach.kharkov.ua
ORCID: 0000-0001-7160-5726

Iryna Ye. Annopolska
anna@ipmach.kharkov.ua
ORCID: 0000-0002-3755-5873

A. Pidhornyi Institute of Mechanical Engineering Problems of NASU,
2/10, Pozharskyi str., Kharkiv, 61046, Ukraine

The effect of steam electrification on the operation of a wet steam turbine, as well as the main processes sensitive to the electrification of the working fluid are considered in the paper. The types of additional losses caused by electrification are indicated. It is noted that these losses are not counted in the currently existing physical and mathematical models, since data on electrification are not taken into account and there is no possibility to make a clear theoretical description of the electrophysical model of a neutral steam even. In this regard, a simplified qualitative physical model of the electrophysical processes that occur during the electrification of the steam flow in the turbine was studied. Based on this, an assumption regarding the properties of the space charge in the steam flow, which is the source of the electric field and determines its intensity and spatial distribution in the flow part, is made. A qualitative analysis of the effect of the space charge field on the physical and thermodynamic properties of the steam flow was carried out with the set assumptions. It is proposed to perceive the process of steam polarization in the space charge field as the main result of its influence, and the dielectric constant of the steam – as the most representative parameter characterizing the thermodynamic state, including with the field influence. The thermodynamic relations of the operation of the dielectric in an electric field are given. The relation between the dielectric constant of steam and the change in the internal energy of the working fluid, its entropy and free energy is shown. It is theoretically substantiated that the influence of the electric field also leads to a change in the isobaric heat capacity and enthalpy. It is concluded that the process of expansion of the wet steam flow of charged steam in the turbine unit can be accompanied by a change in the main thermodynamic parameters of the working fluid, and therefore, its design characteristics can change, including the losses that occur in the process of expansion. On the basis of previously obtained experimental data on real turbines, a numerical assessment of the change in the thermodynamic parameters of the working fluid under the influence of an electric field is carried out. The performed numerical studies unequivocally indicate the need to take into account the phenomena caused by the electrification of the wet steam flow in the low-pressure cylinder in the existing physical and mathematical thermodynamic models of the wet steam expansion process, as well as to clarify the main thermodynamic parameters and calculated characteristics of the flow of electrified wet steam depending on the change in its dielectric constant.

Keywords*: wet steam turbines, steam electrification, dielectric constant, thermodynamic parameters.*

Introduction

As it is known, the working fluid can be electrified during the operation of wet steam turbines, while charged drops that form an electric space charge appear in the flow of electrically neutral water steam. Their presence significantly affects the working processes of the turbine unit [1]. The most sensitive to this are: condensation process, nature of the steam flow, and erosion-corrosion processes. In addition, it should be noted that the expansion process of the condensing steam in the electric field of the space charge belongs to the non-equilibrium type of thermodynamic processes with additional energy losses due to the flow of electrophysical processes and changes in the internal energy of the steam. Fig. 1 shows a diagram of losses caused by the steam flow electrification.

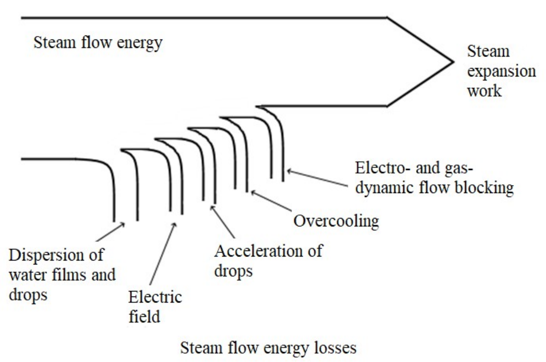

Fig. 1. Energy losses affected by steam flow electrification

Physical model of electrophysical action on steam

Currently, the influence of electrification is not taken into account in the existing physical and mathematical models of thermodynamic and gas-dynamic processes used in the design of wet steam turbine units. This is primarily because electrification data are not taken into account, and also because it is currently impossible to carry out a rigorous theoretical description of the electrophysical model of wet neutral steam even [2].

