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RESEARCH AND USE OF THE SKIN EFFECT IMPACT IN THE TECHNOLOGY OF DISINFECTION OF FODDER MIXTURES BY ELECTRIC CONTACT HEATING

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Abstract- The article reviews electric parameters of the disinfection process of the fodder mixtures by electric contact heating, as well as their influence on the extent of the skin effect when the chamber is powered by the currents of different frequency. Equivalent schematic substitute of the electric contact heating chamber is offered. The diagrams of changes in the electrical conductivity of the heated medium versus the frequency of the supply voltage are presented. An equation has been drawn up that describes the influence of the key attributes of the disinfection process on the value of total impedance of the electronic appliance. Calculations are provided for the thickness of the skin layer and the diagram of its alteration depending on the supply voltage frequency.

Keywords: Electronic Contact Heating, Skin Effect, Fodder Mixtures Disinfection, Conductivity.

1. INTRODUCTION

The issues of ensuring high-quality and safe farm animals feeding are of paramount importance for the increase in animal husbandry productivity. Since the feedstock is a favorable medium for proliferation of multiple organisms, including the pathogenic ones, it brings along a high risk of infection and exogenic intoxication of the animals, which poses a serious issue for the entire animal husbandry.

Currently, there exists a whole set of different methods to fight bacterial infestation of the feedstock. They all solve the task at hand to some extent, but have some drawbacks preventing them from being used everywhere [1, 2]. Besides, active developments are being conducted in the area of innovation technology aimedat the increase in the energy efficiency and reduction of equipment costs. In this regard, development of technology and technical means for sterilization of fodder mixtures by electric contact (EC) heating comes in very helpful.

2. RESEARCH TARGET

EC technology is known to be based on Joule-Lenz's law that characterizes immediate heat of a certain conductive medium by the heat generated within its space as result of electric current flowing through it [1, 2, 3]. The fodder mixture with the humidity of 51-78% plays the part of a conductive medium, which suggests that the technique is not suitable for dry feedstock sterilization since its implementation requires a conductive medium. But the technique is widely used in the technology relying upon liquid feedstock, e.g., hog production [1, 2].

To achieve a disinfection effect with the EC technique fodder mixture temperature should be maintained at 80 °C [1, 2]. This can be done by means of altering the power supplied to the load using a PID controller in the pulse-length mode for that matter that is widely used in continuous temperature control systems [4, 5, 6].

As a rule, the operating frequency of a pulse-length modulator (PLM) in thermal controllers of different brands may differ significantly. Besides, as regards the present technology, higher frequencies may not only ensure a more precise temperature control but may also reduce the total power component [7]. On the other hand, a significant increase in the operating frequency of a PLM with a sufficiently large cross-section of the volume with the fodder mixture can lead to an uneven distribution of currents with the appearance of a skin effect, and, as a result, to a temperature gradient, which will negatively affect the final result [8].

3. SKIN EFFECT CHARACTERISTICS

The nature of the appearance of the skin effect in a conductive medium is similar to the skin effect that occurs in massive conductors, when eddy currents are formed in the mixture while a high-frequency current is passed through the volume of the mixture, which impede the uniform distribution of the current density in the cross section. The current is displaced towards the surface of the conductive medium, and the larger the geometric dimensions of the dielectric chamber of the installation, and the higher the frequency of the supply voltage, the stronger the skin effect [8, 9].

To determine permissible values of the frequency used to heat the fodder mixture voltage, it is necessary to analyze the electrical parameters of the installation, which have the greatest influence on the degree of manifestation of the skin effect.

Dimension of the skin layer may be calculated using the equation below [2, 8]:

$$\Delta = \sqrt{\frac{2}{\chi\omega\mu_r\mu_0}} \quad (1)$$

where, μ_r is relative magnetic permeability; μ_0 is magnetic constant that is $4\pi\times10^{-7}$ H/m; χ is specific conductivity of fodder mixture; ω is phase rate determined by the ratio: $\omega = 2\pi f$, and f is supply voltage frequency.

The above expression (1) indicates that the key parameters affecting the extent of the skin effect given a constant magnetic permeability μ_r include the phase rate ω that depends on the supply voltage frequency f and specific conductivity of the medium χ.

