Wet electrostatic precipitators in food processing plants

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ABSTRACT

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| With the improvement of living standards, people's demand for animal-derived food has surged, leading to the rapid development of the animal feed industry. Its production covers raw material crushing, mixing, granulation, drying and other complex links, resulting in exhaust gas rich in particulate dust, volatile compounds and other pollutants. If untreated direct emissions, not only seriously affect the surrounding air quality, threatening ecology and health, but also make enterprises face harsh environmental regulations and public opinion pressure. Now for the “14th Five-Year” window, environmental regulations are tightening, public awareness of environmental protection, effective control of food processing and feed production plant exhaust emissions is imminent. Vertical cellular wet electrostatic precipitator as a high-efficiency exhaust purification equipment, with a unique structure and principle, in the removal of exhaust particulate matter on the advantages of significant, for the solution of the industry exhaust pollution to bring new opportunities. In-depth investigation and optimization of the performance of this equipment is of great significance in promoting the green and sustainable development of the food processing and feed production industries. Application of electrostatic precipitators in animal feed production. |

*Keywords: electrostatic precipitator, dust removal efficiency, environmental protection, particulate matter*

1. INTRODUCTION

In the past few decades, along with the rapid advancement of industrialization and urbanization, energy use has increased dramatically, and the pollution problem of air has become more and more serious, especially the frequent occurrence of haze weather, which poses a major threat to the health of the population and sustained socio-economic growth. Haze mainly consists of fine particulate matter, sulfide, nitrogen oxides and other pollutants. Today, the state's environmental protection regulation has been strengthened as well as people's environmental protection awareness has been gradually increased, and the importance of air quality is also increasing. Various types of industrial manufacturing, agricultural production and some aspects of daily life will produce many dust and exhaust pollutants. These pollutants will not only damage the atmospheric environment, breaking the ecological balance, but also seriously jeopardize human health, such as triggering respiratory diseases, cardiovascular diseases and so on.

2. research significance

With the improvement of people's living standards, the demand for food of animal origin continues to grow, promoting the rapid development of the animal feed industry. The animal feed production process involves several complex processes, such as raw material crushing, mixing, pelletizing, drying, etc., which generate a large amount of exhaust gas. The exhaust not only contains dust particles but also may contain volatile organic compounds (VOCs), ammonia and other pollutants. If these pollutants are emitted directly into the atmosphere without effective treatment, they will not only have a serious impact on the air quality of the surrounding environment, threatening the ecological balance and human health, but also lead to the production of enterprises facing increasingly stringent environmental regulations and public opinion pressure [14,15].

When dealing with exhaust gases from animal feed production and food processing plants, traditional exhaust gas treatment technologies have a certain degree of inadequacy. Taking the bag filter as an example, as a common dust removal device, its working principle is to intercept the dust particles with the help of filter bags. However, in the treatment of animal feed and food processing plant production tail gas, because the tail gas contains a certain proportion of grease and moisture, which is very easy to cause filter bag clogging, reduce the effect of dust removal, increase the maintenance cost of the equipment. In contrast, the wet electrostatic precipitator, as a highly efficient modern dust removal equipment, works on the principle of ionizing the gas using a high-voltage electric field, which produces ions and electrons that collide with dust particles and become electrically charged, and are subsequently captured by the electrodes under the action of the electric field [16,17]. In addition, the equipment is equipped with a spraying system that enhances the capture of tiny particles by spraying water mist and effectively removes aerosols and some gaseous pollutants from the exhaust gas. The advantage of the wet ESP is its efficient capture of small particles, which effectively removes pollutants such as PM2.5 and PM10 and meets strict environmental standards. Its low operating resistance reduces fan energy consumption and operating costs. Wet processing allows it to be adapted to animal feed production as well as the high humidity exhaust gases emitted from food processing, avoiding equipment malfunction and decreased efficiency [18-20]. Applying wet ESP to feed exhaust gas treatment not only effectively reduces the emission of pollutants such as dust, VOCs and ammonia and improves environmental air quality, but also reduces the concentration of dust in the workshop, providing a healthier and safer working environment for workers. For feed manufacturers, the use of advanced exhaust gas treatment technology can help to improve corporate image, enhance market competitiveness, in line with the sustainable development strategy. At the same time, with the increasingly stringent environmental regulations, the use of high-efficiency exhaust gas treatment equipment is also an inevitable choice for enterprises to fulfill their social responsibility and avoid environmental penalties.

