DESIGN AND RESEARCH OF COMPOUND DUST COLLECTION AND STERILIZATION DEVICE WITH PHASE-CONTROLLED BUNDLED CONDUCTOR FOR LIVESTOCK AND POULTRY HOUSING SPACE
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畜禽舍空间相控分裂导线复合除尘杀菌装置设计研究

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ABSTRACT
Livestock-scale breeding is the inevitable trend of future livestock and poultry husbandry. Closed breeding requires an excellent environment and livestock and poultry housings contain a lot of dust, pathogenic microorganisms and harmful gases, affecting the health of livestock and poultry and breeding personnel. Most of the common sterilization and dust collection devices for livestock and poultry housings on the market are too high energy consumption, and easy to cause secondary pollution. Therefore, an environmental purification device was designed to absorb dust in the air and kill harmful bacteria by using high-voltage pulsed electric field. The device was designed using phase control principle and bundled conductor. COMSOL Multiphysics was used to simulate the layout of single conductor, twin bundled conductor and quad bundled conductor. It was found that when the conductor was designed as twin bundled conductor or quad bundled conductor, the gradient distribution of spatial electric field intensity was more uniform and the downward trend of the electric field was slower, which could effectively improve the dust collection and sterilization efficiency of the device. At the same time, a variety of electric field environments can be set up by using phase differences to meet different environmental requirements of livestock and poultry. The compound dust collection and sterilization device with phase-controlled bundled conductor for livestock and poultry housing space includes a high voltage pulse generator, bundled conductor, high voltage special timer, insulator and other parts, which can effectively reduce the dust content in the air, the concentration of pathogenic bacteria, harmful gases, etc. after assembly test and can also reduce the humidity in the livestock and poultry housings.

摘要
畜禽规模化养殖是未来畜牧养殖的必然趋势，封闭饲养需要优良的环境，畜禽舍内含有大量灰尘、病原微生物和有害气体，影响畜禽动物和养殖人员健康。市面常见畜禽舍杀菌除尘装置大多能耗过高，且容易造成二次污染，为此，设计一款利用高压脉冲电场吸附空气中灰尘，杀灭有害病菌的环境净化装置，该装置设计利用相位控制原理和分裂导线，由 COMSOL Multiphysics 软件模拟仿真单导线、二分裂导线、四分裂导线三种导线布设，发现导线设计为二分裂或四分裂时，空间电场强度梯度分布更均匀且电场下降趋势更缓慢，可有效提高装置除尘杀菌效率；同时利用相位差可设置多种电场环境，满足不同畜禽环境需求。空间相控分裂导线复合除尘杀菌装置包括高压脉冲发生器、分裂导线、高电压专用定时器、绝缘子等部件，组装后经测试可有效降低空气中灰尘含量、致病菌浓度、有害气体等，亦可降低畜禽舍内湿度。

INTRODUCTION
In recent years, the scale of China's poultry breeding industry has grown steadily year by year, and the overall output of poultry meat has shown an upward trend (*Zhang et al., 2021*), with the development of animal husbandry, large-scale livestock and poultry breeding is an inevitable trend of animal husbandry in the future (*Dai et al., 2021*). As of 2020, the large-scale rate of livestock and poultry breeding in China has reached 67.5% (*Wei et al., 2022*), the pattern of breeding entities has undergone profound changes, large-scale breeding has developed rapidly, the quality and safety of livestock and poultry products have remained at a high level, and major animal diseases have been effectively controlled.

The large-scale and intensive breeding mode puts forward higher requirements for the environmental quality of livestock and poultry houses (*Wang et al., 2018*). In the breeding process, livestock and poultry are often raised in a specific closed space, due to the activities of livestock and poultry, feed, manure, etc. will cause dust, harmful gases, pathogenic microorganisms and other environmental pollutants in the air. The environment in the house is also affected by temperature and humidity (*Huynh et al., 2005*), and in a humid environment, pathogenic microorganisms multiply rapidly, which can easily lead to the disease of livestock and poultry herds and affect the healthy growth of livestock and poultry.

