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ИСПОЛЬЗОВАНИЕ НИЗКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ ДЛЯ ОБЕЗЗАРАЖИВАНИЯ ОТКРЫТЫХ ПОВЕРХНОСТЕЙ ПРОИЗВОДСТВЕННЫХ ПОМЕЩЕНИЙ

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Приведены результаты исследований по инактивации микроорганизмов на открытых поверхностях птицеводческих помещений с использованием низкотемпературной неравновесной плазмы. В качестве ее источника использован электроискровой разряд переменного тока при атмосферном давлении. Типы разряда – стримерный, факельный. Рассмотрено одновременное воздействие электромагнитных полей, заряженных частиц и химически активных соединений, образующихся при электроискровом разряде, на эффективность инактивации патогенной микрофлоры для различных поверхностей (акриловый грунт, эпоксидная смола, лак яхтный, бетонно-графитовая смесь). Обрабатываемый материал (биологический макет подстилочной поверхности пола в птичнике с нанесенным защитным слоем) установлен после электроискровой разрядной камеры, продуваемой плазмообразующим газом (атмосферный воздух). Основными поражающими факторами являются активные химические соединения: озон; свободные радикалы (OH, O, O_2), ультрафиолетовое излучение в диапазоне 750–1600 ТГц, электромагнитное излучение от 50 Гц до 980 МГц, заряженные частицы и колебательно возбужденные молекулы азота и кислорода. Получены характеристики плотности потока электромагнитного излучения при электроискровом разряде. По результатам исследований максимальный эффект обработки открытых поверхностей низкотемпературной неравновесной плазмой достигается при использовании в качестве защитного материала поверхностей эпоксидной смолы. Количество инактивированных микроорганизмов при экспозиции 10–20 с достигает 100%. При инактивации микроорганизмов, находящихся на открытых поверхностях, длительность экспозиции экономически нецелесообразно принимать более 20 с. В исследованиях не выявлено существенного различия при использовании стримерного или факельного разрядов для обработки открытых поверхностей помещений.

Ключевые слова: низкотемпературная неравновесная плазма, электроискровой разряд, микроорганизмы, инактивация, патогенная микрофлора

THE USE OF LOW-TEMPERATURE PLASMA FOR DISINFECTION OF OPEN SURFACES OF INDUSTRIAL PREMISES

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The results of research on inactivation of microorganisms on open surfaces of poultry houses using low-temperature non-equilibrium plasma are presented. AC electrospark discharge at atmospheric pressure was used as its source. Discharge types are streamer, flare. The simultaneous effect of electromagnetic fields, charged particles and chemically active compounds formed by electrospark discharge on the efficiency of pathogenic microflora inactivation for various surfaces (acrylic primer, epoxy resin, yacht varnish, concrete-graphite mixture) is considered. The material to be treated (a biological model of the bedding surface of the floor in the poultry house with the applied protective layer) is installed after the electrospark discharge chamber blown with plasma-forming gas (atmospheric air). The main affecting factors are active chemical compounds: ozone; free radicals (OH, O, O_2), ultraviolet radiation in the range of 750–1600 THz, electromagnetic radiation from 50 Hz to 980 MHz, charged particles and vibrationally excited nitrogen and oxygen molecules. Characterizations of electromagnetic radiation flux density at electrospark discharge are obtained. According to the research results, the maximum effect of treatment of exposed surfaces with low-temperature non-equilibrium plasma is achieved when epoxy resin is used as a surface protection material. The number of inactivated microorganisms at exposure of 10-20 s reaches 100%. When inactivating microorganisms on exposed surfaces, it is not economically feasible to take exposure time longer than 20 s. The studies found no significant difference when using streamer or flare discharges to treat outdoor facility surfaces.

Keywords: low-temperature nonequilibrium plasma, electrospark discharge, microorganisms, inactivation, pathogenic microflora

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Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

Conflict of interest

The authors declare no conflict of interest.