During the period from 2015 to 2025, the global environmental protection situation is grim, countries pay more and more attention to air pollution control, and the wet electrostatic precipitator market size continues to grow. In China's market, for example, with the expanding industrial scale and the strict implementation of environmental protection policies, the wet electrostatic precipitator demand is strong, and the market size continues to expand. The global market size is also rising steadily due to the accelerated industrialization of emerging countries and the improvement of environmental protection standards. In the overall electrostatic precipitator market, the share of wet electrostatic precipitators is gradually increasing by virtue of its efficient dust removal capability and adaptability to complex working conditions. For example, wet electrostatic precipitators accounted for approximately 53% of the global electrostatic precipitator market sales in 2023.

In this context, wet electrostatic precipitator (WESP), as a kind of high-efficiency flue gas purification equipment, has gradually received widespread attention. WESP combines the advantages of wet dust removal and electrostatic dust removal, and through water film cleaning and electrostatic field action, it can effectively remove fine particles, acid mist, heavy metals and other pollutants in the flue gas, and realize the goal of ultra-low emission.

However, the popularization and application of wet electrostatic precipitators also faces some challenges. First, the environmental protection equipment of feed production plants is compactly arranged with limited space, so how to arrange efficient wet ESPs in limited space has become a difficult problem. Secondly, the design, manufacture, operation and maintenance of wet ESP are still immature and need to be continuously studied and optimized. In addition, the performance of wet ESP is affected by many factors, such as the nature of flue gas, operating parameters, structural form, etc. How to maintain efficient and stable dust removal effect in actual operation is also an urgent problem to be solved.

The application of wet ESP to animal feed exhaust treatment can not only effectively reduce the emission of dust particles, volatile organic compounds and ammonia and other pollutants, improve the air quality of the surrounding environment, and protect the ecological balance, but also reduce the concentration of dust in the production plant, creating a healthier and safer working environment for the operators. For animal feed manufacturers, the use of advanced exhaust gas treatment technology helps to improve the social image of enterprises, enhance their market competitiveness, in line with the strategic requirements of sustainable development. Moreover, with the increasingly stringent environmental regulations, actively adopting efficient exhaust gas treatment equipment is also an inevitable choice for enterprises to fulfill their social responsibility and avoid facing penalties due to environmental issues.

Therefore, this study provides an in-depth analysis of wet ESP technology, aiming to explore effective ways to improve the dust removal efficiency of the wet ESP and to solve the problems faced in its practical application by combining numerical simulation and experimental research. This study not only has important academic value but also provides technical support for the flue gas treatment of coal-fired power plants, promotes the in-depth development of China's air pollution prevention and control, and contributes to the realization of the beautiful vision of blue sky, white clouds and fresh air. Meanwhile, with the continuous tightening of environmental protection policies and the improvement of public environmental protection awareness, the wet electrostatic precipitator technology will be more widely used and promoted in the future, becoming one of the important tools for air pollution control.

3. research purpose

Wet Electrostatic Precipitator (WESP), as a highly efficient air purification device, is specially designed to treat dust, acidic droplets and fine particles such as PM2.5 in humid gases and is a high-quality equipment for effectively reducing dust emissions and controlling flue gas pollution. Its advantages are significant, including good dust removal efficiency, low pressure loss, simple operation process, low energy consumption and low maintenance costs, while the design is rich and diverse to meet the needs of different scenarios. At present, the domestic wet ESP combines international advanced technology with localized independent innovation, and in this process, there is still room for improvement in the knowledge of the manufacturing process and installation details of the equipment, so it is inevitable that it encounters challenges in actual operation, and it needs continuous technical improvement and optimization.