For healthy breeding of livestock and poultry, strict disinfection can reduce the incidence of disease on farms by 80%. Doing a good job of disinfection can bring greater economic benefits to the safe production of farms. The commonly used disinfection methods of livestock and poultry housings at home and abroad mainly adopt physical disinfection and chemical disinfection. The air purification equipment of physical disinfection mainly includes mechanical ventilation equipment, spray dust collection equipment, wet dust collection equipment, ventilation filtration equipment, electric dust collector, ozone sterilization disinfector, ultraviolet lamp, etc. The above equipment can maintain the air quality of livestock and poultry housings to a certain extent, but there are problems such as poor comprehensive control ability, large energy consumption, large land area, and easy to cause secondary pollution, which will affect the health of livestock and poultry.

Based on the demand for environmental control of livestock and poultry housings, this paper proposes a new type of research and design program of space phase-controlled bundled conductor compound dust collection sterilization device for livestock and poultry housings. Using pulsed electric field technology (*Pataro et al., 2015; Bonetta et al., 2014; Sui et al., 2016*) and the phase control principle, a stable spatial electric field is formed in the space of livestock and poultry housing, and the bundled conductors are laid under the spatial electric field to improve the efficiency of sterilization and dust collection, which can not only guarantee the air quality in the housing but also take into account the function of dust collection and humidity reduction.

MATERIALS AND METHODS

Main components of the device

The design of the device is simple in structure, and the main components include a high-voltage pulse generator, bundled conductor, high-voltage special timer, insulators and so on. In the livestock and poultry housing, the output end of the high-voltage pulse generator, whose input end is connected to the mains through the timer, can be set to different phase voltage output. The bundled conductors described in this paper are twin bundled conductors or quad bundled conductors, and when the bundled conductor is connected to the output of the high-voltage pulse generator, it can output different phase DC electricity, and the phase difference can form different difference positions such as 60°, 90°, 180°, etc., which can provide a variety of electric field environments such as positive electric field, negative electric field, compound electric field, etc. The different types of spatial electric fields formed by using phase control to realize different conductor connections can be applied to a variety of environmental scenarios.

Technical Principles

Due to the uneven distribution of the electric field in the livestock and poultry housing, more and more free electrons and ions will be produced in the space (*Wang et al., 2020*). Affected by the electric field force, the ions will have directional movement and collide with dust particles in the air (*Liu et al., 2005*). The charged dust particles will have directional removal movement under the action of high voltage and high-frequency electric field force, while harmful gases such as carbon dioxide and ammonia will condense with dust particles in the house. Part of the charged dust particles migrate to the conductor and eventually deposit on the conductor, while the other part of the charged dust particles deposit on the wall, ground, livestock and poultry surface, equipment and facilities in the house, thus playing the purpose of dust collection. After the periodic action of the electric field, most of the pathogenic microorganisms attached to the dust particles are killed and the air quality in the house is improved. With the circulation of the dust collection and sterilization system, the electric field corona can prevent the outside dust particles from entering the livestock and poultry housing (*Wang et al., 2005*), blocking the transmission channel of the disease air. The high-voltage discharge releases ozone ions at the same time (*Gaëtan et al., 2022*), which can kill bacteria and viruses. The microorganisms in the house can be double eliminated, and the whole livestock and poultry housing environment is in a state of fewer bacteria and cleanliness, reducing the incidence of diseases in the respiratory system of livestock and poultry.

The spatial electric field formed in the livestock and poultry housing also has the function of reducing humidity (*Arif-Uz-Zaman et al., 1996; Zhang et al., 2017*). Its principle is to use the internal interaction between the ion beam and water molecules in the air and the external blowing effect. In this process, the random motion of water molecules becomes a directional movement along the direction of the increase in the intensity of the electric field under the action of electric field forces. Water vapor turns into liquid water (*Xie et al., 2003*) under the action of electric field forces and is attached to the surface of the internal structure of the livestock and poultry housing, such as the wall and the ground, and then the air humidity decreases.

Simulation design of phase-controlled bundled conductor

Simulation design process

COMSOL Multiphysics achieves the simulation of real physical phenomena by solving partial differential equations (single field) or partial differential equations (multi-field) based on the Finite Element Method (FEM), which is widely applied in high voltage electric field simulation (*Zhao et al., 2022; Yu Z., 2022; Pataro et al., 2015*). The COMSOL simulation steps of the compound dust collection and sterilization device with phase-controlled bundled conductor for livestock and poultry housing space include module selection, model housing, boundary constraint adding, grid construction, setting research and solution, data post-processing, etc.