INTRODUCTION

The transition from agricultural production to an industrial basis is primarily associated with an increase in the density of livestock and poultry in production facilities. This circumstance necessitates the creation of highly effective technical systems for disinfecting materials and media used in the production processes of goods.

Electrophysical methods for inactivating pathogenic microflora (direct and indirect), currently employed, typically utilize electromagnetic radiation (EMR) within a specific frequency range of varying intensity [1–3]. Comprehensive research results on electrophysical methods for microorganism inactivation are available in previous works [4–9]. The geometric dimensions of microorganisms and their electrophysical characteristics, which determine the degree of lethality when processed in electromagnetic fields, exhibit sufficiently large ranges of variation. It seems advisable to employ EMR across the entire spectrum - from radio frequencies to hard ultraviolet radiation (UVR) [10].

One possible way to implement such an approach is the use of non-equilibrium low-temperature plasma (NE LTP) generated during an electric spark discharge [6–8]. To assess the effectiveness of using NE LTP, it is necessary to determine the spectrum and radiation flux density generated during an electric spark discharge across the entire electromagnetic wave scale, while evaluating the degree of microorganism inactivation present in the air and on exposed surfaces (floor, walls) [11, 12].

The purpose of research is to determine the effectiveness of using low-temperature plasma in the inactivation of pathogenic microorganisms on various protective surfaces in indoor poultry facilities.

MATERIAL AND METHODS

The object of the study is the system for inactivating pathogenic microorganisms in a poultry facility. The microorganisms under investigation include *Bacillus subtilis*, *Staphylococcus aureus*, *Staphylococcus albus*, *E. coli*, and others. The microorganisms were applied to segments of standard ceramic tiles measuring 48 × 48 mm. Various protective surface layers are applied to the tiles as a substrate. The options for protective layers included acrylic primer, epoxy resin, yacht varnish, and concrete-graphite mix.

Total microbial count (TMC) was determined according to MG 4.2.734–99 "Microbiological

Monitoring of the Production Environment".

A plasma torch was used as the NE LTP source (see Fig. 1). The setup parameters are presented in Table 1.

Measured parameters:

– spectrum and flux density of electromagnetic radiation in the range from 3000 m to 100 nm;

– processing time of the test material;

– quantity of positive and negative air ions;

– ozone concentration and percentage of microorganism inactivation.

Controlled parameters:

– air temperature;

– air humidity;

– plasma-forming gas temperature.

Measurement instruments used:

– air ion counter MAC-01;

– multi-functional instrument Testo 435-2;

– universal gas analyzer GANK-4;

– multi-channel spectrometer "Kolibri";

– radiometer of UV-range (a, b, and c subranges) TKA-PKM;

– infrared radiation density measuring instrument "MK-meter";

– temperature measurement - infrared thermometer with switchable optics Testo 845, Kelvin Compact 1200/175 pyrometer.

Experimental Procedure

The treated material (a biological model of the floor bedding surface in a poultry house with an applied protective layer) was installed after the electric spark discharge chamber, which was purged with plasma-forming gas (ambient air). The main damaging factors include active chemical compounds: ozone, free radicals (OH, O, O2), ultraviolet radiation in the range of 750–1600 THz, electromagnetic radiation from 50 Hz to 980 MHz, charged particles, and vibrationally excited nitrogen and oxygen molecules.

Табл. 1. Параметры электроискровой установки для генерации плазмы

Table 1. Parameters of the electrospark unit for plasma generation

Parameter	Value
Voltage of high-voltage source, kV	12
Air velocity in the discharge chamber, m/s	1–4
Cross-sectional area of the discharge chamber, mm^2	80–110
Maximum power consumption of the installation, W	1500–3000
Calculated electric field strength in the discharge gap, V/m	450 000
AC frequency, kHz	20

The exposure to NE LTP during the discharge in gas was varied from 5 to 300 seconds. Upon removing the opaque screen from the surface of the quartz tube, the effectiveness of electromagnetic radiation exposure in the radio and ultraviolet ranges was additionally assessed.

