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EXPERIMENTAL EVALUATION OF THE WET STEAM FLOW ELECTRIFICATION EFFECT ON ITS DIELECTRIC PROPERTIES

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It has been established that in order to study thermo- and electrophysical phenomena in wet steam turbines, studies of the wet steam flow volume charge effect on its dielectric and thermophysical properties have recently been carried out at A. Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. According to their results, it was established that the most representative electrophysical parameter, which allows to evaluate changes in the thermophysical properties of steam, which occur under the action of its own volume charge, is its dielectric constant. It is assumed that the value of the dielectric constant of an electrified steam can be significantly different from the value for a neutral steam, and a mathematical assessment of its possible change is made. It has been confirmed that the influence of electrophysical phenomena caused by the wet steam flow electrification is significant, but is not taken into account in the existing physical and mathematical thermodynamic models of the steam expansion process. It is proved that in order to clarify the main thermodynamic parameters and calculated characteristics of the electrified wet steam flow, it is necessary to determine how its dielectric constant changes. On the basis of the analysis, the relevance of experimental determination of the dielectric constant of a wet steam flow with a volume charge in order to obtain the dependence of its change on the temperature and pressure of the flow, as well as the density of the volume charge, is substantiated. To perform the research, a gas dynamic laboratory plant, which allows to obtain a wet steam flow with a volume charge, was used. The internal space of the flow part of a real wet steam turbine has a significant size and allows the formation of a flow with a volume charge of a complex spatial configuration and structure. It is emphasized that in the flow part of the plant of a small volume, in contrast to the turbine flow part, significant technical difficulties arise when organizing the conditions for the occurrence of a wet steam flow with a volume charge. Taking this into account, at the first stage, it was decided to conduct a study of a steam flow with a volume charge flowing into the atmosphere in a laboratory room with a sufficient volume to form its spatial structure. To estimate the value of its dielectric constant, the inductive method (L-method) of determining dielectric properties, in which the substance under study is introduced into the inductive solenoid cell, was chosen. Experiments were conducted and, according to the obtained data, it is possible to make a preliminary assessment of the change in dielectric constant in the presence of a volume electric charge in the steam flow.

Keywords: *wet steam turbines, thermophysical properties of the working fluid, dielectric constant, volume charge of steam flow.*

Introduction

In the previous paper [1], the subject of study was the influence of the volume charge of the wet steam flow on its dielectric and thermophysical properties. Based on the analysis of the results, the relevance of the experimental determination of the dielectric constant of a wet steam flow with a volume charge is substantiated. However, it is worth remembering that the measurement of the dielectric constant (DC) of the flow of a two-phase steam-droplet medium with a volume charge is a non-trivial scientific and technical problem. Until now, the measurement of the dielectric constant of the steam flow was used in thermal power equipment to determine its humidity only under the conditions of the absence of electrification [2]. In addition, the dielectric constant is one of the main parameters for monitoring the working fluid state, which allows to estimate not only its humidity, but also its density and phase state [3]. One of the most common methods of the DC measuring is

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considered to be dielcometric using a capacitor C-cell, the advantage of which is low inertia and comparative ease of use, high reliability of the equipment. However, this parameter is measured, as a rule, only for the case of an electrically neutral dielectric, and the studied substance is a dielectric placed in a measuring capacitor, the capacitance of which depends on the dielectric properties. In addition, the presence of a volume electric charge in the dielectric significantly complicates the processes in the capacitor cell.

In addition to the above, the paper [1] discusses various options for choosing a physical model of the steam flow volume charge structure and its influence on the properties of the wet steam medium as a dielectric (electrical conductivity, polarization, and energy dissipation). According to the results, it is assumed that the water steam is in the electric field, which is created by positively charged droplets distributed in the volume. The conductivity of the medium under the influence of the volume charge field was assumed to be insignificant, the energy dissipation losses under the influence of the variable component of the electric field were assumed insignificant as well. In addition, the presence of small negatively charged droplets was not taken into account. Polarization of water steam as a polar medium was considered the main factor of the field effect on steam. Taking into account these assumptions, a qualitative electrical model of the steam flow with a volume charge internal structure geometry was chosen. However, according to this model, there are significant difficulties in experimental determination of the dielectric polarization in a capacitive C-cell, since an external polarizing voltage must be applied to it. The static option of applying an electric field is unacceptable in this case because it will excite conduction currents and interact with the volume electric charge of the flow. Obviously, in this case, it is necessary to use methods with a variable polarizing field with parameters that provide minimal disturbance to the environment under study.