The geometric model network division of livestock and poultry housing space is shown in Figure 1. The calculation results were visualized, and the electric potential distribution on the space section plane of the livestock and poultry housing was obtained as shown in Figure 2. The spatial electric field intensity was larger near the bundled conductor, and the further away from the conductor, the smaller the electric field intensity.

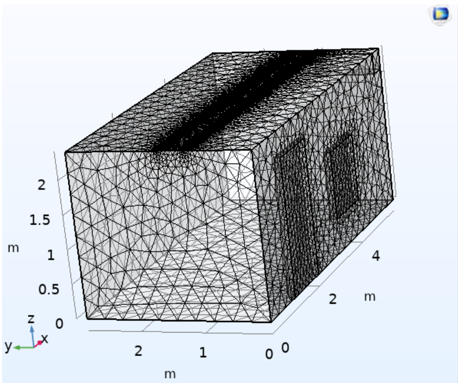


Fig. 1 - The geometric model network division of the livestock and poultry housing

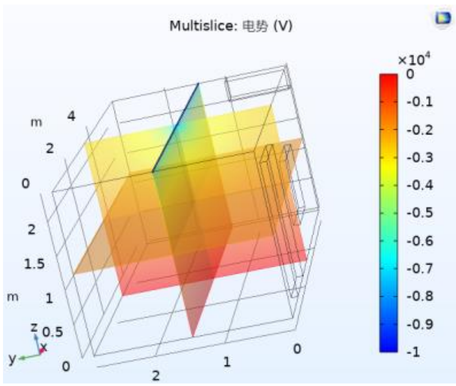
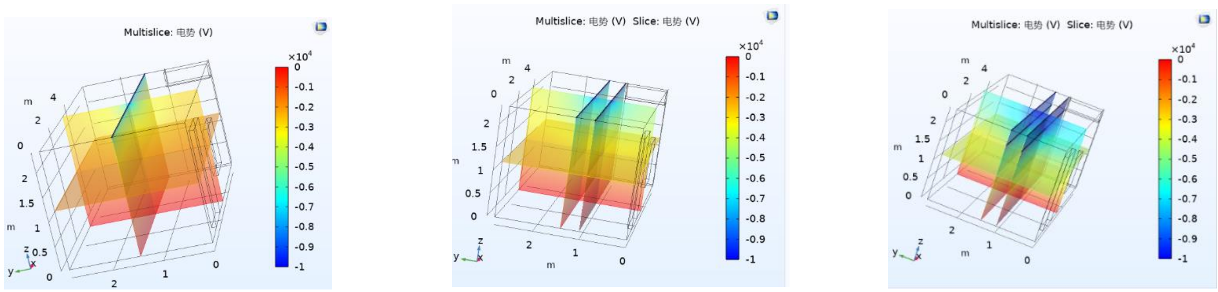


Fig. 2 - The electric potential distribution on the space section plane of the livestock and poultry housing