4. RESEARCH OF ELECTRIC PARAMETERS OF EC TECHNOLOGY

The disinfection process with the use of the EC technology has been experimentally proven to be accompanied by the alteration of the physical properties of fodder mixture, such as moisture content and volume. The mixture conductivity value has been found to be affected by the temperature [6, 7, 9].

EC unit chamber with the fodder mixture in it in the form of an equivalent circuit is shown in Figure 1 [7, 9].

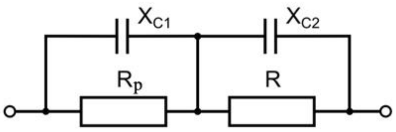

Figure 1. Equivalent circuit of EC heating unit: R_P - total polarization resistance from two electrodes; X_{C1} - double electric layer capacitance; R - test sample resistance; X_{C2} - reactive impedance [7]

As the circuit diagram above shows, apart from the Ohm resistance of fodder mixture R and the polarization resistance R_P forming as a result of double electric layer (DEL) at the border of conductive medium and electrode, the circuit also includes a reactive impedance component (X_{C1} and X_{C2}). This is due to the fact that the chamber with the parallel-plane contact electrodes has some electric capacity like a capacitor that is usually neglected due to an insignificant influence as a result of a large distance between the electrodes and the equivalent circuit is shown in a simplified form (Figure 2); a significant contribution is attributed to reactive impedance X_{C1} generated due to presence of two capacities of DEL [10].

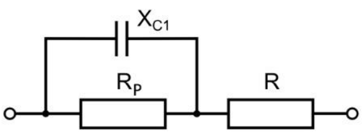

Figure 2. Simplified circuit of the EC heating unit: R_P - total polarizing impedance from two electrodes; X_{C1} - capacitance of double electrical layer; R - resistance of the test sample [7]

According to the circuit, given the exclusion of X_{C2}, total unit impedance Z shall be expressed as [6, 9, 10, 11]:

$$Z = Z_1 + R \quad (2)$$

where, R is reactive resistance of fodder mixture; and Z_1 is impedance of parallel elements.

Electric conductivity $\chi_1 = \frac{1}{Z_1}$ shall be defined using the expression below [2, 7]:

$$\frac{1}{Z_1} = \frac{1}{R_P} + \frac{1}{X_C} = \frac{1}{R_P} + j\omega C_e \quad (3)$$

where, ω is phase rate; and C_e is DEL capacity.

Using expression (3), calculate the impedance value Z_1 [7]:

$$Z_1 = \frac{\frac{1}{R_P}}{\frac{1}{R_P^2} + \omega^2 C_e^2} - \frac{j\omega C_e}{\frac{1}{R_P^2} + \omega^2 C_e^2} \quad (4)$$

Given expressions (2) and (4), find the ratio for to calculate electric conductivity of the mixture in the unit chamber [2, 7]:

$$\chi = \frac{\frac{1}{R_P^2} + \omega^2 C_e^2}{\frac{1}{R_P} - j\omega C_e + R\left(\frac{1}{R_P^2} + \omega^2 C_e^2\right)} \quad (5)$$

The research has shown that at varying conductivity of the medium mainly depending on the moisture content and composition of the fodder mixture, DEL capacity may vary within certain limits [9]. Relative to the EC technology, total DEL capacity for different configurations of the electrodes and disinfection chambers of different sizes may be within the range of 20-200 µF [7, 10].

The polarization resistance is known to depend on the frequency of the supply voltage and reduces with its increase; it can be calculated knowing total impedance of the fodder mixture [10]. The value of total specific conductivity χ of the fodder mixture has been empirically proven to be within the range of 11-18 mSm/cm, while the impedance value of the polarization layer amounts to 10-30% of χ [6, 9].

Given formula (5), at specified values of R and R_P and total DEL capacity C_e, the calculations have been made in the Mathcad system and the following graphs have been plotted $\chi=f(f)$ (Figures 3-7).

