A CRITICAL REVIEW OF MODELS USED IN NUMERICAL SIMULATION OF ELECTROSTATIC PRECIPITATORS

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Abstract. The electrostatic precipitators (ESP) have been drawing more and more attention due to their high efficiency and low costs. Numerical simulation is a powerful, economical and flexible tool to design ESP for industry applications. This review summarizes the available numerical models to simulate different physical processes in ESP, including ionized electric field, air flow, particle charging and motion. It has been confirmed that the available models could provide acceptable results and the computing requirements are affordable in industry applications. The coupling between different physical processes can also be considered in simulation. However, there are still some problems not solved, such as selection of a suitable turbulence model in EHD simulation and the coupling criteria. The future study should focus on these issues. This review also includes new types of ESP developed in recent years, such as dielectric barrier discharge (DBD) ESP and corona assisted fibrous filter. These new types of ESP have had high efficiency and low energy consumption. Even though nearly all new ESP types can be modeled using the available numerical models, the most challenging issue is the DBD simulation.

Keywords: particle precipitation, numerical simulation, corona discharge, DBD discharge

KRYTYCZNY PRZEGLĄD MODELI UŻYWANYCH W SYMULACJI NUMERYCZNEJ ELEKTROFILTRÓW

Streszczenie. Elektrofiltry są obiektem nieustającej uwagi ze względu na ich wysoką sprawność i niski koszt. Symulacja numeryczna jest bardzo skutecznym, ekonomicznym i elastycznym narzędziem przy projektowaniu przemysłowych elektrofiltrów. Ten artykuł podsumowuje dostępne modele numeryczne do symulacji różnych procesów fizycznych występujących w elektrofiltrach, włączając zjonizowane pole elektryczne, przepływ powietrza, ładowanie cząstek i ich trajektorie. Zostało potwierdzone, że dostępne modele mogą dostarczyć zadowalających wyników nawet używając sprzętu komputerowego dostępnego w zastosowaniach przemysłowych. Wzajemne sprzężenia między różnymi procesami fizycznymi mogą być analizowane podczas symulacji. Ciągle istnieją jednak problemy nierozwiązane, na przykład wybór odpowiedniego modelu turbulencji przepływu gazu albo kryteriów sprzężeń. Przyszłe badania powinny skoncentrować się na ich rozwiązaniu. Ten przegląd omawia też nowe rodzaje elektrofiltrów zaproponowanych w ostatnich latach, na przykład elektrofiltry oparte na wyładowaniach z barierą dielektryczną albo wspomagane wyładowaniem koronowym filtry włókniste. Te nowe typy elektrofiltrów mają wysoką sprawność i niski pobór energii. Jeśli nawet prawie wszystkie nowe typy elektrofiltrów mogą być modelowane z użyciem istniejących modeli numerycznych, najtrudniejsze jest modelowanie wyładowania z barierą dielektryczną.

Słowa kluczowe: elektrofiltry, wyładowanie koronowe, trajektoria cząstek, symulacja numeryczna

Introduction

In the recent years, serious pollution of ambient atmosphere due to particulate matter (such as PM2.5) has drawn worldwide attention. Exposure to fine, or ultra-fine, particles of biological and non-biological origin in indoor or outdoor environments has seriously negative influence on human health [27]. Public concerns regarding air quality have necessitated the development of efficient and economical particle filtration techniques [9, 38]. The fibrous filters and electrostatic precipitator shave been two typical air cleaning systems [24].

The fibrous filters are made up of fibres, which could capture particles by diffusion, interception or impaction processes. The ESPs are based on the corona discharge and remove charged particles by electrostatic force. The fibrous filters have high pressure drop and should be replaced periodically due to the particle accumulation, resulting in higher operating costs. Differently from the fibrous filters, the pressure loss in ESP can be ignored and it should only be cleaned rather than replaced periodically. Therefore, ESP is more economical. Recently, new types of the advanced ESP with high filtration efficiency, low electric energy consumption and by-product generation were developed [16–18, 24]. Therefore, utilizing of ESP is more and more promising in the future.

Although experimental methods are effective for the ESP development and design, this approach can be very expensive and time consuming. Another approach based on the numerical simulation is a powerful and economical tool to design ESPs with acceptable accuracy. Recently, many researchers utilized the numerical simulation to design ESPs [12–15, 20, 22, 29, 35–37]. The influence of different design parameters on the ESP performance was investigated in detail. The numerical models usually consist of three parts: the ionized electric field model, the air flow model and particle charging and motion model. These physical processes can be simulated using commercial software or in-house codes [22, 61–65]. Recently, the numerical models have

been significantly improved and some of the simulated results agreed well with the experimental data.