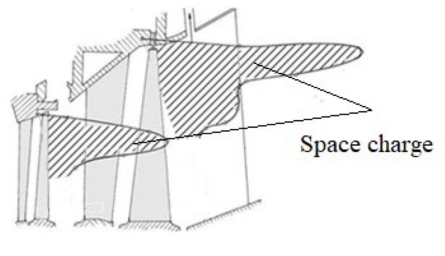

Fig. 2. Fragments of the cross section of the space charge core in LPC

Electrification of wet steam complicates the modeling task even more, so at this stage it is possible to try to build only an approximate qualitative model of the complex thermodynamic process in the turbine, based on the most general physical processes occurring during steam electrification. They are considered further in more detail.

The main electrical factor that affects the thermodynamic process of wet steam expansion during its spontaneous electrification is currently considered to be the electric field of the space charge that arises in the steam volume [1] due to the presence of charged drops in the steam flow. This field is considered as an external electric field acting on a dielectric – water steam, which performs expansion work. At the same time, the array of charged drops exerts an electro- and gas-dynamic influence on the working fluid flow, increasing the losses due to the acceleration of droplet moisture [1].

The characteristics of the field source given in the literature [1] show that its core is actually an annular area in the peripheral zone of the low-pressure cylinder (LPC) flow part space, in which most of the coarse moisture is concentrated. Depending on the water-chemical regime, the space charge core may somewhat change its shape, but it generally retains its view. Fragments of two cross sections of the space charge core in the LPC space [1] are shown in Fig. 2.

In general, the charged area of the working fluid in the LPC is shown in a simplified form as a fragment of the flow part, in which the space charge gradually increases. This is shown in Fig. 3.

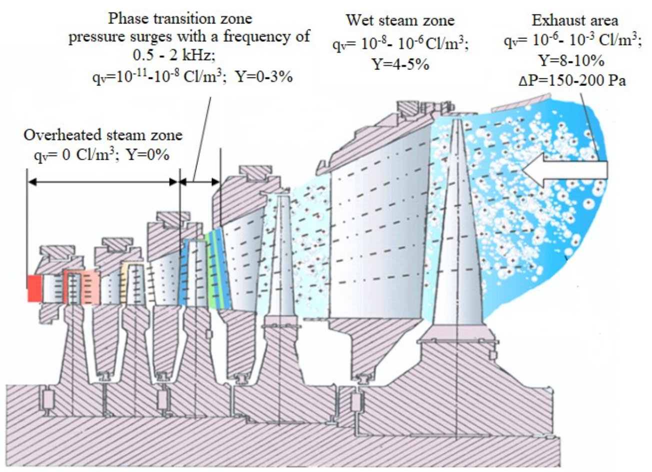

Fig. 3. LPC area containing space charge

However, the diagrams and figures showing the kinetics of the electrification process do not reflect the nature of the electric field effect on the physical and thermodynamic properties of water steam. In view of this, they should be supplemented with appropriate diagrams of electrophysical processes.

From this point of view, the working fluid in the final stages of the turbine can be considered as a two-component medium – the steam phase, which performs useful work, and the droplet phase, dispersed in the steam volume and which is the source of the electric field distributed in the volume, and also exerts an electro- and gas-dynamic downstream effect. As shown by the studies carried out on real turbines, the droplet phase is charged heterogeneously: large drops are mostly positively charged, and small drops are negatively charged. In general, the steam flow in the turbine usually has a positive charge, which masks the negative charge, which is significantly smaller in magnitude. To simplify the physical model of thermo- and electrophysical processes in the turbine, only the positive charge of the flow will be considered in this paper. In addition, the spatial heterogeneity of the distribution of the liquid phase along the height of the blades, in the edge wake, etc. won't be taken into account.

For a correct assessment of the electric field influence on the physical properties of the steam, it is necessary to use the corresponding electrophysical model of wet steam with an electric field source. In this case, given that from a physical point of view water steam is a dielectric medium, there are several possible approaches to the construction of a simplified physical model of such a medium with a field source.

Static options, under which the following is considered:

– a fixed volume of steam is considered as a homogeneous dielectric, limited by a channel of variable profile with grounded conductive walls, and the source of the electric field is the space charge - a local charged area inside the dielectric volume;

– the volume of wet steam is considered as a two-phase medium - a dielectric, which is a mechanical mixture of gas and charged droplet phases with uniform filling of the space inside the grounded conductive channel.

