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To cite this article: A L Zuev *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **581** 012027

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Experimental study of electrical impedance in airways filled with electrolyte solution aerosol

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Abstract. This article presents the results of an experimental study of electrical impedance in a model cell through which the air flow containing aerosol particles of the 10% sodium chloride solution generated by an ultrasonic nebulizer passes. The active and capacitive components of admittance were determined at different values of alternating current frequency, flow rate and aerosol atomization intensity. Measurement results were compared with the most probable electrical conductivity models. An equivalent electrical circuit in the form of a parallel RC-circuit, which corresponds well to the obtained frequency dependences of impedance magnitude and phase shift angle, is proposed. In addition, a linear regression model describing the dependence of the impedance module logarithm on two parameters of the flow of aerosol particles at different electrical current frequencies is developed.

1. Introduction

Rheographic methods based on registration of bioelectrical impedance (resistance of biological media and tissues to an alternating current) found broad application in the last decades in modern medicine for noninvasive diagnosis of human diseases due to their exceptional availability, simplicity and cheapness. These methods can be used to evaluate the status of the cardiovascular system (rheocardiography and the other analogous techniques), to examine the composition of human body tissues (the assessment of the ratio of fat, musculoskeletal and water masses), to analyze the molecular composition of biological fluids, to apply a conductometric method for counting blood cells, etc.

Researchers from the Department of Propaedeutics of Internal Medicine at Perm Medical University were the first who suggested using impedancemetry in clinical diagnostics of respiratory diseases [1-3]. They have developed a novel method of electrical impedance spirometry to record variations in the electrical impedance of the entire set of biological objects that constitute an electrical circuit when an electrical current propagates from the respiratory tract to the skin of the human chest: lung tissues, aerosol exhaled by the patient during the respiratory cycle, bronchial secretion electrolyte, etc.

The underlying concept of the method consists in preliminary saturation of the respiratory tract with small droplets of a conductive fluid (0.9% sodium chloride solution) generated by an ultrasonic nebulizer. Electrical impedance measurements were performed using a bipolar method, in which one electrode was installed in the nebulizer mouthpiece (without direct contact with the patient body), and another electrode was located on the chest skin in the region of 4th intercostal space. The electrical circuit between the electrode in the nebulizer mouthpiece and the mucous membrane of the respiratory tract was closed due to the flow of aerosol particles of the conducting fluid exhaled by the patient.

Analysis of the results of clinical studies has revealed a significant difference in the average modular value of electrical impedance between the groups of patients with various disorders of the external respiration function and the group of practically healthy subjects. A significant growth in the impedance magnitude was found for patients with bronchial asthma (BA) in comparison with controls. The method is also able to detect early pneumonia signs; it shows approximately 90% sensitivity when compared



with conventional spirometry. In some cases (e.g. in the case of allergic inflammation of the respiratory tract), the sensitivity of the method exceeds that of the common spirometry by 30%, which makes it possible to diagnose bronchial asthma in the patients who had no yet clinically significant symptoms of this disease.

However, further development of electrical impedance spirometry and its introduction into clinical practice is impossible, without revealing physical mechanisms responsible for changes in the electrical conductivity of the respiratory tract and lung parenchyma. Real physical factors causing the differences in bioimpedance values in patients with disorders in large and small respiratory tracts have not been sufficiently studied and fully understood. The increase of electrical resistance can be attributed to the changes in blood vessels, small airways, lung parenchyma, bronchial tree diameter, bronchial secretions, which may arise in damaged lung tissues, during the development of fibrosis and pneumocirrhosis, pulmonary edema, and the formation of hydrothorax. A reduction in the respiratory tract diameter can lead to a decrease in ventilation indicators, which is typical of patients with bronchial asthma. Another important indicator of the medical assessment of respiratory organs is the strength of the respiratory musculature, determined by the rate of air flow expired by the patient during the respiratory cycle. A typical symptom of respiratory disorders in BA and diseases of lung parenchyma is a decrease in the rate of this flow. These findings suggest that the sensitivity of the electrical impedance spirometry method is probably caused by the dependence of the electrical impedance of the aerosol moving in the tube on the rate of its flow. Meanwhile, the mechanism governing such dependence still remains unclear, and hence this assumption requires further experimental verification.