As an important construction form of vertical ESP, the core feature of honeycomb WESP lies in the unique honeycomb structure of the dust collection plate design. With its efficient intermittent flushing mechanism, compact layout, and small footprint, the honeycomb WESP has the advantages of high space utilization, low material consumption, and easy installation and maintenance due to its modular design. However, in view of the fact that its application in China is still in its infancy, the key research on its structure optimization and flow field simulation is still insufficient, so the urgency and importance of the current in-depth study.

4. Current status of wet electrostatic precipitator research

4.1 Electrostatic precipitator (ESP) basic structure and classification applications

The basic principle of an electrostatic precipitator (ESP) is to effectively separate dust particles or liquid droplets from dusty gases through the action of electrostatic forces (i.e. Coulomb forces). The working principle of this highly efficient dust removal equipment, also known as an electrostatic precipitator or electro dust collector, is the same core mechanism, although it may vary in structure from one type to another. The electrostatic precipitation process can be broadly divided into several key steps such as corona discharge, gas ionization, particle charging, particle deposition, and ash removal. This technology has significant advantages, such as high dust removal efficiency because the separation force acts directly on the particles; at the same time, the small pressure drop of the gas stream as it passes through the dust collector makes the energy consumption relatively low; in addition, the ESP can handle a large amount of flue gas and has good resistance to high temperatures and corrosion, so it is widely used in a variety of industrial fields. Electrostatic precipitator is mainly composed of the following key parts:

i) High-voltage power supply system: It provides DC high-voltage electricity, which is used to form an uneven electric field inside the dust collector, triggering gas ionization and dust charging.  
ii) Discharge electrode (corona electrode): usually made of metal wire or metal tube, with different shapes, located at one end of the electric field, responsible for generating corona discharge to promote gas ionization.  
iii) Dust collection electrode (dust collection pole): located at the other end of the electric field, used to collect dust particles after charging. Depending on the design, the dust collection electrode can be flat, tubular or other shapes.  
iv) Dust cleaning system: according to the different ways of dust cleaning, electrostatic precipitators can be divided into dry, wet and semi-wet type. Dry type dust collector removes the dust on the dust collecting electrode by mechanical vibration, acoustic wave dust cleaning or airflow back blowing; wet type dust collector utilizes water film or water mist to flush the surface of dust collecting electrode, and then the dust is discharged with the water flow; semi-wet type dust collector combines the features of both dry type and wet type.  
v) Shell and air circuit system: including the shell of the dust collector, inlet and outlet flue, airflow distribution board, etc., which is used to guide the dusty gas into the dust collector and optimize its flow state.

Electrostatic precipitators can be divided into Table 1 according to the application scenarios.

**Table 1. Classification and Application of Electrostatic Precipitators**

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| **Classification** | **Electrostatic precipitator form** | **Characteristics** |
| Divided by cleaning method | Dry Electrostatic Precipitator | Applicable to most industrial occasions, especially in dry environment with stable operation, various ways of dust cleaning and easy maintenance. |
| Wet Electrostatic Precipitator | It has advantages in dealing with high humidity, sticky dust or the need to strictly control the discharge of humidity and can effectively prevent the dust from flying and secondary pollution. |
| Semi-wet electrostatic precipitator | Combining the advantages of dry type and wet type, it is suitable for dust treatment under specific working conditions. |
| According to the direction of gas movement | Vertical Electrostatic Precipitator | The gas flows from bottom to top, which is suitable for applications with limited space or special arrangement. |
| Horizontal Electrostatic Precipitator | The gas moves in the horizontal direction, has compact structure, small footprint, easy to integrate with other equipment. |
| Divided by dust collecting pole type | Tubular Electrostatic Precipitator | The dust collection pole is a round, square or hexagonal tubular structure, suitable for handling dust with a specific shape or particle size distribution. |
| Plate-type electrostatic precipitator | The dust collection pole consists of several flat plates, simple structure, low manufacturing and maintenance costs, widely used in various types of industrial dust removal occasions. |