The evaluation was based on the reduction in bacterial contamination of the bedding material in the experimental sample compared to the control. For this, 5 grams of the combined sample from each experimental exposure were weighed and added to 50 ml of sterile saline solution (dilution 1:10). The flask with the suspension was placed on a shaker at a frequency of 100 oscillations/minute and allowed to stand for 30 min-

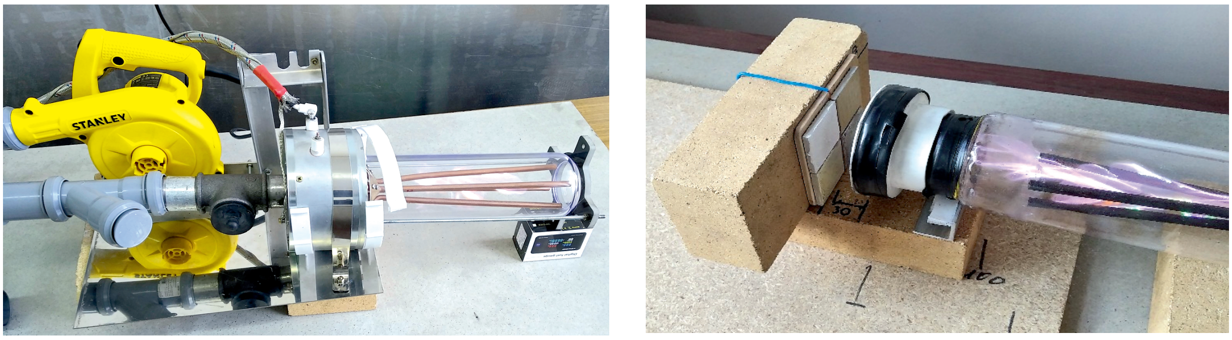

Рис. 1. Установка для генерации низкотемпературной плазмы (составлена авторами)

Fig. 1. Installation for low-temperature plasma generation (compiled by the authors)

utes at room temperature of 8 °C. Then, the suspension was centrifuged at 3000 rpm to separate large particles. Subsequently, successive dilutions were prepared from the obtained supernatant using the EasySpiral spiral seeding device. Each dilution was seeded in triplicate on Petri dishes with meat-peptone agar, with each dish receiving 100 µl. After 20 hours of incubation at 37 °C, the grown colonies were counted using the Scan 500 device. The arithmetic mean of the cups was taken as the final result. The microbial contamination of the investigated substrate was determined. The presence of growth of individual microorganism species was assessed on selective nutrient media.

The levels of electric and magnetic field intensity generated by low-temperature plasma, as well as radiation flux density, were measured at a distance of 20 cm from the surface of the glass tube of the plasma torch. Measurements were taken at fixed frequencies using the ATE-8507 device. The distance between the electromagnetic radiation flux density sensors and the electric spark chamber was 0.4 m.

RESULTS AND DISCUSSION

The parameters of electromagnetic radiation (EMR) generated during the electric spark discharge are presented in Table 2.

The flux density of EMR in the range of 190–400 nm is presented in Table 3.

The ozone concentration in the air stream was 7–8 mg/m^3.

The calculation of the electric field intensity in the interelectrode space was carried out using the ELCUT program. The maximum electric field intensity was 400,000–500,000 V/m. The general distribution of equipotential electric fields in the gas discharge chamber is shown in Fig.2.

To study the dynamic characteristics of the electric spark discharge, oscillography and high-speed video recording of the discharge current and voltage on the electrodes were performed in the modes of electric spark and streamer discharges (see Fig. 3, 4). The spectrum of NE LTP radiation in the range of 600–1500 THz is shown in Fig. 5.