In this paper, we present the results of the model experiment carried out to test an assumption that the value of electrical impedance depends on the diameter of the respiratory tract and the velocity of aerosol particles in it. Distribution of aerosol particles was generated by a medical ultrasonic nebulizer. Important parameters that affect the properties of the obtained aerosol are the acoustic power of the ultrasonic radiator and the airflow velocity above the liquid surface. The concentration of particles in the aerosol thus generated depends on both parameters [4]. The conductivity of the aerosol flow is determined by several mechanisms. The aerosol particles obtained in the nebulizer can have an electrical charge when particle ionization occurs due to the accidental collision (friction) between particles or between particles and surrounding surfaces during the aeration of the solution of a conducting liquid by ultrasonic waves [5-6]. Therefore, the magnitude of the resulting electric current must be proportional to the velocity of the flow of charged particles, i.e. the expiratory flow rate. Due to temperature difference, the aerosol can condense on the walls of the tube in which it moves. In the case of good wettability of the walls, a thin liquid film is formed on them; its thickness also depends on the flow rate and the nebulization intensity. When the electrodes touch the walls, the conductivity of such a condensation film must also be taken into account.

2. Experimental procedure

The electrical conductivity of the aerosol flows of saline solutions was investigated using an experimental setup consisting of an aerosol generator, a measuring cell and a gauge for measuring the impedance magnitude and phase shift angle.

The measuring cell was a polystyrene tube of diameter 1 mm and length 70 mm, through which the aerosol flow of the conducting fluid was blown. Silver chloride (AgCl) plate electrodes of length 25 mm and width 8 mm (spaced 3mm apart in one plane) were placed inside the measuring cell in one plane near the internal wall of the tube. It is exactly this design of the measuring cell and electrodes that has been used earlier in clinical studies of the electrical impedance spirometry method [3] and has demonstrated its effectiveness in analyzing the respiration of patients.

Aerosols were generated by the Omron Ultrasonic Nebulizer Ne-u17. To this end, the nebulizer reservoir was filled with a 10% sodium chloride (NaCl) or calcium chloride (CaCl₂) solution. The volume of the liquid was 50 ml. The aerosol in the nebulizer is obtained by exposing the liquid to ultrasonic vibrations at different nebulization (spraying) intensity, corresponding to ten levels from 1 to 10. The average particle size is ~4-6 μm. The nebulizer has a fan to evacuate the aerosol from the reservoir chamber. The nebulizer air flow rate can vary from 0 to 17 l/min (11 levels – from 0 to 10) [7].

In order to simultaneously determine the impedance magnitude and phase shift angle, we used the RCL-meter GW-Instek LCR-8105G with the following technical characteristics: resolution – 6 decimal

places, frequency range – 20 Hz to 5 MHz, impedance measuring range – 0.1 Ohm to 100 MOhm, voltage amplitude – 10 mV to 2.0 V, and basic accuracy of measurements – 0.1% [8]. The tests were carried out according to a bipolar scheme: the unipolar current and potential electrodes of the RCL-meter were jointly connected to the electrodes of the measuring cell. The voltage amplitude was assumed to be equal to 2.0 V. The LCR-meter operation was controlled by a personal computer. The original computer program enables the computer to execute a series of tests consisting of 10 measurements (doubles) of electrical impedance sequentially for each electric current frequency with saving the results in a data file. All measurements were done at 1 min interval after the aerosol begins to travel through the measuring cell.

Mathematical treatment of the experimental results is frequently performed subject to the normal law of random measurement distribution, i.e. the result of each measurement is influenced by a great number of factors, and each factor makes a small contribution to the value of error. At the same time, in a number of works, the necessity of mandatory verification of the hypothesis concerning the normal distribution of a random error is pointed out. This problem is solved by applying fit criteria, including Pearson's chi-square criterion and Kolmogorov's criterion. In our investigation, we use the Shapiro-Wilk criterion, which is well suited for assessing a small number of data [9]. A statistical distortion was excluded from the obtained series of electrical impedance values. In each statistical sampling, the average value of every factor and its standard deviation were calculated. The measurement result was excluded if its value did not fall within the interval of three standard deviations from the average value of the remaining sample [10].