**4.2 Wet electrostatic precipitators**

The core principle of the wet electrostatic precipitator (WESP), as a highly efficient dust removal technology, lies in the utilization of electric field force to trap particles in dusty gases. In a WESP, a high voltage electric field is applied between the anode and cathode to form a non-uniform electric field. When the dusty flue gas passes through this electric field region, the dust particles in the flue gas are charged by the electric field force and migrate towards the electrodes of opposite polarity due to the electric charge. Different from the traditional dry ESP, WESP adopts water film as the cleaning medium, i.e., a continuous water film is formed on the electrode surface, which effectively avoids the secondary dust problem caused by mechanical vibration cleaning by means of water flushing or water spraying. When the charged particles migrate to the electrode surface covered by the water film, they are captured by the water film and discharged out of the system with the water flow, thus realizing continuous and efficient dust removal effect. In addition, the presence of the water film increases the humidity of the flue gas, reduces the specific resistance of the dust particles, effectively prevents the occurrence of the phenomenon of anti-corona, and improves the capture efficiency of particles, especially for the removal of pollutants such as PM2.5, acid droplets, gypsum, and heavy metal fines, etc., which can satisfy the stringent requirements of the ultra-low emission of the coal-fired units (≤5mg/m³). WESP can work under high flue gas flow rate and has strong adaptability to changes in flue gas composition, and can deal with a variety of pollutants at the same time, which improves the overall purification efficiency[1].

The classification of WESPs is based on their structural layout, which can be divided into two basic categories: horizontal WESPs (see Figure 1) and vertical WESPs (see Figure 2). Further, based on the specific morphology of the collection electrodes, WESPs can be subdivided into plate-type WESPs (this type consists of a series of parallel-arranged flat plates that constitute its main dust-collecting electrode plates), and tube-type WESPs (which are characterized by a metal tube as the core with built-in corona electrodes, while the inner wall of the metal tube serves as the dust-collecting surface). This categorization not only exhaustively describes the structural characteristics of the WESP but also highlights the design versatility and functionality of the WESP.

Vertical WESPs have a unique vertical configuration and multiple bundle design and are mainly designed to handle vertically flowing flue gases. Its dust collection electrodes are mostly circular or polygonal cross-section conductive tubes, and the discharge electrodes are uniformly distributed between the plates. Under the same cross-sectional area, the dust removal efficiency of the vertical WESP is nearly twice that of the horizontal WESP. Riser electrodes are available in a variety of forms, with honeycomb tubes being a good example of space and material saving, although installation and maintenance are relatively difficult. The outer ring tube of the round tube dust collection electrode is like the plate type WESP.

The main features of the riser type WESP are summarized as follows:

i)Electric field strength uniformity: dust collection and corona electrode spacing is uniform, to ensure a balanced distribution of electric field strength.

ii) Space and material saving: vertical design effectively reduces the footprint and material consumption.

iii) Large flow rate processing capacity: In case of large flue gas flow rate, multiple tubes can be connected in parallel to enhance the processing capacity.

iv) Low-resistance and high-efficiency structure: simple design, low operating resistance, low energy consumption and high dust removal efficiency.

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| Fig.1. Horizontal Wet Electrostatic Precipitator | Fig.2. Vertical Wet Electrostatic  Precipitator |

**4.2 Current status of electrostatic precipitator research**

Wet Electrostatic Precipitators (WESPs) have been used in sulfuric acid and metallurgical applications since 1907, and the range of applications has gradually expanded. Several U.S. power plants, such as Bruce Mansfield, AES Deepwater, and Mirant Dickerson, have demonstrated in detailed test reports that WESPs are effective in removing PM2.5 particulate matter, with removal efficiencies generally exceeding 90%, which has resulted in a significant increase in environmentally friendly power production and the need for more stringent emission standards. It significantly improves the level of environmentally friendly power production and meets the needs of more stringent emission standards. The application of this technology not only represents a significant advancement in dust removal technology but also demonstrates the industry's relentless pursuit of air quality improvement.

Nouri's[2] experimental investigation reveals that the average corona current value and its temporal characteristics are closely related to the relative humidity, pointing out that the corona voltage tends to decrease with the increase of ambient humidity.

Bian[3] and others combined experimental observation and numerical simulation to analyze the regulation of negative corona discharge characteristics by gas humidity and pressure and found that high humidity or low pressure can effectively reduce the onset voltage of the negative corona, and the cathode corona voltage is also significantly reduced under this circumstance. In addition, the research results also emphasize the significant advantage of the ion density of the negative corona in the critical region, which is denser compared to the positive corona.