Simulation study of conductor distribution mode

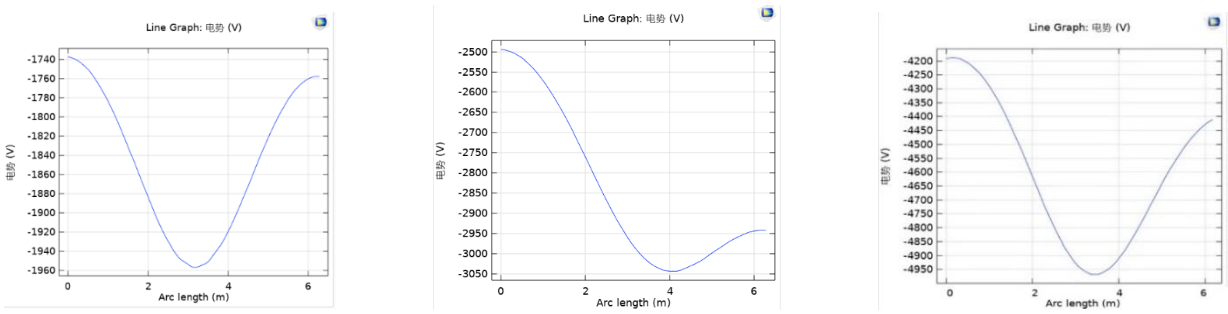
In order to suppress corona discharge and reduce line reactance, UHV transmission lines usually adopt bundled conductor erection. That is, each phase conductor is composed of several small diameter intraphase conductors, which are spaced a certain distance apart and arranged in a symmetrical polygon. The number of bundled conductors of the UHV transmission line is generally 3 ~ 4. Based on the principle of UHV bundled conductor, the conductors of the compound dust collection and sterilization device with phase-controlled bundled conductor for livestock and poultry housing space are set as twin bundled conductors or quad bundled conductors. The spacing of adjacent conductors is 30 cm-50 cm, and it is connected to the output end of the high-voltage pulse generator. The bundled conductors are introduced by using phase control, which can increase the intensity of the electric field around the livestock and poultry housing, thus improving the sterilization and dust collection efficiency of the device.

In order to study the electric field distribution after the device was connected with bundled conductors, this paper used Comsol Multiphysics software for simulation. The spatial electric field intensity is set to -10kV, and the conductor distributions of electric field are set to three different connection modes, including single conductor, twin bundled conductor, and quad bundled conductor. Figure 3 and Figure 4 respectively show the electric field distribution under the three modes of conductor connection in the space of livestock and poultry housings. Under the same electric field intensity and the same section, the electric field gradient distribution and electric field intensity of the quad bundled conductor is better than that of the twin bundled conductor, and the electric field characteristics of the twin bundled conductor are better than that of the single conductor.



(a)Single conductor - 10kV (b) Twin bundled conductor - 10kV (c) Quad bundled conductor- 10kV

Fig. 3 -10kV space electric field sectional potential distribution



(a) Single conductor - 10kV parallel section potential line diagram (b)Twin Bundled Conductor - 10kV parallel section potential line diagram (c)Quad Bundled Conductor- 10kV parallel section potential line diagram

Fig. 4 - 10kV space electric field parallel section potential line diagram

Simulation study of high voltage positive electric field, negative electric field, compound electric field

The high-voltage pulse generator used in the design and research device has adjustable output voltage (0-70kV), pulse width (0-49μs), frequency (0-990Hz), duty ratio and phase of the output end. The parameters that affect the processing effect of high voltage pulsed electric field are mainly divided into two categories: processing working parameters and microorganisms' own characteristics parameters (*Uchida et al., 2008; S.Monfort et al., 2010; Somolinos et al., 2009).* The processing working parameters include electric field intensity, processing time, pulse waveform, pulse width and processing time, etc.

Comsol Multiphysics software was used to simulate the electric field distribution under high voltage pulse positive electric field, negative electric field and compound electric field, and to investigate the sterilization effect of the device under different electric fields. The output voltage of the compound dust collection and sterilization device with phase-controlled bundled conductor for livestock and poultry housing space was set to 35 kV, and in the simulation test, the voltage on the high voltage conductor was set as positive 35 kV, negative 35 kV and compound 35 kV.

Treatment of Escherichia coli by high voltage pulsed electric field

Escherichia coli is a common pathogenic bacterium in livestock and poultry housings, and its killing degree directly determines whether a sterilization method can meet the requirements of industrial production. Therefore, the effective sterilization method of Escherichia coli has always been the focus of research, and the high-voltage pulsed electric field has been proven to play a certain sterilization effect *(Matra et al., 2020; Tanino et al., 2020).* Therefore, in this paper, in the process of using high voltage pulsed electric field to kill Escherichia coli, factors such as electric field intensity and processing time in the sterilization process were analyzed to verify the sterilization effect of the designed spatial electric field on Escherichia coli in livestock and poultry housings.

The Escherichia coli used in the experiment was provided by the College of Life Sciences of Shanxi Agricultural University. The bacterial suspension of the experimental group was placed in a set electric field for treatment, and the results were counted and recorded by plate counting method, and the average value was taken.