3. Results and discussion

In the experiments with the 10% sodium chloride solution, the frequency dependencies of impedance magnitude and phase shift angle were obtained at frequencies 20, 100, 500 Hz, 1, 5, 10, 20, 30, 40 and 50 kHz for six values of the air flow rate V (levels 1, 3, 5, 7, 8, 10) and five values of the nebulization intensity W (levels 2, 4, 6, 8, 10), respectively. Thus, the total number of the analyzed combinations of the parameters of the electrical current and the aerosol particle flow was 300 different variants. The measured values of the impedance magnitude reached rather high values ~ 1-100 MOhm. Typical curves of the frequency dependencies for the impedance magnitude and phase shift angle with the other fixed parameters are shown in figure 1 and figure 2. It was found that at frequencies below 5 kHz no significant change in the impedance magnitude is observed in the case when the frequency increases (the active component of the resistance remains constant), and the phase angle values are close to zero (the capacitive component of the resistance is practically absent). At higher frequencies, a significant decrease in the impedance magnitude and an increase in the negative value of the phase shift angle from 0 to -78 degrees are observed. The obtained results indicate that at lower frequencies (20–5000 Hz) the aerosol impedance magnitude is mainly determined by the active resistance, and at higher frequencies (10–50 kHz) the conductivity increases because of the capacitive component. In this case, the curves of the corresponding frequency components in a logarithmic scale have a constant slope.

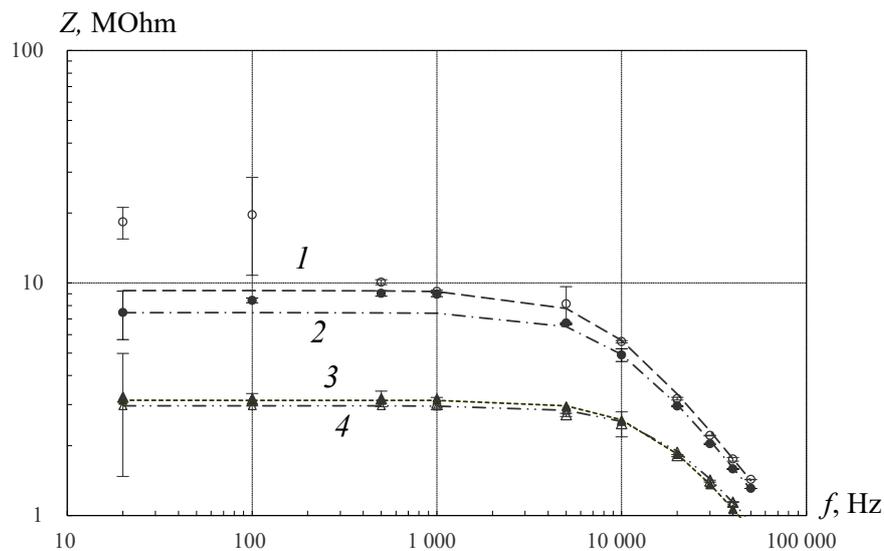


Figure 1. Impedance magnitude Z versus frequency f at $W = 4, V = 5$ (1); $W = 4, V = 8$ (2); $W = 8, V = 5$ (3); $W = 8, V = 8$ (4). Lines – calculated dispersion dependencies for the corresponding parallel RC -circuits.

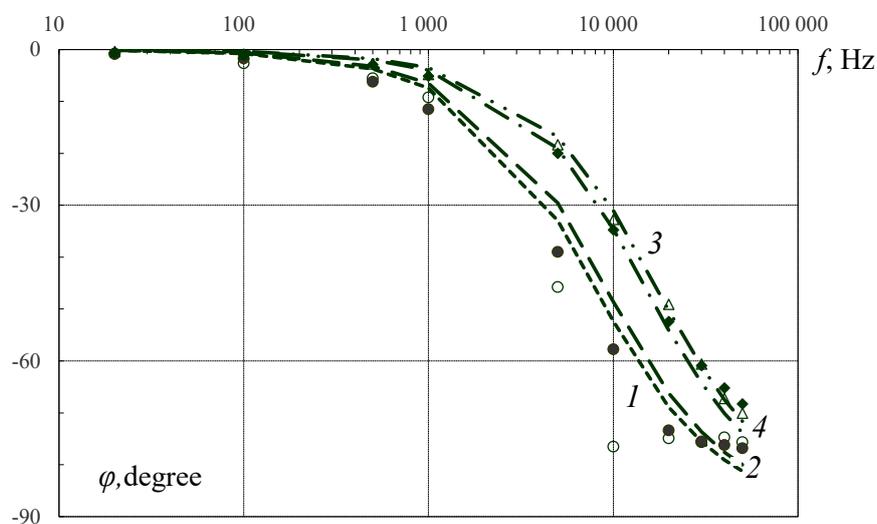


Figure 2. Impedance phase angle φ versus frequency f at $W = 4, V = 5$ (1); $W = 4, V = 8$ (2); $W = 8, V = 5$ (3); $W = 8, V = 8$ (4). Lines – calculated dispersion dependencies for the corresponding parallel RC -circuits.