Theoretical justification of the method

Taking into account the above-mentioned difficulties, the inductive method (L-method) of the Q-meter for determining the dielectric properties of a liquid, given in papers [4, 5], was chosen to assess the dielectric constant of a wet steam flow with a volume charge. According to this method, the studied substance is contained inside an inductor (L-cell) of a sequential oscillating circuit (Fig. 1).

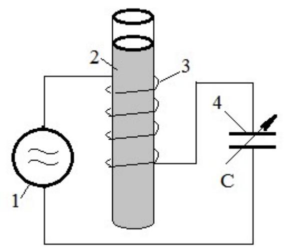

Fig. 1. The inductive method (L-method) of the Q-meter for determining the dielectric properties of a liquid:
1 – generator; 2 – L-cell with a liquid sample; 3 – L-cell inductor; 4 – measuring capacitor

The essence of the method is that the presence of a substance inside the L-cell of an oscillating circuit tuned to resonance with the generator frequency G reduces the quality factor of the circuit Q, causing losses of electromagnetic energy in the circuit, and changes its resonance frequency (correspondingly, the capacitance C value changes for the resonance condition) (Fig. 2).

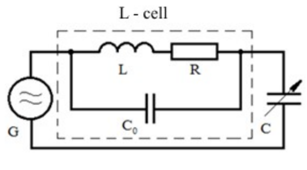

Fig. 2. Electrical diagram of a sequental circuit with an L-cell:
G – alternator; L – inductance; R – active resistance of the inductor; C – measuring capacitor; C_0 – inter-turn capacitance of the inductor 1

The resonance condition of such circuit with quality factor $Q=\omega L/R$ is

$$\omega^2 = \frac{1}{LC} - \frac{R^2}{4L^2} = \frac{1}{LC\left(1+\dfrac{1}{4Q^2}\right)}, \qquad (1)$$

where $\omega=2\pi f$ is the circular frequency of the generator signal; L is the a inductance; R is a active resistance of the inductor; C is the capacitance of the electric capacitor.

When $Q>20$, the contribution from Q can be neglected [4, 5]. Given that the L-cell has its own inter-turn capacitance, the resonance condition can be expressed as

$$\omega^2 = \frac{1}{L(C+C_0)}. \qquad (2)$$

This method makes it possible to determine the value of the tangent of the dielectric loss angle (tg δ) of the liquid and its dielectric constant ε_L (the index "L" indicates the inductive method of measurement) in weak electric fields of the L-cell according to the ratio

$$\operatorname{tg}\delta = \frac{Q_1C_1 - Q_2C_2}{Q_1Q_2(C_1 - C_2)}; \qquad (3)$$

$$\varepsilon_L = \alpha(\Delta C - \Delta C^*), \qquad (4)$$

where Q_1, Q_2, C_1, C_2 are value of the quality factor and measuring capacitance of the oscillating circuit before (index 1) and after (index 2) the introduction of the test substance into the L-cell; $\Delta C=C_1–C_2$ is the change in resonance capacitance when the test substance is introduced into the L-cell in a dielectric vessel, and ΔC^* is the change in capacitance when an empty vessel is introduced; α is the constant of the measuring cell, which is determined by calibration experiments.

Considering the fact that the L-method was used to study the electrophysical properties of water and various liquids contained in a test tube inside the L-cell or flowing through the cell in a dielectric channel, it was necessary to find out the possibility of using the L-cell with steam flow at the first stage of experiments, and then work out the technique of using the L-cell for working with a wet steam flow in a neutral and electrified state.

Experimental part

The work was carried out on a gas dynamic plant [6]. The L-cell was installed on the section of the nozzle, through which a stream of steam passed.

The diagram of the plant is given in Fig. 3, the structural diagram of the dielectrometric system is shown in Fig. 4, and its general view is shown in Fig. 5.

The inductive cell is connected to the output of the TESLA BM560 quality factor meter (Q-meter). The Q-meter operates in the frequency range of 50 kHz–35 MHz. A frequency of 4.8 MHz was chosen for the research taking into account [2, 4, 5].

The design of the L-cell is a two-section inductor wound on a cylindrical fiberglass frame with a diameter of 90 mm, with the number of turns 5 and 10. The quality factor of the system is about 300, which corresponds to the condition (Q>20) in the equation (1).