Табл. 2. Значения напряженности электрического поля и плотности потока ЭМИ по диапазонам частот

Table 2. Values of electric field strength and electromagnetic radiation flux density by frequency ranges

EMI frequency	Electric field intensity, V/m	Flux density, W/m^2
100 kHz	270	148
200 kHz	149	62
500 kHz	128	45
1 MHz	174	84
10 MHz	192	98
13,56 MHz	158	67
100 MHz	138	60
900 MHz	0,93	0
1,8 GHz	0,7	0
2,4 GHz	0,5	0

Табл. 3. Плотность потока электромагнитного излучения в ультрафиолетовом спектре

Table 3. Electromagnetic radiation flux density in the UV spectrum

UV range	EMI flux density value, mW/m^2
UVA	48
UVB	50
UVC	130

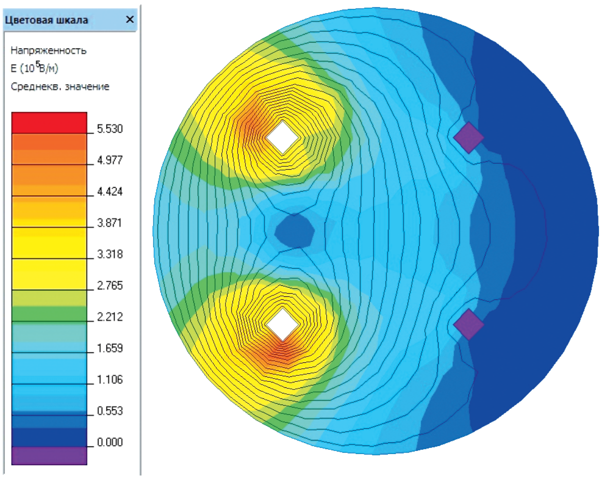

Рис. 2. Распределение напряженности электрического поля в приэлектродном пространстве плазмотрона

Fig. 2. Distribution of electric field strength in the near-electrode space of the plasmatron

The results of microorganism inactivation by electromagnetic radiation and chemically active compounds of NE LTP for various protective surfaces are presented in Table 4, and the results of the effectiveness of microorganism inactivation for streamer and torch discharges are in Table 5.

Based on the research results, the maximum effect when treating open surfaces with low-temperature non-equilibrium plasma was achieved when epoxy resin was used as the protective material. The assessment of the effectiveness of yacht varnish requires additional research.

The results presented in Table 5 allow the conclusion that streamer and torch discharges

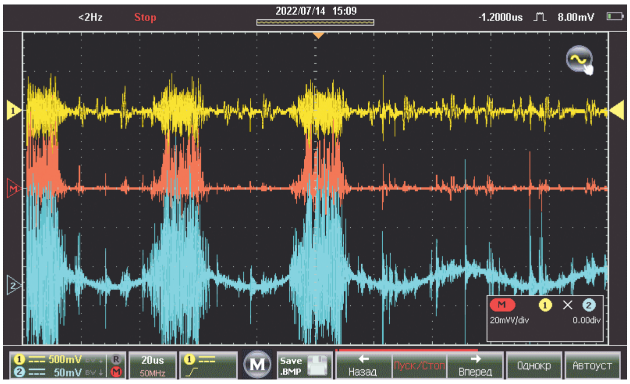

Рис. 3. Осциллограмма факельного разряда (ток, напряжение)

Fig. 3. Oscillogram of the electrospark discharge (current, voltage)

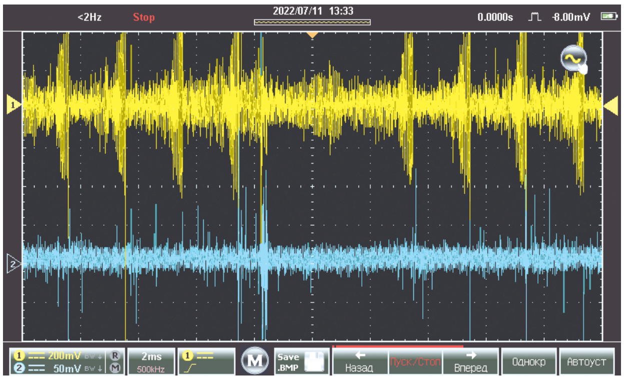

Рис. 4. Осциллограмма стримерного разряда (ток, напряжение)

Fig. 4. Oscillogram of the streamer discharge (current, voltage)