RESULTS

Numerical simulation analysis

Comsol Multiphysics software was used to establish the simplified geometric model of the livestock and poultry housing, and the conductor distribution was set as quad bundled conductors with a distance of 40 cm. Firstly, a positive 35 kV pulse voltage was applied to the space of the livestock and poultry housing, the electric field distribution is shown in Figure 5 (a), and the electric field shows a gradient downward trend from the conductor end to the ground end. The electric field intensity near the conductor reaches 3×10^4 V. Figure 5 (b) shows the electro-potential diagram of the section parallel to the conductor. It can be seen from the diagram that the distribution of the spatial electric field is uneven and changes with the radius within the effective processing area, and the electric field intensity meets the sterilization requirements.

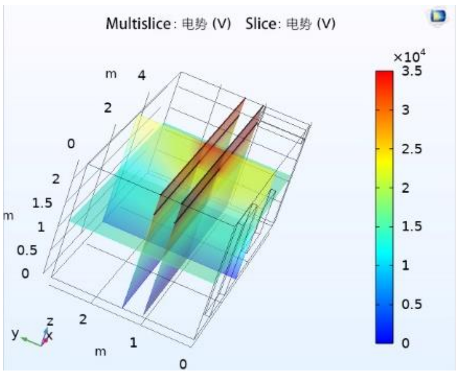


Fig. 5(a)- Quad bundled conductors 35kV positive electric field potential distribution

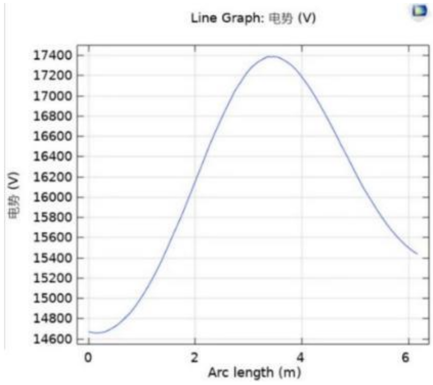


Fig. 5(b)- Quad bundled conductors 35kV positive electric field parallel section potential line diagram

A negative 35 kV pulse voltage is applied to the space of the livestock and poultry housing in the simulation, and its electric field distribution is shown in Figure 6 (a). The electric field shows a gradient downward trend from the conductor end to the ground end, and the electric field intensity near the conductor reaches -3× 10^4V. Figure 6 (b) shows the electro-potential diagram of the section parallel to the conductor. It can be seen from the diagram that the distribution of the spatial electric field is uneven and changes with the radius within the effective processing area, and the intensity of the electric field meets the sterilization requirements.

In the simulation, a compound pulse voltage of 35 kV is applied to the space of livestock and poultry housing, and its electric field distribution is shown in Figure 7 (a). The electric field presents a gradient downward trend from the conductor end to the ground end. The upper conductor is set to positive 35 kV, and the lower conductor is set to negative 35 kV, which corresponds to the phase difference of 180° between the bundled conductors of the physical device, forming a positive and negative compound electric field. Figure 7 (b) shows the electro-potential diagram of the section parallel to the conductor. It can be seen from the diagram that the distribution of spatial electric field intensity is uneven, and compared with electro-potential diagram in Figure 5, and Figure 6, the electric field intensity shown in figure 7 is relatively weaker, but its overall electric field intensity still meets the sterilization requirements.

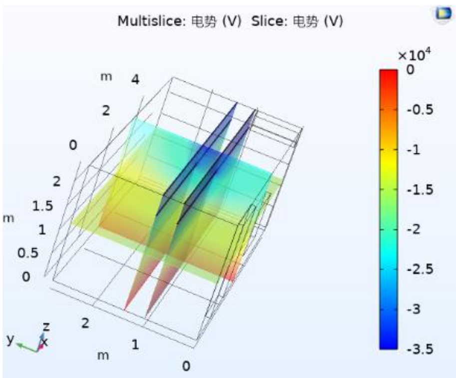


Fig. 6(a)- Quad bundled conductors 35kV negative electric field potential distribution