Dey[4]. addressed the pharmaceutical industry where soft nanoparticle (e.g., protein, lipid) suspensions are required for drug delivery and treatment. To be able to collect soft nanoparticles directly into the liquid medium, the efficacy of a wet electrostatic precipitator for the collection of nanoscale particulate matter was explored in depth using Scanning Migration Particle Spectrometry (SMPS) technology. The device was used to separate the ionization zone from the dust collection zone, a circular pole line with a diameter of 1.27 cm was selected, and a flue gas residence time of 0.7 seconds was set. The results of the study showed that for fine particulate matter in the size range of 80 to 600 nm, the measured collection efficiencies were in the range of 70-90%, while for finer particulate matter in the range of 20 to 80 nm, the collection efficiencies were relatively low, with a range of 40-70%.

Al-Hamouz[5] experimentally and numerically evaluated the effect of different geometrical and operational parameters of a single-stage wire-tube ESP on its fly ash collection efficiency, and successfully designed a single-stage wire-tube ESP with a length of 2 m, a height of 1 m, a wire-to-collector plate spacing of 0.2-0.3 m, and an electrode-to-electrode (wire-to-wire) spacing of 0.16-0.21 m. This design is based on the results of an experimental study of a single-stage wire-tube ESP, and the results are presented in the following section. Electrostatic precipitator. The validity of the numerical method was also demonstrated by comparing the computational results with current and previously obtained experimental data.

Hwang[6] proposed a hexagonal collector plate as the anode device, and 42 discharge electrode shapes were selected. Through numerical analysis, the collection efficiency of the ESP was improved by about 20% by optimizing the discharge electrode shapes, and the power consumption and ozone production before and after the optimization were almost the same. It is concluded that by optimizing various discharge electrode shapes, it is beneficial to significantly improve the performance of the ESP while maintaining power consumption and ozone generation, which can improve energy efficiency and reduce the operation cost.

Liu[7] analyzed the emission reduction characteristics and energy consumption of multiple pollutants by collecting 158 WESP datasets. The results showed that WESP could effectively remove PM, PM2.5, SO3, droplets and mercury. It is estimated that the annual CO2 emission from a coal-fired power plant in China using WESPs is 1.68x106t. By using a Tier 2 energy-efficient WESP (7.83t/MW) from GB/T 37484-2019, an annual CO2 emission reduction of 7.33×105t can be realized. if it can be controlled at Tier 1 (5.20 t /MW), it can further reduce 3.18× 105t.

On the other hand, Lin's[8] team at National Chiao Tung University, Taiwan, designed an innovative parallel-plate unipolar wet ESP with a width of 75 mm, an effective settling length of 48 mm, and a gap of 9.0 mm for controlling fine and nano-sized particles without the need for a scraper. The collector plate was made of sandblasted copper plate coated with TiO2 nano powder, and three gold wires were used as discharge electrodes, and the gold wires were periodically purged using a pulse jet valve. Under experimental conditions, when the dust collector was under no initial loading, the flue gas flow rate of aerosol particles was set to 5 l/min, and the discharge electrode voltage reached 4.3 kV, the system demonstrated very high collection efficiencies for particles with particle sizes ranging from 16.8 nm to 615 nm, reaching excellent levels of 96.9% to 99.7%.

Chen's[9] team designed a wet ESP specifically for the treatment of nano to micron-sized particles emitted from semiconductor manufacturing processes. Experimental data show that the removal efficiency of nanoparticles can already reach a high level of 67.9% to 92.9% without the assistance of fine water mist; and when fine water mist is introduced to assist, this efficiency is even more significantly improved and nearly perfect, reaching a range of 99.2% to 99.7%.

Tsinghua University has developed an electrostatic precipitator that can purify difficult-to-treat viscous dust gases, which utilizes a continuously rotatable electrode structure to continuously adjust the position of the electric field, more fully allowing the electrons generated by the electrode device to contact with the dust to achieve a better separation of the dust and gas, and can achieve a processing air volume of 3000 m3/h.