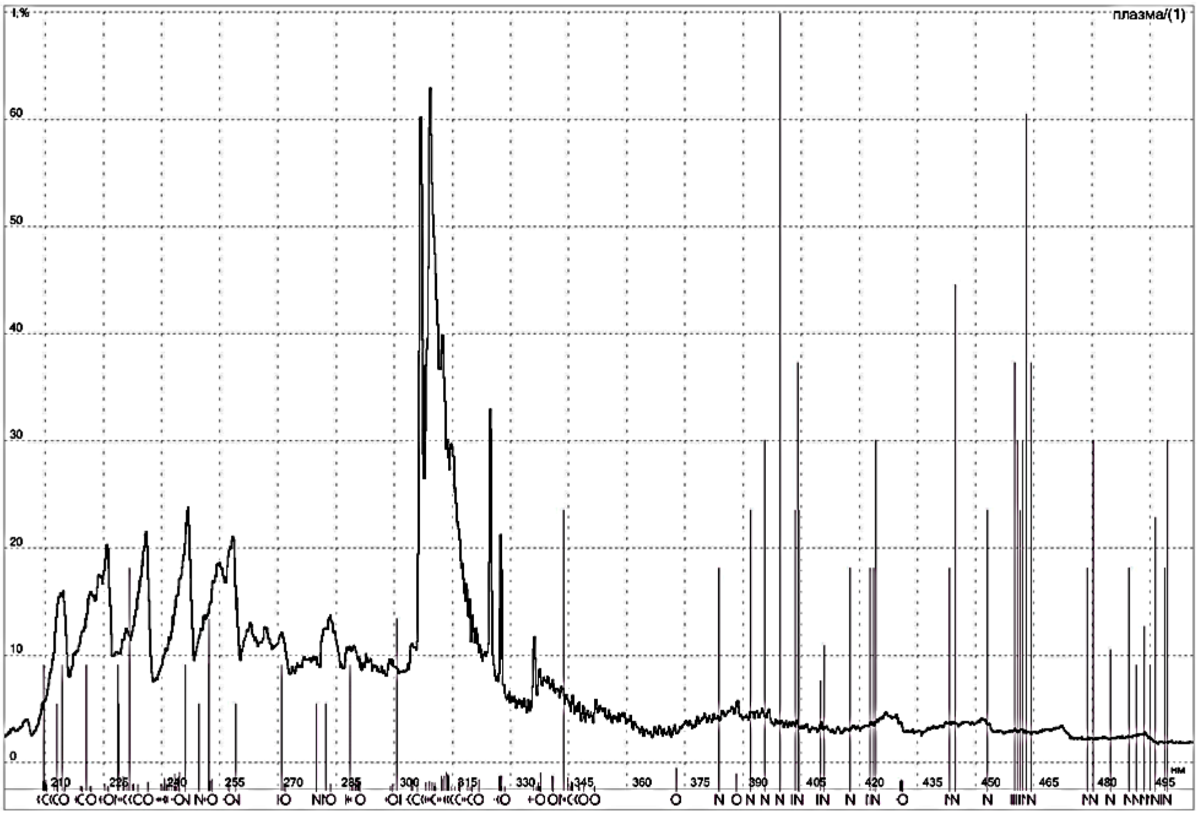

Рис. 5. Спектр излучения ННП в диапазоне 600–1500 ТГц

Fig. 5. Emission spectrum of the LNP in the range of 600–1500 THz

Табл. 4. Оценка инактивации микроорганизмов ННП на различных защитных поверхностях

Table 4. Evaluation of inactivation of LNP microorganisms on various protective surfaces

Sample number, substrate material (primer coat)	Exposure time, s	Number of bacteria, CFU/ml		Bacteria inactivation rate, relative units	Bacteria inactivation, %
		before treatment	after treatment		
Control (uncoated tiles)	Uncoated	1,30E + 06	1,30E + 06	1,00	0,00E + 00
Uncoated tiles	5	1,30E + 06	2,00E + 05	6,50	85
	10		2,00E + 05	6,50	85
Epoxy coating	5	1,30E + 06	3,00E + 05	4,33	77
	10		0,00E + 00	∞	100
Acrylic coating	5	1,30E + 06	2,00E + 05	6,50	85
	10		9,00E + 05	1,44	31
Tiles with flecks of metal	5	1,30E + 06	0,00E + 00	∞	100
	10		0,00E + 00	∞	100

Note. The distance to the plasma flare (L) was 30 mm.