Kinetic option:

– steam is a two-phase flow inside a conductive grounded channel, consisting of a gaseous dielectric that performs the expansion work and a dispersed phase in the form of charged particles, which can be given either as conducting spheres of small radius or as drops of polarized water in a liquid state with a point charge inside the drop.

Taking into account the difference in the speeds of the liquid and steam phases, a more appropriate model of the medium with a field source will be the kinetic option.

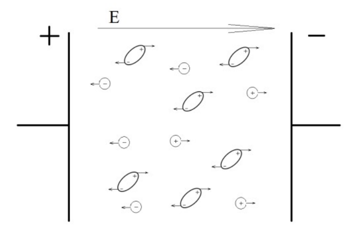

Fig. 4. The volume of a dielectric with dipoles and free charges in a stationary field

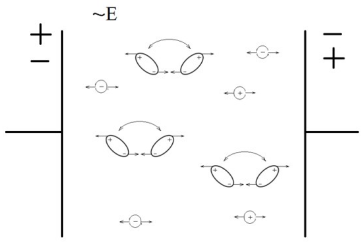

Fig. 5. The volume of the dielectric in the alternating field

As it is known [3], the main processes that occur in a dielectric under the action of an external electric field are electrical resistance, polarization, and energy dissipation. In electrical engineering, the processes of electrical resistance and polarization in a constant electric field are schematically shown in the form of a dielectric volume with a conventional image of free and bound charges, to which the field of external electrodes is added (Fig. 4).

In an alternating electric field, charged particles and dipoles perform oscillating motion (Fig. 5).

It should be noted that the nature of the action of an external electric field on a specific dielectric depends on its molecular properties. Thus, water and, accordingly, water steam is a polar dielectric, which does not conduct electricity in the absence of free electrically charged particles in it, but in the presence of charged particles in the steam volume, a conduction current will arise in the electric field. In addition, the action of the electric field causes the substance polarization. As it is known, the ability of the substance to polarize is quantitatively estimated by its relative dielectric constant ε, which is a dimensionless quantity [3]. Energy dissipation can occur when an alternating electric field acts on the dielectric.

The factors of the electric field acting on the steam flow with the set assumptions are considered.

Since in this case we take into account only positively charged large drops as a source of an electric field external to the steam flow, the electrical resistance of the steam due to positively charged particles is not taken into account. The effect on the thermophysical properties of the steam of small negatively charged droplets in its volume in an electric field, which can provide some conduction current, is not taken into account as well, especially since the number of negative droplets is significantly smaller than of positive ones.

The dielectric will be polarized in an electric field. Water steam, on one hand, consists of polar molecules, so its polarization has two components: orientational and electronic. On the other hand, the electric field acting on the steam can be considered as variable in time, since the steam speed exceeds the speed of the droplet phase, and taking into account point sources, it can be cinsidered significantly heterogeneous in structure. Fig. 6 schematically shows the distribution of the electric field strength along the LPC flow part.

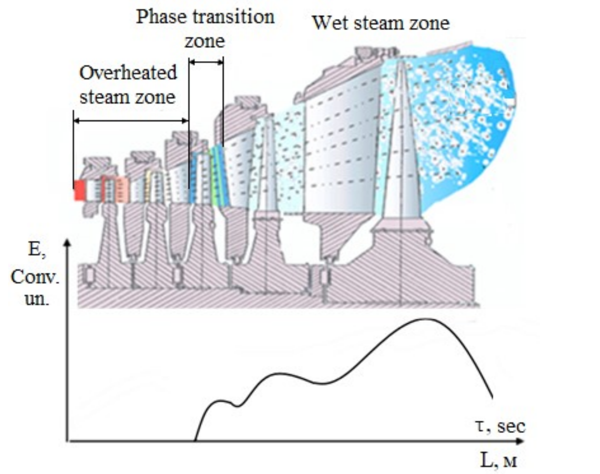

Fig. 6. Qualitative image of the change in the electric field strength of the space charge E along the length of the wet steam part of the LPC L(m) and over time τ(s)

In this case, to simplify the physical model under consideration, it makes sense to consider only the polarization of the steam phase, because the droplet phase is not in the external electric field (the droplet phase itself is the source of the field), in connection with which there is some uncertainty in the evaluation possibility of the influence nature of its own space charge on the droplets polarization. However, based on the fact that the polarization of the droplet phase does not perform the work of expansion, it can be ignored in this case. The spatial distribution of the electric field strength *E* around the core of the space charge *Q* is shown in Figs. 7, 8.