Dispersion dependencies of such type are typical of the parallel RC -circuit [11-13], which allows us to offer this type of an equivalent circuit and to calculate the corresponding values of the active resistance R and capacitance C at the given flow rate and nebulization intensity.

The parameters R and C are calculated as follows. The impedance magnitude Z for the parallel RC -circuit is described by the expression:

$$Z = \frac{R}{\sqrt{1 + (\omega RC)^2}}$$

After transformation, this equation becomes

$$\frac{1}{Z^2} = \frac{1}{R^2} + C^2 \omega^2$$

Using the method of linear regression [14] (the dependent variable Z^{-2} , and the independent variable ω^2), from the above expression we can obtain the coefficients R^{-2} and C^2 .

The values R lie within the range from 3.1 to 90 MOhm, and the values C within the range from 0.56 to 4.5 pF. The solids lines in figures 1 and 2 are plotted using the calculated data. It is seen that the theoretical results coincide well with the experimental data. Within the entire measurement range, the mean error was about 30% for R and 5% for C .

The typical dependences of the calculated value of the capacity C on the airflow rate and the nebulization intensity are represented by the curves given in figures 3 and 4. It is seen from the curve $C(V)$ (figure 3) that at the different prescribed values of nebulization intensity the capacitance increases in a monotonic fashion as the rate of the aerosol flow generated by the nebulizer fan increases, and the dependence is close in this case to the linear one. Besides, the capacity also increases with increasing nebulization intensity (see $C(W)$ in figure 4).

However, both the values of the capacitance itself and its changes are very insignificant being of only a few pF, which cannot make a significant contribution to the impedance due to its capacitive component at relatively low AC frequencies used in the experiments.

In turn, the experimental data on the dependence of the active resistance on the aerosol velocity $R(V)$ and on nebulization intensity $R(W)$ indicate that the resistance decreases monotonically with both aerosol velocity and nebulization intensity. In this case, the active resistance changes in much more significant limits, decreasing tens of times, in comparison with the capacitance. In particular, at $W = 4$, $V = 8$ are as follows: $R = 8.5 \pm 0.6$ MOhm, $C = 2.50 \pm 0.04$ pF; at $W = 8$, $V = 5$: $R = 2.91 \pm 0.05$ MOhm, $C = 3.26 \pm 0.03$ pF. Figure 5 presents the graph showing the dependence of the impedance magnitude obtained at low frequencies of 20 Hz and 50 kHz (when the total resistance is caused by the active component only) on the aerosol flow velocity at different nebulization intensities. It is shown that the straight lines with a negative slope coefficient best represent the obtained experimental data. The graphs showing the dependence of the impedance magnitude logarithm on the intensity of spraying aerosol particles at different values of the airflow velocity are also the straight lines with a negative slope coefficient (figure 6).

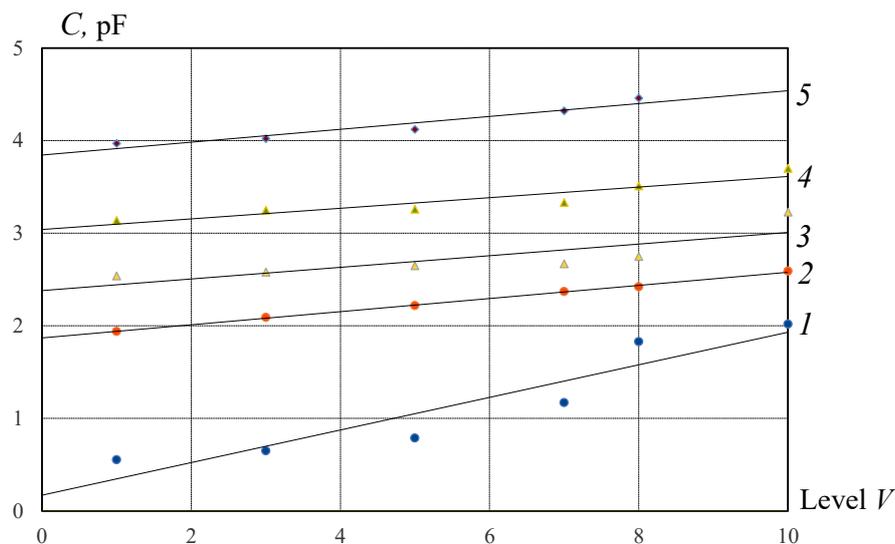


Figure 3. Capacitance C of the equivalent RC -circuit versus aerosol particle flow rate V at nebulization intensity $W = 2$ (1); $W = 4$ (2); $W = 6$ (3); $W = 8$ (4); $W = 10$ (5).