The method of determining the reaction of the system to the flow of steam was as follows: after warming up and adjusting the dielectric system, the value of the output quality factor of the system was set in the resonance mode at the operating frequency without steam flow. Next, the steam generator was turned on

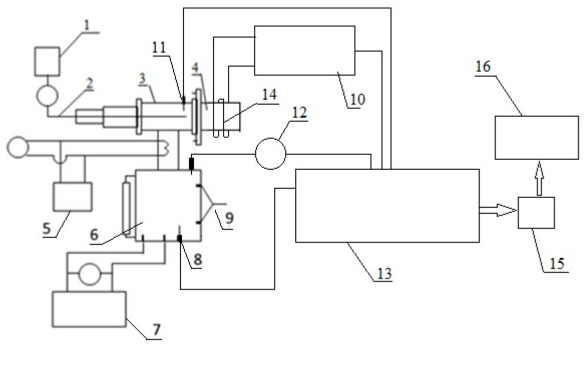

Fig. 3. Scheme of steam plant with steam ionization by corona discharge:
1 – high voltage source; 2 – high voltage input; 3 – ionization chamber of the boiler; 4 – nozzle part of the ionization chamber; 5 – steam superheater; 6 – boiler; 7 – power source of boiler heaters; 8 – water temperature sensor in the boiler; 9 – water level signaling sensors in the boiler; 10 – Q-meter (quality factor meter) BM 560; 11 – temperature sensor in front of the nozzle; 12 – pressure gauge in the ABB boiler; 13 – analog input module MBA8; 14 – inductor at the nozzle exhaust (L-cell); 15 – AC4 interface converter; 16 – personal computer

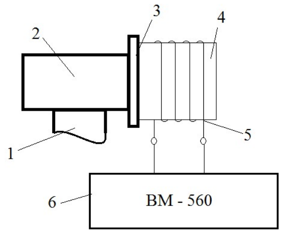

Fig. 4. Scheme of the dielectrometric system:
1 – output of the steam generator; 2 – steam superheater; 3 – nozzle insert; 4 – housing of the inductive cell (L-cell); 5 – inductor winding; 6 – quality factor meter

Fig. 5. General view of the dielectric system

and the stream of steam from the nozzle floated through the interior of the L-cell into the atmosphere. At the same time, the quality factor signal and the change in the capacitance of the measuring capacitor were recorded under the resonance condition.

The result of measurements

Two experiments were conducted in which the possibility of using the method of recording the dielectric properties of the steam flow and setting the measurement channels was evaluated. The graphs of the first experiment are shown in Fig. 6.

The most significant parameter is the quality factor signal given in conventional units. Preliminary coordination of the output signal of the Q-meter and the input of the MVA8 measurement channel made it possible to obtain a small range of the quality factor signal of about 10 conventional units. As can be seen in Fig. 7, the appearance of the steam flow from the nozzle and its passage through the inductive sensor is clearly monitored on the quality factor graph. The gradual increase in steam flow correlates with the course of the quality factor curve. The start moment of steam electrification does not lead to a noticeable jump in the quality factor values. Based on this, it is possible to draw a preliminary conclusion about a slight change in the dielectric properties of the wet electrified steam flow.

In the second experiment, the conversion factor of the Q-meter signal was changed in order to increase its amplitude and a time stamp channel was introduced.

The second graph shows that, as in the previous experiment, the values of the quality factor *Q* at the moment of the appearance of a volume charge in the steam flow do not change by a significant jump. The change in the course of the quality factor curve when the electrification is turned on is most likely related to the conditions of the steam flow spread in the atmosphere: during electrification, condensation significantly intensifies and the steam flow increases in the cross section due to the forces of electrostatic repulsion.

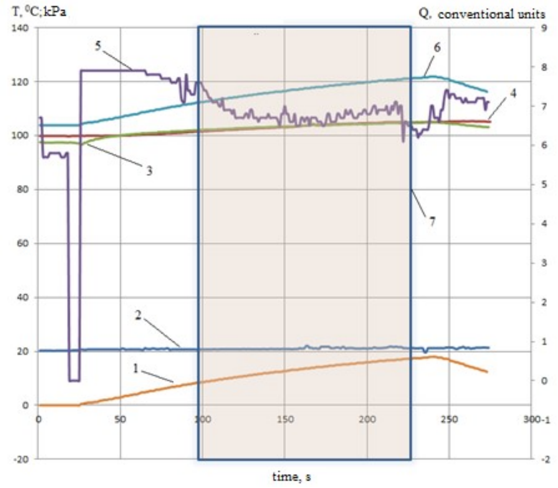

Fig. 6. Results of the first experiment:
1 – nozzle pressure drop; 2 – temperature in the laboratory; 3 – temperature in front of the nozzle; 4 – temperature in the boiler; 5 – quality factor; 6 – boiler pressure; 7 – the selected area of volume charge presence