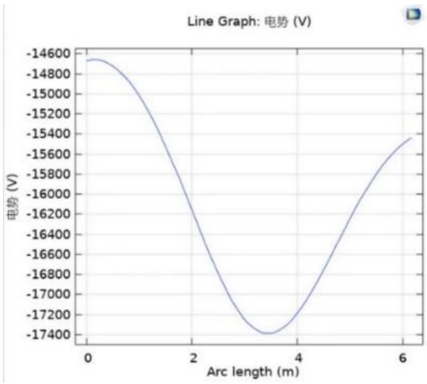


Fig.6(b)- Quad bundled conductors 35kV negative electric field parallel section potential line diagram

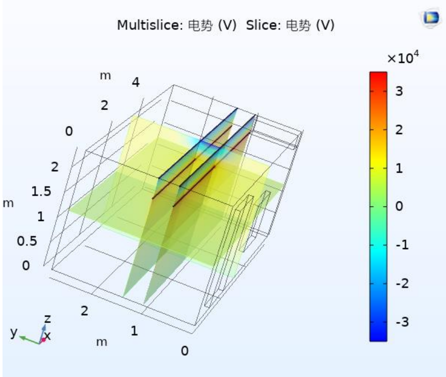


Fig. 7(a)- Quad bundled conductors 35kV composite electric field potential distribution

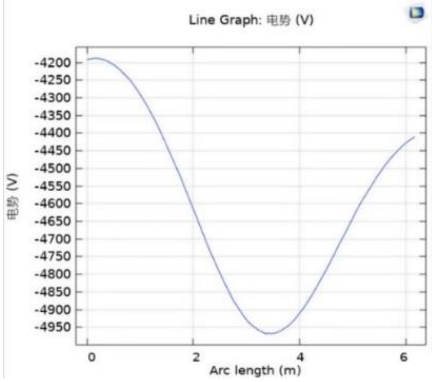


Fig.7(b)- Quad bundled conductors 35kV composite electric field parallel section potential line diagram

The simulation results show that the compound dust collection and sterilization device with phase-controlled bundled conductor for livestock and poultry housing space can meet different scenarios, the conductor connection is set to a twin bundled conductor or quad bundled conductor, the electric field gradient distribution and electric field intensity are optimized, and the sterilization, dust collection and dehumidification efficiency of the device is improved. The high-voltage pulse generator can provide a variety of electric fields at the same time, including positive electric field, negative electric field and compound electric field, and its electric field intensity can meet the sterilization requirements. When the device is activated, different wiring modes are selected according to the air quality in the house. When the concentration of dust particles in the house is high, the phase difference between the bundled conductors of the device can be set to 180°, and the electric field between positive and negative phases can be established with the ground connection point, and the positive and negative charges will be released respectively. Dust particles in the air are respectively charged with positive and negative charges at different levels and after charging, the chances of collision of dust particles increase due to the attraction effect of positive and negative charges and the coagulation effect is enhanced. Under the action of high voltage and high-frequency periodic vibration electric field, dust can be more quickly attached to the conductor or the wall, ground of livestock and poultry housing and the surface of equipment and facilities, and the dust collection efficiency is improved and the air cleaning rate is enhanced.

Analysis of Escherichia coli test results

Relationship between lethality of Escherichia coli and electric field intensity

The test groups were placed under the set positive and negative high voltage pulsed electric field, the test temperature was 20℃, the processing time was 1 h, different electric field voltages of 2 kV, 5 kV and 10 kV were adopted, and the conditions of frequency and duty ratio were set the same. The Escherichia coli bacterial solution was treated, and the origin software was used for analysis. The effects of different voltages on the lethality rate of Escherichia coli are shown in Figure 8. As can be seen from Figure 8, positive and negative high voltage pulsed electric fields have obvious lethal effects on Escherichia coli, and the lethality rate of Escherichia coli increases with the increase of voltage. Under the voltage of 10 kV, the average lethality rates of positive and negative high voltage pulsed electric field against Escherichia coli reach the highest, which are 20.80% and 25.92% respectively. When the voltage is 2 kV, the average lethality rates of positive and negative high voltage pulsed electric field against Escherichia coli are 3.73% and 5.38% respectively. The lethal effect of electric field on Escherichia coli is not obvious. When the voltage is 5 kV, the average lethality rates of positive and negative high voltage pulsed electric field against Escherichia coli are 11.12% and 14.26% respectively, and the lethal effect of the electric field against Escherichia coli is enhanced.