The analysis of the resulting data has shown non-linear increase in the electric conductivity χ relative to frequency f. In case of low capacity of DEL (Figure 3), the values of total conductivity (for different combinations of R and R_P) reach their maximum at the frequencies higher than 2-2.5 kHz. In this case, at frequencies of up to 500 Hz, the reactive component of the impedance manifests itself most pronounced. At higher capacity values (Figure 5), a steeper conduction front is observed, the maximum of which shifts towards lower frequencies.

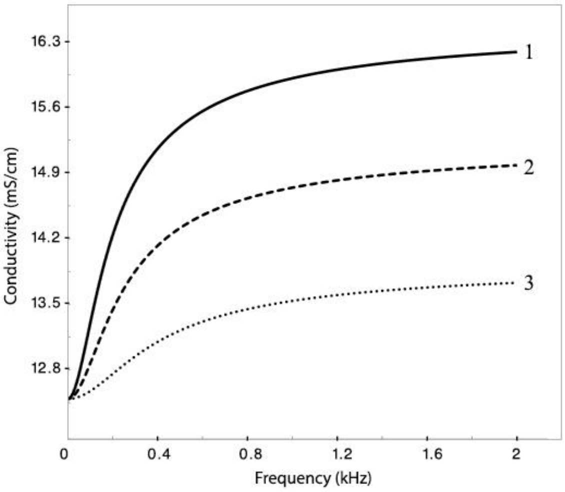

Figure 3. Dependence between the total conductivity and frequency with total capacity of double electric layer 20 µF: 1- R=220 Ohm, R_P=70 Ohm; 2- R=238 Ohm, R_P=52 Ohm; 3- R=260 Ohm, R_P=30 Ohm

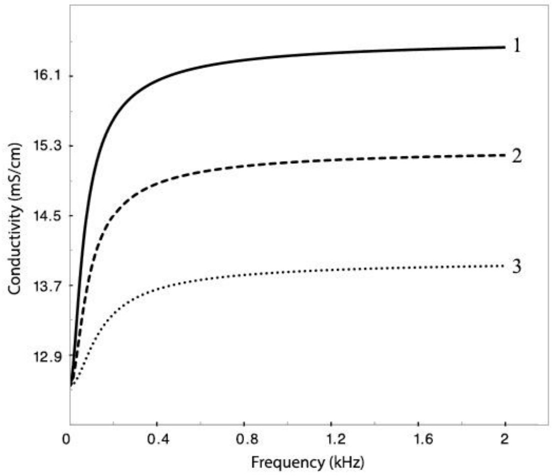

Figure 4. Dependence between the total conductivity and frequency with total capacity of double electric layer 60 µF: 1- R=220 Ohm, R_P=70 Ohm; 2- R=238 Ohm, R_P=52 Ohm; 3- R=260 Ohm, R_P=30 Ohm

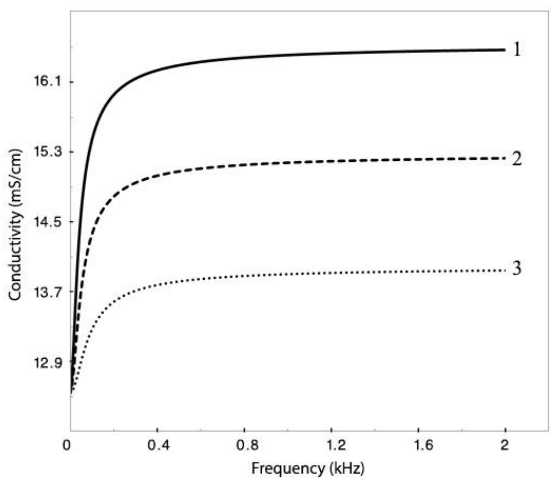

Figure 5. Dependence between the total conductivity and frequency with total capacity of double electric layer 100 µF: 1- R=220 Ohm, R_P=70 Ohm; 2- R=238 Ohm, R_P=52 Ohm; 3- R=260 Ohm, R_P=30 Ohm