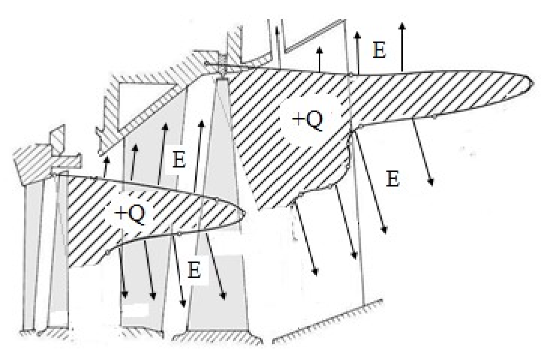

Fig. 7. Field strength E with respect to the core of the volume charge Q

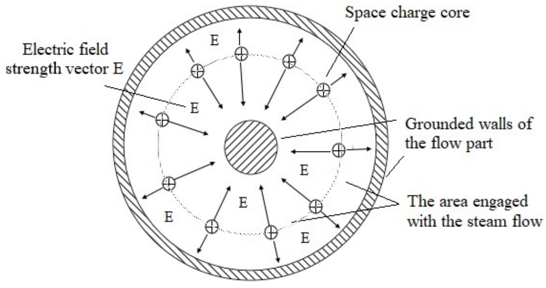

Fig. 8 Cross section of the flow part with the space charge core

The process of the steam polarization will be complex in space and time, and the dielectric constant, which is the main characteristic of the dielectric polarization, is considered as a complex quantity in electrical engineering in such case. Accordingly, under the action of an alternating electric field, in addition to polarization, the absorption of field energy to heat the dielectric occurs. However, in this case, bearing in mind the accepted simplifications, the dielectric constant is set as a real value without an imaginary part, neglecting heating losses due to their insignificance. Thus, in the physical model, energy losses due to heating, as well as conductivity, are not taken into account. In general, the set assumptions and simplifications make it possible to qualitatively consider the most important physical processes in the steam flow in the turbine during its electrification and to single out the dielectric constant as the most representative parameter characterizing these processes.

Mathematical model of thermo- and electrophysical processes

The mathematical apparatus used to describe a complex thermodynamic system in which the work of the dielectric occurs under the action of an electric field is considered further. For simplicity, the electrostatic field option is chosen.

As is known from the theoretical foundations of thermodynamics [4, 5], a thermodynamic system in which, in addition to the expansion work, other types of work are performed, is a complex thermodynamic system. In particular, under the influence of external fields of different physical nature, water and water steam can change their thermophysical and physical properties. This effect can be considered a factor of additional work that is performed on the thermodynamic system.

In this case, the general equation of the 1st and 2nd laws of thermodynamics has the form (in the case of equilibrium)

$$TdS = dU + pdV - \sum \varsigma dx \,, \tag{1}$$

where ς is a generalized force; x is a generalized coordinate; ςdx is a work carried out on the system.

If only the work of expansion is considered, then equation (1) is simplified and takes the form

$$TdS = dU + pdV \,. \tag{2}$$

Work of dielectric in an electrostatic field

For dielectric, taking into account only the polarization from the applied external stationary electric field, equation (1) will take the form

$$TdS = dU + pdV - PdE \,, \tag{3}$$

where E is a field strength; P is a dielectric polarization.

Given that the substance polarization is estimated through relative dielectric constant and electric field strength:

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

where $\varepsilon = f(T)$ is a dielectric constant of the medium; $\varepsilon_0 \approx 8{,}854 \cdot 10^{-12}$ F/m is a electrical constant, we will get that in the case of an electric field, the equation of state of the working fluid will be determined not by two independent variables $p=f(T, V)$, but by three $p=f(T, V, E)$.