Table 1

Lethality rate of E. coli treated with high-voltage pulsed electric field under different voltage conditions/%

	Voltage /KV	Fatality rate 1	Fatality rate 2	Fatality rate 3	Average fatality rate	Standard deviation
Positive high voltage pulsed electric field	2	3.96	3.78	3.45	3.73	0.258650343
	5	11.53	11.42	10.42	11.12	0.611582646
	10	21.48	20.14	20.79	20.80	0.670099495
Negative high voltage pulsed electric field	2	4.94	5.88	5.33	5.38	0.47226405
	5	14.12	14.62	14.05	14.26	0.313734003
	10	26.78	25.28	25.71	25.92	0.772420438

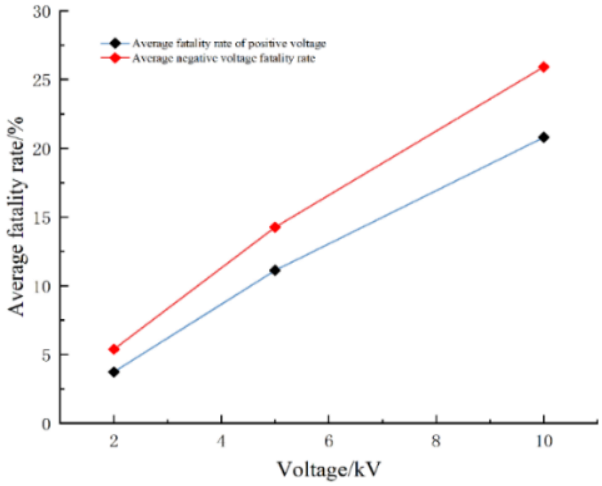


Fig. 8 - Relationship between voltage and average lethality of E. coli

As can be seen from Table 1, with the increase of positive and negative high voltage pulsed electric field voltage, the average lethality rate of Escherichia coli increases, and the standard deviation is all less than 10%, indicating that the test data are stable and the average lethality rate is reliable.

Analyzing the above data results, the intensity of the high voltage pulsed electric field has different effects on the lethality rate of Escherichia coli. When the electric field intensity is low, the lethality rate of Escherichia coli is low, and with the increase of positive and negative electric field intensity, the lethality rate of Escherichia coli increases, and the effect of negative high voltage pulsed electric field on the lethality rate of Escherichia coli is better than that of positive high voltage pulsed electric field.

Relationship between lethality rate of Escherichia coli and processing time

The test groups were placed under the set positive and negative high voltage pulsed electric fields, the test temperature was 20℃, the processing time was 1h, 2h, 3h and 4h, respectively, with different electric field voltages of 2 kV, 5 kV and 10 kV were adopted, and the conditions of frequency and duty ratio were set the same. The Escherichia coli bacterial solution was treated, and the origin software was used for analysis. The effects of different times and voltage on the lethality rate of Escherichia coli are shown in Figure 9 and 10. It can be seen from Figure 9 and Figure 10 that both positive and negative high voltage pulsed electric fields have significant lethal effects on Escherichia coli. As the time of electric field processing increases, the lethality rate of Escherichia coli increases. When the voltage is 2 kV and the processing time is 4 h, the average lethality rates of positive and negative high voltage pulsed electric field against Escherichia coli reach the maximum, which is 40.41% and 42.71% respectively. When the voltage is 5 kV and the processing time is 4 h, the average lethality rates of positive and negative high voltage pulsed electric field against Escherichia coli reach the maximum, which is 54.50% and 58.14% respectively. When the voltage is 10 kV and the processing time is 4 h, the average lethality rate of positive and negative high voltage pulsed electric fields against Escherichia coli reach the maximum, which are 62.36% and 72.14%, respectively.