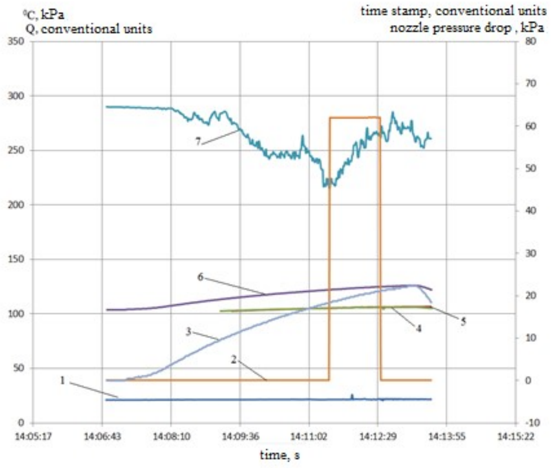

Fig. 7. Graph of the second experiment:
1 – temperature in the laboratory; 2 – time stamp (presence of volume charge); 3 – nozzle pressure drop; 4 – temperature in front of the nozzle; 5 – temperature in the boiler; 6 – boiler pressure; 7 – quality factor

Discussion

In [1], it was assumed that the electric field in the turbine flow part has a quasi-static character: constant and variable components, and the thermodynamic work of the dielectric (steam) in the field of the droplets volume charge is polarization. In [7], it was suggested that the dielectric constant of a pair containing a volume charge with a high density can differ significantly from the DC of a neutral pair, and, accordingly, the work of polarization (since the DC characterizes the ability to polarize in an external electric field [8]). This assumption was based on the DC determination due to the force of interaction between two test charges according to Coulomb's law in a vacuum and the studied medium

$$F = \frac{q_1 q_2}{2\pi\varepsilon_0 \varepsilon r^2}, \tag{5}$$

where the DC characterizes the weakening of the interaction compared to vacuum

$$\varepsilon = \frac{F_{\text{vacuum}}}{F_{\text{medium}}}. \tag{6}$$

According to the authors [7], when test charges are introduced into the flow part with a volume charge, their interaction can be weakened by shielding the volume charge field. Considering the nature of the source of the electrostatic field in the flow part and the specifics of the volume charge, it can be assumed that in this case some shielding of the volume charge of large positively charged droplets may occur due to a smaller number of small negatively charged droplets distributed in the flow volume. In addition, the shielding process will depend on the mobility of negative droplets. In this case, some increase in the effective value of the dielectric constant of the flow with a volume charge can be expected. In addition, the presence of neutral moisture droplets can contribute to the polarization of the wet steam flow (since the DC of water is much greater than the DC of steam).

The DC and, accordingly, the polarization of the working fluid affect not only the work of expansion [1], but also the accumulation of electric field energy in the volume of the dielectric [7].

$$W_v = \frac{\varepsilon\varepsilon_0 E^2}{2}.$$

In fact, the energy W_v is the additional loss of conversion of the working fluid energy into the electric field energy. In [7], the value of W_v was estimated for a working fluid with a slight polarization (the DC close to unity as in a neutral pair). In this case, W_v=0.177 J/m^3 of steam flow. According to the authors [7], if ε increases by several orders of magnitude, the energy of the electric field can reach ~100 J/m^3 or more. Experimental determination of the actual value ε of a steam flow with such electrophysical characteristics requires the development of a special method.

In the used L-method [4], the quality factor signal formed by the change in the magnetic flux $\Delta\Phi$ inside the L-cell is mainly determined by the difference in its components $\Delta\Phi_1$ and $\Delta\Phi_2$:

$$\Delta\Phi = \Phi_0 \left(\frac{1}{8} r_0^2 \mu\varepsilon\omega^2 \, \frac{5}{384} r_0^4 \mu^2 \omega^2 \chi^2 \right) = \Delta\Phi_1 - \Delta\Phi_2, \tag{7}$$

where r_0 is the radius of the dielectric volume in the sensor; μ is the magnetic permeability; ω is the circular frequency; χ is the specific electrical conductivity of the studied substance.

The first component is associated with the occurrence of displacement currents that depend on the dielectric constant in the cell, the second - eddy currents that are proportional to the specific electrical conductivity χ^2. The use of an L-cell for dielcometry is legitimate when $\Delta\Phi_1$>>$\Delta\Phi_2$ and $\chi<\chi_{\max}$. The value $\chi_{\max}$ is proposed to evaluate at condition [4]

$$\frac{\Delta\Phi_2}{\Delta\Phi_1} = \frac{5 r_0^2 \mu \chi^2}{48\varepsilon} < 0.05. \tag{8}$$

Since the specific electrical conductivity of water steam is low, condition (8) for using the L-method is fulfilled.