Therefore, the introduction of additional work (electric field) leads to an increase in the number of variables in the equations of the working fluid state, and the function of the substance state will be described by three variables. In this case, it becomes incorrect to directly use a table or a diagram of the thermodynamic properties of water and water steam to determine the extensive quantities S, i, U. Therefore, there is a need to find analytical relations that allow to perform a quantitative assessment of the change in these values under the action of an electric field (EF).

The main thermodynamic functions describing the state of the working fluid are free energy $A=U-TS$, internal energy U and entropy S.

Considering the effect of EF as parameters of independent variables, as a rule, the temperature T and the electric field strength E are chosen, assuming that the volume of the dielectric is kept constant.

Then the 1st law of thermodynamics (3) can be expressed as follows:

$$dU = TdS + EdD,$$

where $D=\varepsilon_0\varepsilon E$ and EdD are electrical induction and work performed by EF in the process of polarization, respectively.

It follows from the given ratios that the dielectric permittivity of the medium plays a significant role in accounting for the EF action.

The thermodynamic functions of the working fluid under the action of EF are determined for the most general case when $\varepsilon = f(T, E)$.

The change in electric induction D will have the form

$$\varepsilon_0^{-1} dD = \left(\varepsilon + E \frac{\partial \varepsilon}{\partial E} dE \right) + E \frac{\partial \varepsilon}{\partial T} dT ,$$

and the change in internal energy

$$dU = TdS + \frac{1}{2}\varepsilon_0 \varepsilon d(E^2) + \varepsilon_0 E^2 \frac{\partial \varepsilon}{\partial T} dT + \varepsilon_0 E^2 \frac{\partial \varepsilon}{\partial (E^2)} d(E^2) = \frac{\partial U}{\partial T} dT + \frac{\partial U}{\partial (E^2)} dE .$$

After certain transformations, the differential equation for the internal energy has the following form

$$\frac{\partial U}{\partial E^2} = \frac{1}{2}\varepsilon_0 \left[\varepsilon + T \frac{\partial \varepsilon}{\partial T} + 2E^2 \frac{\partial \varepsilon}{\partial E^2} \right].$$

As a result of its integration, we get

$$U - U_0(T) = \frac{1}{2}\varepsilon_0 \int \left(\varepsilon + T \frac{\partial \varepsilon}{\partial T} + 2E^2 \frac{\partial \varepsilon}{\partial (E^2)} \right) d(E^2) .$$

For integration, data on the specific dependence $\varepsilon = f(T, E)$ is required. The constant of integration depends on T because the equation is integrated to partial derivatives.

For entropy and free energy, we get dependencies

$$S = S_0(T) + \frac{1}{2}\varepsilon_0 \int \frac{\partial \varepsilon}{\partial T} d(E^2); \quad A = A_0(T) + \frac{1}{2}\varepsilon_0 \int \left(\varepsilon + 2E^2 \frac{\partial \varepsilon}{\partial (E^2)} \right) d(E^2) .$$

Therefore, if ε=const, the entropy does not change; if $\varepsilon = \varepsilon(T)$, then

$$S = S_0(T) + \frac{1}{2}\varepsilon_0 \frac{\partial \varepsilon}{\partial T} E^2 . \tag{4}$$

The effect of EF also leads to a change in isobaric heat capacity and enthalpy. So, in an isobaric-isothermal process, as follows from [4]

$$C_{p,E}(E, p, T) - C_p(T, p) = T\varepsilon_0 \int_0^E \frac{\partial^2 \varepsilon}{\partial T^2} E dE ; \tag{5}$$

$$i(E,p,T)-i(p,T)=\varepsilon_0\int_0^E\left(T\frac{\partial\varepsilon}{\partial T}-\varepsilon+1\right)EdE\,. \tag{6}$$