Table 2

Lethality rate of E. coli treated with high-voltage pulsed electric field under different time and voltage conditions/%

	Time/ h	2 kV Average fatality rate	2 kV Standard deviation	5kV Average fatality rate	5kV Standard deviation	10kV Average fatality rate	10kV Standard deviation
Positive high voltage pulsed electric field	1	9.32	0.7254	16.30	0.4007	27.51	0.4005
	2	20.56	0.7060	28.45	0.8429	37.63	0.5278
	3	29.33	0.4703	44.50	0.4313	57.49	0.4229
	4	40.41	0.8082	54.50	0.4195	62.36	0.5314
Negative high voltage pulsed electric field	1	10.41	0.8549	19.34	0.6635	29.58	0.4541
	2	19.12	1.3807	30.14	0.4767	40.02	2.6006
	3	32.76	0.9404	47.09	0.9660	59.12	1.2971
	4	42.71	0.1323	58.14	0.9061	72.14	1.6783

As can be seen from Table 2, the average lethality rate of Escherichia coli increases with the increase of processing time under the positive and negative high voltage pulsed electric field voltage of 2 kV, 5 kV and 10 kV, and the standard deviation is all less than 2.7, indicating that the test data are stable and the average lethality rate is reliable.

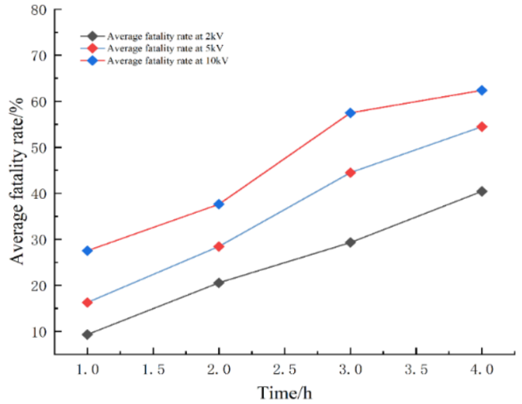


Fig. 9- Relationship between positive high-voltage pulsed electric field time and average lethality of E. coli

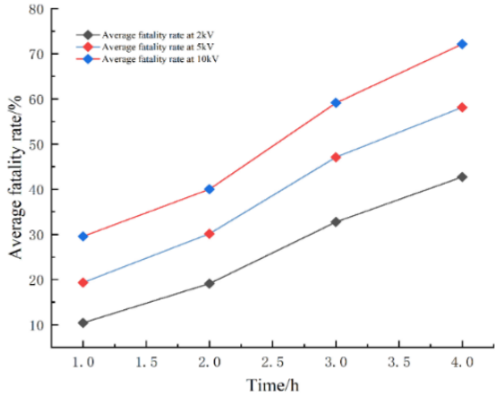


Fig. 10- Relationship between negative high-voltage pulsed electric field time and average lethality of E. coli

Based on the above data results, it is indicated that the processing time of positive and negative high - voltage pulsed electric fields have a very significant influence on Escherichia coli. Escherichia coli has a certain survival rate under the condition of short processing time. Although Escherichia coli can be inactivated after a long processing time, the highly active Escherichia coli can still continue to grow and develop. With the increase of positive and negative high voltage pulsed electric field processing time, the lethality rate of Escherichia coli becomes higher and higher.

The space electric field provided by the device can effectively kill Escherichia coli. The electric field distribution and intensity of the device can meet the actual needs by setting.

CONCLUSIONS

This study focuses on exploring the effect of different electric conductor wiring modes on sterilization and dust collection effect in the electric field of livestock and poultry housing space. It mainly analyzes the electric field distribution of single conductor, twin bundled conductor and quad bundled conductor, and verifies the sterilization effect against Escherichia coli when the electric field intensity is set to 2 kV/cm, 5 kV/cm and 10 kV/cm. From the Comsol simulation results, it can be seen that the electric field gradient distribution and electric field intensity of the quad bundled conductors are better than the twin bundled conductors, and the twin bundled conductors are better than the single conductors. The spatial electric field can be set into a variety of electric field forms, including positive electric field, negative electric field, compound electric field, etc. by the phase regulation of the high voltage pulse generator and the change of the wiring mode of the bundled conductor. The device is designed to be applied to different livestock environmental conditions and meet the daily sterilization and dust collection and dehumidification requirements of livestock and poultry housings. Through this investigation, the wiring mode of the electric conductor of sterilization and dust collection device for the livestock and poultry housing space was optimized and the efficiency of sterilization, dust collection and dehumidification and the stability of the device were enhanced by using the phase control and bundled conductor concept.

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