Табл. 5. Результаты инактивации микроорганизмов ННП для различных видов электроискрового разряда

Table 5. Results of inactivation of LNP microorganisms for various types of electric spark discharge

Discharge characteristic	Substrate material	Exposure time, s	Number of bacteria		Bacteria inactivation rate	Bacteria inactivation
			before treatment	after treatment		
			CFU/ml		relative units	%
S	Uncoated	5	8,60E + 05	4,30E + 05	2,00	50,00
S		10		1,00E + 04	86,00	98,84
S		20		3,00E + 04	28,67	96,51
F		5		3,40E + 05	2,53	60,47
F		10		6,00E + 04	14,33	93,02
F		20		1,50E + 05	5,73	82,56
S	Yachting varnish	5	6,10E + 05	1,20E + 05	5,08	80,33
S		10		1,00E + 04	61,00	98,36
S		20		3,30E + 05	1,85	45,90
F		5		0,00E + 00	∞	100,00
F		10		3,60E + 05	1,69	40,98
F		20		6,10E + 05	1,00	0,00
S	Epoxy resin	5	7,10E + 05	2,00E + 04	35,50	97,18
S		10		0,00E + 00	∞	100,00
S		20		0,00E + 00	∞	100,00
F		5		1,00E + 04	71,00	98,59
F		10		0,00E + 00	∞	100,00
F		20		0,00E + 00	∞	100,00
S	Graphite, yacht varnish on top	5	6,60E + 05	1,00E + 05	6,60	84,85
S		10		9,00E + 04	7,33	86,36
S		20		3,00E + 05	2,20	54,55
F		5		7,00E + 04	9,43	89,39
F		10		1,00E + 04	66,00	98,48
F		20		1,70E + 05	3,88	74,24

Note. S - streamer, F - flare.

are approximately equivalent in terms of microorganism inactivation effectiveness on open surfaces.

The number of inactivated microorganisms with an exposure time of 10–60 s and the use of epoxy resin as a protective coating reached 100%.

When inactivating microorganisms on open surfaces, it is not economically advisable to use an exposure duration of more than 20 s.

Free radicals (hydroxyl group, etc.) were recorded in the plasma emission spectrum. The assessment of the impact of free radicals on microorganism inactivation requires further study.

In the future, it is necessary to assess the contribution of each of the damaging factors (electromagnetic radiation in the radio range, ultraviolet radiation, charged particles, ozone) to the degree of inactivation for different groups of microorganisms.

The obtained research results and a literature review of works by other authors [5–9] on this topic allow us to conclude the presence of a synergistic effect of the impact of damaging factors of low-temperature non-equilibrium plasma on the studied microorganisms.

Compared to the traditional method of surface treatment for air disinfection in a room (ozone treatment), the use of a low-temperature plasma generator allows achieving the required inactivation parameters and significantly reducing the exposure duration by simply changing the geometric dimensions of the electric spark chamber.

CONCLUSIONS

1. The maximum effect of treating open surfaces with low-temperature non-equilibrium plasma is achieved when epoxy resin is used as the protective material. The number of inactivated microorganisms with an exposure time of 10–20 s reaches 100%.
2. When inactivating microorganisms on open surfaces, it is not economically advisable to use an exposure duration of more than 20 s.
3. There is no significant difference observed when using streamer or torch discharges for treating open surfaces in rooms. Energy consumption is significantly lower for streamer discharge with comparable technological effects.

In further research on this topic, it is advisable to test the developed plasma torch prototype in production conditions with the presence of real microbial populations and assess the contribution of each of the damaging factors to the degree of inactivation for different groups of microorganisms.

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