Taking into account that ε is a function only of temperature and does not change in an isothermal process, then $\frac{\partial\varepsilon}{\partial T}=\frac{d\varepsilon}{dT}=\text{const}$ and $\frac{d^2\varepsilon}{dT^2}=\text{const}$ respectively, by equations (4–6) and through simple transformations, we finally obtain the relation:

$$\Delta S=S(E,p,T)-S_0(p,T)=\frac{1}{2}\varepsilon_0\frac{d\varepsilon}{dT}E^2\,; \tag{7}$$

$$\Delta C_p=C_p(E,p,T)-C_{P_0}(p,T)=\frac{1}{2}\varepsilon_0 T\frac{d^2\varepsilon}{dT^2}E^2\,; \tag{8}$$

$$\Delta i=i(E,p,T)-i_0(p,T)=\frac{1}{2}\varepsilon_0(T\frac{d\varepsilon}{dT}-\varepsilon+1)E^2\,. \tag{9}$$

Thus, the process of expansion of the wet steam flow of charged steam from the point of view of mathematical modeling can be accompanied by a change in the main thermodynamic parameters of the working fluid, and therefore, its calculated characteristics can change, including the losses that occur in the process of expansion.

An important role in determining the entropy, enthalpy and heat capacity of the working fluid when taking into account the EF influence is played by the dependence of the change in relative permittivity on the EF strength and the steam temperature in the wet steam part of the steam turbine unit. It is known that for most dielectrics, which are a homogeneous medium, the dielectric constant does not depend on the strength of the electric field, decreases with temperature increase, and for water and superheated water steam, it can be found from the data available in the reference literature, for example [6].

In this case, it is assumed that the source of the field is droplet moisture and the field acts only on water steam. In this setting, the task of determining the dielectric constant of the mixture is simplified to the determination of the steam phase. At the same time, the question of the space charge effect on its carrier, moisture drops, remains open-ended.

As a result, there is a need for an experimental study of the change in the relative permittivity of the substance of droplet moisture and wet steam, including for the case when the droplet phase is electrically charged.

Experiments on real turbines previously carried out by IPMach specialists make it possible to conduct a preliminary quantitative assessment of the change in the dielectric constant of the working fluid. Thus, in the course of experiments on the T-37/50-8.9 steam turbine of CHP-2 "Eshar" it was found [1] that the wet steam flow is most strongly electrified in the zone of the last stage of the turbine and the exhaust nozzle, the charge of the wet steam flow behind the last stage is maximum and can reach 10^5–10^6 V/m, and the space charge density of the flow will reach 10^{-3} C/m^3.

The analysis of the changes in the turbine operation mode during the neutralization of the steam space charge showed that the main result of the neutralization was a decrease in flow pulsations and back pressure in the last stage by 100 Pa, as well as a local increase in the steam flow rate.

Using these results and assuming that changes in thermo- and gas-dynamic parameters of the flow are related to its neutralization, it is possible to make an indirect estimate of the relative permittivity of the flow at the last stage of the turbine. Knowing the temperature behind the turbine, the change in pressure and flow speed (12 m/s), it becomes possible to determine the change in enthalpy and entropy in the last stage as a result of the flow neutralization.

In this case, bearing in mind (7),

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

substituting the latter in (9) and solving relative to ε, we have

$$\varepsilon=1+\frac{2(T\Delta S-\Delta i)}{\varepsilon_0 E^2}\,.$$

In our case, this dependence allows to estimate the relative permittivity of the flow for specific parameters of the process and the magnitude of the electric field strength only approximately, because the change in the parameters by degree was certainly influenced by post-factor phenomena associated with the electrification of the flow [7].

As a result of the calculation, the value of ε is equal to ~34. Taking into account that the moisture content behind the last stage in the studied mode does not exceed 6%, using the principle of additivity, it can be assumed that for neutral wet steam, the dielectric constant will not exceed a value close to 4.4, which is significantly less than the obtained value ε.

The conducted numerical studies confirmed the need to take into account the phenomena caused by the electrification of the wet steam flow in the LPC in the existing physical and mathematical thermodynamic models of the process of expansion of wet steam, to specify the main thermodynamic parameters and calculation characteristics of the flow of electrified wet steam, for which it is necessary to have information about the value of its relative permittivity.

It should be added to the above that since the process of steam expansion in most stages of LPC takes place below the saturation line, it is necessary to have information about the real steam density and its humidity, which significantly depends on the additional losses that occur in the steam flow, and the erosion and corrosion processes in the LPC last stages. To be able to control the quality of the turbine operation, to influence its characteristics in order to improve efficiency and reliability, it is necessary to know the final humidity of the flow at the exit from the turbine and the steam density at the entrance to the condenser. At the same time, it should be taken into account that the temperature and pressure, which can be measured during research, clearly determine the density of superheated steam only. In the state of saturation, as well as during the phase transition, the temperature and pressure of the working fluid are interrelated parameters, but do not determine its phase state, enthalpy, and density.