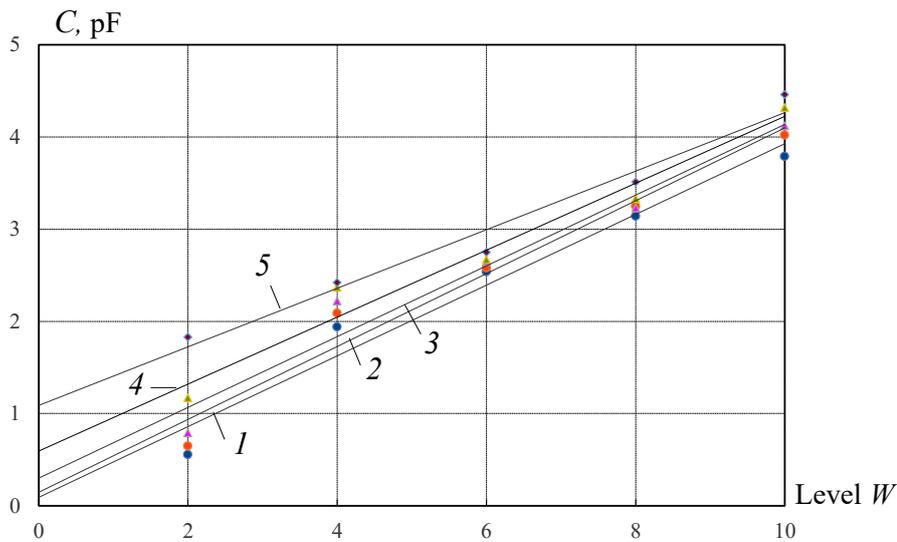


Figure 4. Capacitance C of the equivalent RC -circuit versus nebulization intensity W at flow rate $V = 1$ (1); $V = 3$ (2); $V = 5$ (3); $V = 7$ (4); $V = 9$ (5).

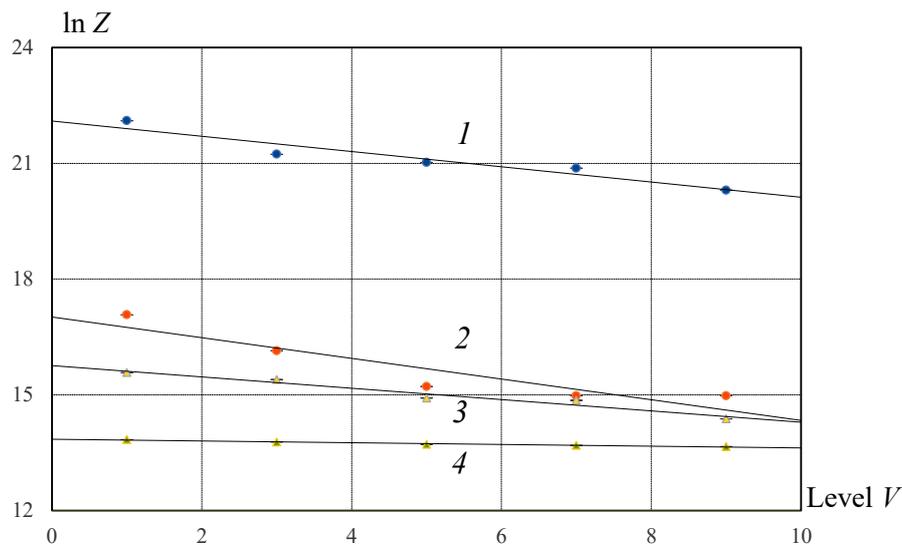


Figure 5. Logarithm of impedance magnitude Z versus aerosol velocity V for frequency $f = 20$ Hz at $W = 2$ (1); $W = 8$ (2); and for frequency $f = 50$ kHz at $W = 2$ (3), $W = 8$ (4).

Based on the experimental data obtained in this study, we have suggested the regularities in the form of expressions (1) и (2) [15]:

$$Z \sim e^{-aV}, \quad (1)$$

$$Z \sim e^{-bW} \quad (2)$$

where a, b are coefficients.