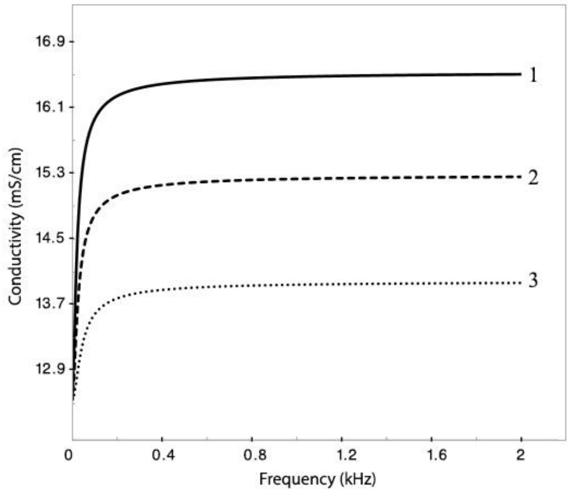

Figure 6. Dependence between the total conductivity and frequency with total capacity of double electric layer 200 µF: 1- R=220 Ohm, R_P=70 Ohm; 2- R=238 Ohm, R_P=52 Ohm; 3- R=260 Ohm, R_P=30 Ohm

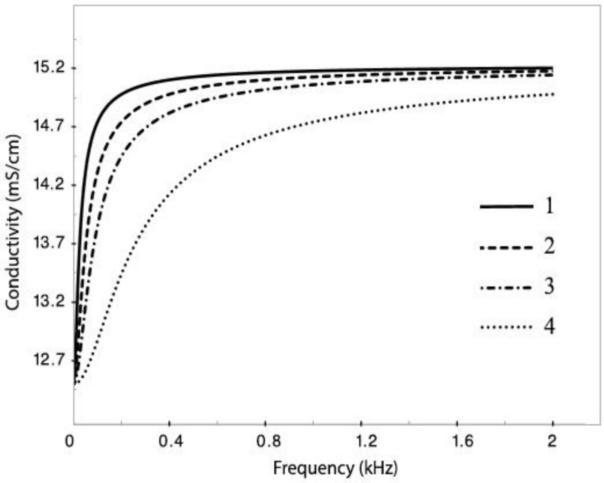

Figure 7. Dependence between the total conductivity and the frequency with active and total polarization resistance R=238 Ohm and R_P=52 Ohm, respectively, at the capacity of double electric layer of 1- 200 µF; 2- 100 µF; 3- 60 µF; 4- 20 µF

Also, the dependencies shown (Figures 3-6) suggest that the higher the value of the polarization resistance, the greater the relative change in the total conductivity curve. With an increase in the frequency of the supply voltage for any values of the capacity of the DEL, the relative change in the electrical conductivity is: 30.4%, 20%, 11.2% (curves 1, 2, 3, respectively).

The thickness of the skin layer was determined for frequencies within the range of 0-10 MHz. Based on the graphs (Figures 3-7) limit values of specific electric conductivity have been determined amounting to χ=0.165 Sm/m (upper threshold) and χ=0.130 Sm/m (lower threshold). Based on these data a dependence has been plotted between the measurement of the skin layer thickness Δ and the supply voltage frequency f (Figure 8), that corresponds to the exponential law.

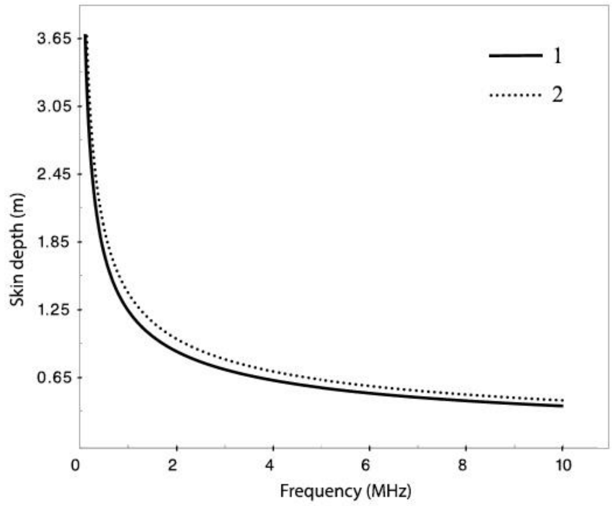

Figure 8. Dependence of the skin layer thickness from the frequency $\Delta=f(f)$: 1- χ=0.165 Sm/m; 2- χ=0.130 Sm/m

Since the volume of the mixture being disinfected by the EC method is limited by the power of a power supply unit used only, the cross-section of the chamber can therefore be large enough up to 3-4 m^2. Frequency range within which the skin effect manifests itself the most pronounced for certain electric parameters requires a closer look; such range falls within 1-10 MHz (Figure 9).