In a number of papers, for example [8], it is proposed to use the electrophysical characteristics of wet steam, in particular, its relative permittivity, to determine the thermodynamic characteristics of the flow. The research carried out by the authors made it possible to propose a simple one-parameter dependence that allows to calculate the density of water and water steam at known values of temperature and relative permittivity at the saturation line. However, even this simplified model does not take into account the natural electrification of the flow.

Conclusions

Based on all of the above and the fact that the humidity and charge of the steam flow are interrelated with its dielectric constant, and currently there are no data in the scientific and technical literature about real humidity and relative permittivity under similar conditions, it can be stated that the study of the interrelations of moisture content and dielectric constant of electrified wet steam in the turbine are of scientific and practical interest. Therefore, a relevant task is to study the relative permittivity of the electrified wet steam flow in order to obtain the dependence of the change in the relative permittivity of the electrified steam on the temperature of the flow and the strength of the electric field. This will allow, when designing the low-potential part of wet steam turbines, to describe the thermo- and gas-dynamic processes taking place in them more realistically, with specified values of enthalpy, entropy, heat capacity of electrified wet steam, and this, in turn, will make it possible to determine energy losses in LPC blade apparatuses more accurately. In addition, the presence of an experimental dependence of the change in the relative permittivity of wet steam in the selected range of changes in temperature and electric field strength will allow to develop a technique for determining the density, heat capacity, and humidity of the flow at the exit of the last stage in a real time scale under different operation modes of steam turbine units.

References

1. Tarelin, A. A. & Sklyarov, V. P. (2012). *Parovyye turbiny: elektrofizicheskiye yavleniya i neravnovesnyye protsessy* [Steam turbines: electrophysical phenomena and non-equilibrium processes]. St. Petersburg: Energotekh, 292 p. (in Russian).
2. Mulev, Yu. V. (1984). *Upravleniye vstroyennymi separatorami pryamotochnykh kotloagregatov SKD na osnove kontrolya vlazhnosti otseparirovannogo para* [Control of built-in separators of once-through boilers SKD based on humidity control of separated steam]: Ph.D. dissertation. Belarusian Polytechnic Institute. Minsk, 212 p. (in Russian).

3. Tareyev, B. M. (1982). *Fizika dielektricheskikh materialov* [Physics of dielectric materials: Proc. allowance for universities.]. Moscow: Energoizdat, 320 p. (in Russian).
4. Sychev, V. V. (2010). *Differentsialnyye uravneniya termodinamiki* [Differential equations of thermodynamics]. Moscow: National Research University "Moscow Power Engineering Institute" Publ., 251 p. (in Russian).
5. Bazarov, I. P. (1991). *Termodinamika* [Thermodynamics]. Moscow: Vysshaya shkola, 376 p. (in Russian).
6. Golubev, B. P., Smirnov, S. N., Lukashov, Yu. M., & Svistunov, Ye. P. (1985). *Elektrofizicheskiye metody issledovaniya svoystv teplonositeley* [Electrophysical methods for studying the properties of heat carriers]. Moscow: Energoatomizdat, 184 p. (in Russian).
7. Tarelin, A. A. (2017). *Postfaktornyye yavleniya elektrizatsii vlazhno-parovogo potoka v turbinakh* [Post-factorial phenomena of electrization of wet-steam flow in turbines]. *Teploenergetika – Thermal Engineering*, no. 11, pp. 32–39 (in Russian).
8. Mulev, Yu. V., Belyayeva, O. V., Mulev, M. Yu., Saplitsa, V. V., & Zayats, T. A. (2011). *Dielektricheskaya pronitsayemost kak odin iz osnovnykh parametrov kontrolya sostoyaniya rabochego tela* [Dielectric constant as one of the main parameters for controlling the state of the working fluid]. *Teploenergetika – Thermal Engineering*, no. 7, pp. 36–40 (in Russian).