In order to determine the dependences of the aerosol impedance magnitude Z on V and W for each electric current frequency, we derive, on the basis of relations (1) and (2), the linear regression [14] (a_1, a_2 and a_3 are some constants):

$$\ln Z = a_1 V + a_2 W + a_3 \quad (3)$$

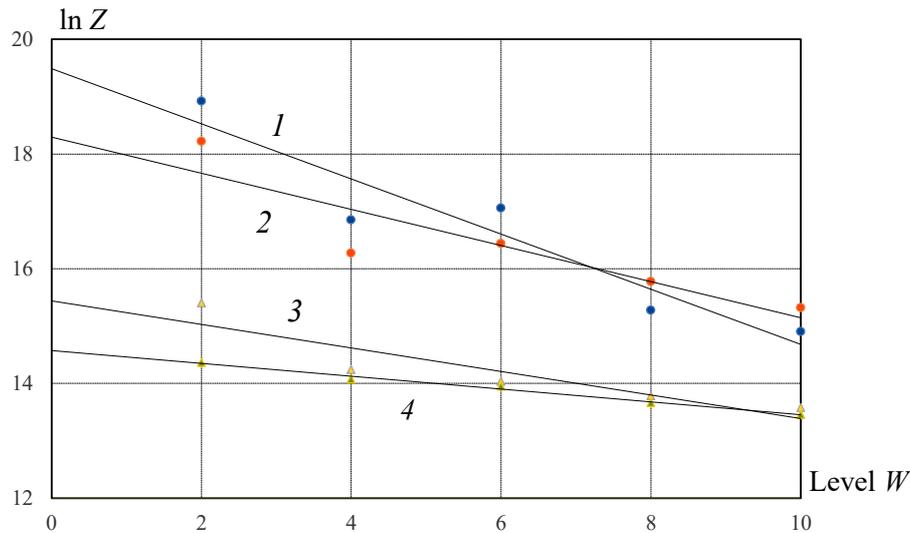


Figure 6. Logarithm of impedance magnitude logarithm Z versus intensity of spraying of aerosol particles W for frequency $f=20$ Hz at $V=2$ (1); $V=8$ (2); and for frequency $f=50$ kHz at $V=2$ (3), $V=8$ (4).

By applying a linear regressive analysis for the model describing dependencies of the impedance magnitude of the aerosol (equation 3), we obtained the results given in Table 1:

Table 1. Values of parameters of regression equation (3), square of the adjusted coefficient of determination and the relative mean square error at frequencies 20 Hz, 1, 10 and 50 kHz

Frequency, Hz	Parameter	Value	R^2_{adj}	Mean square error S_n , %
20	a_1	-0.153 ± 0.009	0.709	8.84
	a_2	-0.618 ± 0.011		
	a_3	17.67 ± 0.09		
1 000	a_1	-0.131 ± 0.006	0.739	5.49
	a_2	-0.386 ± 0.006		
	a_3	15.53 ± 0.05		
10 000	a_1	-0.097 ± 0.003	0.756	3.39
	a_2	-0.219 ± 0.004		
	a_3	13.28 ± 0.03		
50 000	a_1	-0.077 ± 0.003	0.797	2.92
	a_2	-0.189 ± 0.003		
	a_3	11.66 ± 0.02		

The calculated values of the adjusted coefficient of determination and the mean square error indicate that equation (3) is in good agreement with the experimental data, and with increasing frequency the mean square error decreases and the proportion of explained variance increases.

4. Conclusion

Thus, the assumption regarding the interaction between electric and kinetic parameters of the flow of aerosol particles of conducting liquid was confirmed in our model experiments. The impedance measurement data on the air flow composed of aerosol particles of the 10% sodium chloride solution traveling through the measurement cell and the calculated results obtained at an alternating flow of different frequency have indicated that an equivalent electric circuit (a parallel RC-circuit in this study) provides an adequate description of the frequency dependence of impedance parameters. The coefficients of the calculated capacitance were found to increase linearly with increasing velocity of the airflow generated by the ultrasonic nebulizer and with the intensity of spraying aerosol particles. The inverse dependencies of the impedance magnitude on the aerosol velocity V and the nebulization intensity W were determined, and the model describing the dependence of impedance magnitude logarithm on two variables was developed. The coefficients of a linear regression model were calculated for each frequency. It is shown that the proposed model describes satisfactorily the experimental data. The obtained results suggest that the velocity of the exhaled air flow can be determined by applying the electrical impedance method, which paves the way for designing a new electrical impedance sensor required to measure the velocity of an expired airflow, as well as methods for medical diagnosis of bronchial obstructive diseases.

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