Huang[10] designed a dust removal device using a grooved version of PVC material as the anode device and systematically carried out multi-dimensional experiments on the uniformity of the water film distribution, the discharge performance and the dust collection efficiency. The study reveals that the PVC plate exhibits excellent water film uniformity coverage characteristics under the same water flow conditions for both horizontal and vertical configurations of the groove.

Ye[11] of Tohoku University proposed a low-cost and high-precision research scheme to solve the problem of high experimental cost of wet ESPs and the difficulty of meshing perforated plates in large-scale ESPs in numerical simulations. The relevant resistance parameters are obtained by determining the simplified models of the perforated plate and the dust collection plate, and it is verified by mesoscale experiments that the flow rate and pressure drop in the upper and lower chambers of the electric field are basically comparable, and the velocity distribution at the inlet of the flue is more uniform. Finally, the scheme is verified to be effective and reliable after being applied to engineering practice.

Li[12] and other experimental and numerical methods to study the compound voltage, positive DC-AC and negative DC-AC corona onset voltage and corona onset electric field strength are reduced with the increase of humidity. And it was concluded that the corona under compound voltage is stronger and produces more space charge compared with the corona under single voltage.

Liu[13] of Tsinghua University shortened the particle traveling distance by decreasing the spacing of the polar plates, while increasing the electric field strength to improve the dissimilarity velocity of the particles. In addition, a method to break through the limitation of breakdown voltage on the enhancement of electric field strength by coating the surface of the polar plates with dielectric material has been proposed.

Khairy Elsayed et al. concluded that the exhaust pipe flare type design can reduce the pressure loss and make the air exhaust smoothly at the outlet, which can reduce the energy consumption of the equipment operation by 66% through the experimental comparison of different parameters. With the continuous improvement of environmental protection requirements, the research and application of wet electrostatic precipitator has also been developed rapidly. The application of large wet ESPs in electric power, cement and other industries is gradually popularized, and the technical level is constantly improved. However, the research on small wet ESPs is relatively small and is mainly in the initial stage. Some of the existing research mainly focuses on drawing on the technical principles of large wet ESPs and optimizing the design of the structure and parameters of small equipment, but there are still deficiencies in the miniaturization and portability of the equipment, as well as the flexibility to adapt to different working conditions, which require further in-depth research and practical exploration.

4. Conclusion

Since its first application in 1907, the wet electrostatic precipitator (WESP) has gone through significant development and innovation and is mainly divided into two mainstream forms: riser type and horizontal plate type. The horizontal plate type WESP has been widely used due to its ability to flexibly regulate the electric field strength and structure size, which can effectively adapt to the needs of different air volumes. However, despite dominating the market, horizontal plate WESPs also face challenges such as large footprint and high investment costs. In contrast, the riser-type WESP shows the advantages of uniform electric field distribution, compact footprint, and excellent operating efficiency, but its engineering practice is still limited since it can only handle vertical airflow.

To deepen the performance and efficiency improvement of WESPs, CFD (computational fluid dynamics) simulation is becoming an important tool for performance modeling. Current simulation studies mainly focus on the optimization strategy of WESP flow field, which is achieved by adjusting flue gas properties and introducing rectification devices.

It is worth noting that the design of WESPs is not based on strict theoretical formulas but is highly dependent on the guidance of empirical or semi-empirical formulas. The key parameters in these formulas, such as the effective migration velocity and the air velocity in the electric field, are selected within a preset range of values based on practical experience with specific dust type flue gases. While this design approach ensures that the dust removal efficiency is met, it is often difficult to ensure an optimal configuration of the flue gas flow field. This is particularly complicated by the fact that the water film clearing mechanism in the wet de-dusting process significantly alters the physical properties of the flue gas, such as the specific resistance of the dust, which in turn affects the flow field characteristics. Therefore, it can be inferred that the flow field behavior of the same size dust collector will be very different under mechanical versus aqueous film cleaning conditions.

In view of the lack of research results on the structural design and flow field optimization of WESP, it is important and urgent to explore this issue in depth.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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