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Аналіз впливу електризації пари на робочі процеси вологопарової турбоустановки

А. В. Нечаєв, А. О. Тарелін, І. Є. Аннопольська

Інститут проблем машинобудування ім. А. М. Підгорного НАН України,
61046, Україна, м. Харків, вул. Пожарського, 2/10

У статті розглянуто вплив електризації пари на роботу вологопарової турбоустановки, а також основні процеси, чутливі до електризації робочого тіла, вказані види додаткових втрат, зумовлених електризацією. Зазначено, що в існуючих на даний час фізичних і математичних моделях ці втрати не враховуються, оскільки дані про електризацію не беруться до уваги і немає можливості зробити чіткий теоретичний опис електрофізичної моделі навіть нейтральної пари. У зв'язку з цим вивчено спрощену якісну фізичну модель електрофізичних процесів, що виникають при електризації потоку пари в турбіні. Виходячи з цього, зроблено припущення щодо властивостей об'ємного заряду в потоці пари, що є джерелом електричного поля і визначає його інтенсивність й просторовий розподіл у проточній частині. Проведено якісний аналіз впливу поля об'ємного заряду на фізичні й термодинамічні властивості потоку пари з прийнятими припущеннями. Запропоновано процес поляризації пари в полі об'ємного заряду сприймати як основний результат його впливу, а діелектричну проникність пари – як найбільш представницький параметр, що характеризує термодинамічний стан, у тому числі за наявності впливу поля. Наведено термодинамічні співвідношення роботи діелектрика в електричному полі. Показано зв'язок діелектричної проникності пари зі зміною внутрішньої енергії робочого тіла, його ентропією й вільною енергією. Теоретично обґрунтовано, що вплив електричного поля призводить також до зміни ізобарної теплоємності й ентальпії. Зроблено висновок про те, що процес розширення вологопарового потоку зарядженої пари в турбоустановці може супроводжуватися зміною основних термодинамічних параметрів робочого тіла, а отже, можуть змінитися його розрахункові характеристики, у тому числі й втрати, що виникають у процесі розширення. На основі отриманих раніше експериментальних даних на реальних турбінах проведено чисельну оцінку зміни термодинамічних параметрів робочого тіла при впливі електричного поля. Виконані чисельні дослідження однозначно свідчать про необхідність як врахування в існуючих фізичних і математичних термодинамічних моделях процесу розширення вологої пари явищ, зумовлених електризацією вологопарового потоку в ЦНТ, так і уточнення основних термодинамічних параметрів і розрахункових характеристик потоку електризованої вологої пари залежно від зміни його діелектричної проникності.

***Ключові слова**: вологопарові турбіни електризація пари, діелектрична проникність, термодинамічні параметри.*

Література

1. Тарелин А. А., Скляров В. П. Паровые турбины: электрофизические явления и неравновесные процессы. Санкт-Петербург: Энерготех, 2012. 292 с.
2. Мулев Ю. В. Управление встроенными сепараторами прямоточных котлоагрегатов СКД на основе контроля влажности отсепарированного пара: дис. … канд. техн. наук: 05.14.14 / Белорусский политехнический институт. Минск, 1984. 212 с.

3. Тареев Б. М. Физика диэлектрических материалов: учеб. пособие для вузов. М.: Энергоиздат, 1982. 320 с.
4. Сычев В. В. Дифференциальные уравнения термодинамики. М.: Издательский дом МЭИ, 2010. 251 с.
5. Базаров И. П. Термодинамика. М.: Высшая школа, 1991. 376 с.
6. Голубев Б. П., Смирнов С. Н., Лукашов Ю. М., Свистунов Е. П. Электрофизические методы исследования свойств теплоносителей. М.: Энергоатомиздат, 1985. 184 с.
7. Тарелин А. А. Постфакторные явления электризации влажно-парового потока в турбинах. *Теплоэнергетика*. 2017. № 11. С. 32–39.
8. Мулев Ю. В., Беляева О. В., Мулев М. Ю., Саплица В. В., Заяц Т. А. Диэлектрическая проницаемость как один из основных параметров контроля состояния рабочего тела. *Теплоэнергетика*. 2011. № 7. С. 36–40.