Analyzing the nature of the change in the quality factor signal when the ionization of the steam flow is turned on, it can be recognized that in this case there is no sharp change in the signal. Therefore, the characteristics of the magnetic flux in the L-cell and the relation between the processes caused by displacement currents and eddy conduction currents do not change significantly. Obviously, the DC in this case does not change significantly. In this case, the absence of a significant change in the quality factor signal can be explained by the fact that the volume charge of the steam flow on the plant is unipolar (only positively charged droplets), it differs from the structure of the volume charge in the turbine flow part (large positive droplets and small negatively charged droplets), that is, it lacks a component capable of shielding the positive charge. In addition, there is no sharp change in the humidity of the flow in the volume of the sensor (L-cell), because the sensor has a limited length, and intensive condensation of the high-speed flow from the nozzle already occurs behind it in the laboratory space.

Conclusions

The conducted experiments showed that the signals of the measuring dielcometric system based on the L-method are related to the presence of a wet steam flow and its flow regime in the L-cell. The nature of the signals correlates with the thermodynamic and electrophysical parameters of the wet steam flow. On the basis of this method, it is possible to develop a system for assessing the dielectric constant and humidity of a steam electrically neutral flow and one that has a volume electric charge.

The obtained data allow to draw a preliminary conclusion about an insignificant change in the dielectric properties of a steam flow with a volumetric electric unipolar charge with the parameters and spatial structure used in this experiment. A simplified unipolar physical model of flow polarization without taking into account the second component of small charged droplets does not allow to simulate the effect of the electric field shielding in the flow and its dielectric polarization increase.

It is obvious that in order to obtain more representative information about the electrophysical properties of a steam flow with a volume charge in the turbine, it is necessary to create conditions in the experimental plant that allow to obtain a volume charge with parameters and structure similar to a real turbine plant, in particular, with a two-component charged dispersed phase represented by positively and negatively charged droplets in the steam flow.

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Експериментальна оцінка впливу електризації потоку вологої пари на його діелектричні властивості

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Констатовано, що задля вивчення теплоелектрофізичних явищ у вологопарових турбінах в ІПМаш НАН України протягом останнього часу проводилися дослідження впливу об’ємного заряду вологопарового потоку на його діелектричні й теплофізичні властивості. За їх результатами встановлено, що найбільш представницьким електрофізичним параметром, який дозволяє оцінювати зміни теплофізичних властивостей пари, що відбуваються під дією власного об’ємного заряду, є його діелектрична проникність. Висловлено припущення, що величина діелектричної проникності електризованої пари може суттєво відрізнятися від значення для нейтральної пари, проведено математичну оцінку її можливої зміни. Підтверджено, що вплив електрофізичних явищ, зумовлених електризацією вологопарового потоку, є суттєвим, але не враховується в існуючих фізичних і математичних термодинамічних моделях процесу розширення пари. Доведено, що для уточнення основних термодинамічних параметрів і розрахункових характеристик потоку електризованої вологої пари необхідно визначити, як змінюється її діелектрична проникність. На підставі аналізу обґрунтовано актуальність експериментального встановлення діелектричної проникності вологопарового потоку з об’ємним зарядом із метою отримання залежності її зміни від температури й тиску потоку, а також щільності об’ємного заряду. Для виконання завдання дослідження використовувався газодинамічний лабораторний стенд, який дозволяє отримувати вологопаровий потік з об’ємним зарядом. Внутрішній простір проточної частини реальної вологопарової турбіни має значний розмір і дозволяє сформуватися потоку з об’ємним зарядом складної просторової конфігурації та структури. Акцентовано, що в проточній частині стенду невеликого об’єму, на відміну від проточної частини турбіни, при організації умов виникнення вологопарового потоку з об’ємним зарядом виникають суттєві технічні складності. З урахуванням цього на першому етапі прийнято рішення проводити дослідження парового потоку з об’ємним зарядом, що витікає в атмосферу, у приміщенні лабораторії з достатнім об’ємом для формування його просторової структури. Для оцінки величини його діелектричної проникності обрано індуктивний метод (L-метод) визначення діелектричних властивостей, в якому досліджувана речовина вводиться всередину індуктивної соленоїдної комірки. Проведено експерименти й отримано дані, за якими можлива попередня оцінка зміни діелектричної проникності за наявності об’ємного електричного заряду в потоці пари.

***Ключові слова**: вологопарові турбіни, теплофізичні властивості робочого тіла, діелектрична проникність, об’ємний заряд потоку пари.*

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