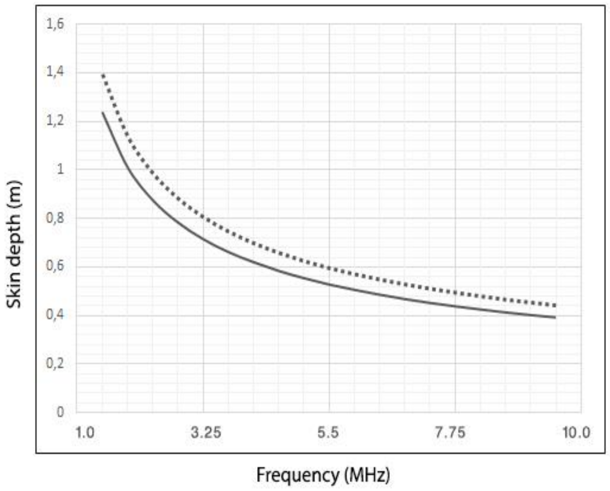

Figure 9. Dependence of the skin layer thickness from frequency $\Delta=f(f)$

The dimensions of the skin layer in this frequency range may turn out to be less than the above dimensions of the section of the EC installation chamber. For example, at frequencies around 10 MHz, the skin layer thickness at χ = 0.165 Sm/m (Figure 8, curve 1) is about 40 cm. With such skin layer max size of the chamber section should not exceed 0.8×0.8 m^2 which is comparable to the equivalent round section area of 0.5 m^2. The similar operation may be performed for the rest frequencies of the range in question. Table 1 shows the dimensions of the skin layer and equivalent section area for the EC installation chamber, calculated for the supply voltage frequencies.

Table 1. Dimensions of the skin layer and equivalent section area

Frequency, MHz	Skin layer dimensions at fodder mixture conductivity Δ, m		Equivalent section area, m^2	
	0.165 Sm/m	0.13 Sm/m	0.165 Sm/m	0.13 Sm/m
1	1.239	1.396	4.823	6.123
2	0.876	0.987	2.410	3.060
3	0.715	0.806	1.606	2.041
4	0.62	0.698	1.208	1.503
5	0.554	0.624	0.964	1.223
6	0.506	0.57	0.804	1.021
7	0.468	0.528	0.688	0.876
8	0.438	0.494	0.603	0.767
9	0.413	0.465	0.536	0.679
10	0.392	0.441	0.483	0.611

5. CONCLUSIONS

The performed analysis of the electrical parameters of the EC technology for disinfecting fodder mixtures to determine the degree of the skin effect showed the following:

1. Theoretically substantiated the dependence between the total electrical conductivity of the fodder mixture and the supply voltage frequency at given parameters of the impedance of the mixture, corresponding to the conditions of its disinfection;
2. The increase in the polarization impedance has shown to result in the increase in the relative change of total mixture conductivity;
3. The dependences between the size of the skin layer and the supply voltage frequency have been obtained, the ranges of the thickness of the skin layer (1.4-0.4 m) for frequencies of 1-10 MHz have been determined;
4. A range of 2 kHz - 1 MHz of the supply voltage frequency has proven to result in the absence of the skin effect irrespective of the dimensions of the EC heating chamber.

NOMENCLATURES

1. Acronyms

EC Electric Contact
PID Proportional-Integral-Differential
PLM Pulse-Length Modulation
DEL Double Electric Layer

2. Symbols / Parameters

χ: specific conductivity of the fodder mixture
ω: phase rate
f: supply voltage frequency
R_P: total polarization impedance
X_{C1}: double electric layer capacitance
X_{C2}: test reactive resistance
R: test sample resistance
C_e: total capacity of double electric layer
Δ: skin layer thickness

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