The models considered in literature dealt many types of ESP. However, there are still some important issues not completely solved. For example, a suitable choice of the turbulence model to simulate the electrohydrodynamic (EHD) flow is still uncertain due to the absence of reliable experimental velocity and turbulence data. Another essential issue is a complex coupling of three major physical processes in ESP. The corona discharge, EHD flow and particle motion can interact with each other. For example, the air flow could affect the ionized electric field, then the electric field would influence the particle charging and motion. The high particle concentration can simultaneously influence the ionized electric field, air flow field and particle behaviour. If all the couplings are considered, the computing time and effort would be considerable and unacceptable. If only the air drag force and electric field force acting on charged particles are considered, the simulation error may be large in some cases. Therefore, the trade-off between the computing effort and accuracy should be considered.

In recent years, many new types of high efficiency ESP were developed with low by-product generation, such as two stage ESP [24], wire attached on dielectric plate to conductive plate ESP [28], the DBD ESP [11, 65] and hybrid ESP combining the fibrous filter and ESP [16, 17]. However, most of the numerical models described above focused on the traditional wire to plate ESP. The model enhancement is essential for the new ESP types.

This review paper firstly summarizes the numerical models used to simulate the ionized electric field, EHD flow, particle charging and motion in ESP. Some simulation results and model validation data are also included. The important conclusions from numerical simulation are presented and the deficiencies of the available models are also discussed. Moreover, the newly developed ESP types are also reviewed, and the application of the existing models for numerical simulation of new ESPs are summarized. In order to simulate these newly developed ESP

more accurately, available model modification and new model development are necessary in future studies.

1. The design of different ESP types

Different ESP designs have some common elements: discharge and collection electrodes. The intensive electric field and space ionic charge is formed between both electrodes. In recent years, many new types of electrostatic precipitators have been developed to overcome shortcomings of traditional ESPs. The experimental, numerical and theoretical investigations of these new ESPs have been conducted. Figure 1 shows different types of ESP investigated in literature. Figure 1(a) is a traditional wire-to-plate ESP with wires placed on the center plane of the channel [12, 13, 23]. The direction of wires is perpendicular to the inlet air flow. One wire or multiple wires could be adopted. Figure 1(b) shows the dielectric barrier discharge ESP. Dielectric plates are attached to the surface of conductive collection plates. Differently from the traditional ESP, the alternating voltage is applied to the discharge wires. The DBD-ESP can simultaneously remove the particles and gaseous pollutant (such as NO_X) [11].

Figure 1(c) shows the hybrid electrostatic filtration system (HEFS) with fibrous filter medium installed downstream of a wire to plate ESP [17, 36]. The particles escaping from ESP are highly charged. Releasing the charged particles from the ESP is a waste of electric energy. The fibrous filter has a higher efficiency for the charged particles than neutral particles because the electrostatic force between the fiber and the charged particles could enhance the filtration efficiency without adding the pressure drop of filter. A low efficiency filter placed downstream of ESP could remove most of the charged particles due to the electrostatic forces. Figure 1(d) shows another hybrid electrostatic filtration system, which combines filter medium and corona discharge. The pin to filter to collection mesh system was used. The filter is attached to a conductive metal grid, which is grounded. Due to the corona discharge, the intensive electric field exists across the filter thickness and the particles could be highly charged in the space between the pin and the filter. The electrostatic force acting on charged particles results in high filter efficiency without adding the pressure drop [16, 53, 54].

Figure 1(e) shows a wet ESP [6]. A tank generating water mist is installed upstream of ESP. Fine water mist at room temperature is used for quenching the high temperature exhaust gas in order to enhance particle condensation growth and improve the collection efficiency of nanoparticles. Experimental results showed that without fine water mist, nanoparticle collection efficiency was 67.9–92.9%, which was greatly enhanced to 99.2–99.7% when the ESP was operated with the fine water mist. For nano-, submicron- and micron-sized particles the efficiency could be higher than 90%. The disadvantage of the wet ESP is that it could increase the humidity of air and would not be suitable for indoor applications. Figure 1(f) shows another type of wet ESP [63]. The free falling liquid droplets are generated in the vicinity and downstream of the discharge wires. The charged particles could be captured by the opposite charged droplets. This physical process is also called the water scrubbing. The efficiency could also be improved by the liquid droplet emission. Similarly to the wet ESP described in Figure 1(e), the air humidity can increase in the precipitation process. Figure 1(g) is the well known as the two stage ESP [24, 52]. The first stage is the particle charging zone. Particles are highly charged before entering the precipitation zone. In the second stage, where a strong electric field is generated between plates, the particles are precipitated. Actually, in the particle charging zone some particles could also be removed.

All these types of ESP were studied experimentally. For the traditional wire-to-plate ESP (Figure 1(a)) and two-stage ESP (Figure 1(g)), the available numerical model could be directly used to simulate their performance [12, 13]. For the hybrid electrostatic filtration system, combining corona discharge and fibrous filter (Figures 1(c) and (d)), the ionized electric field, EHD flow and particle behavior out of filter medium could be simulated easily.
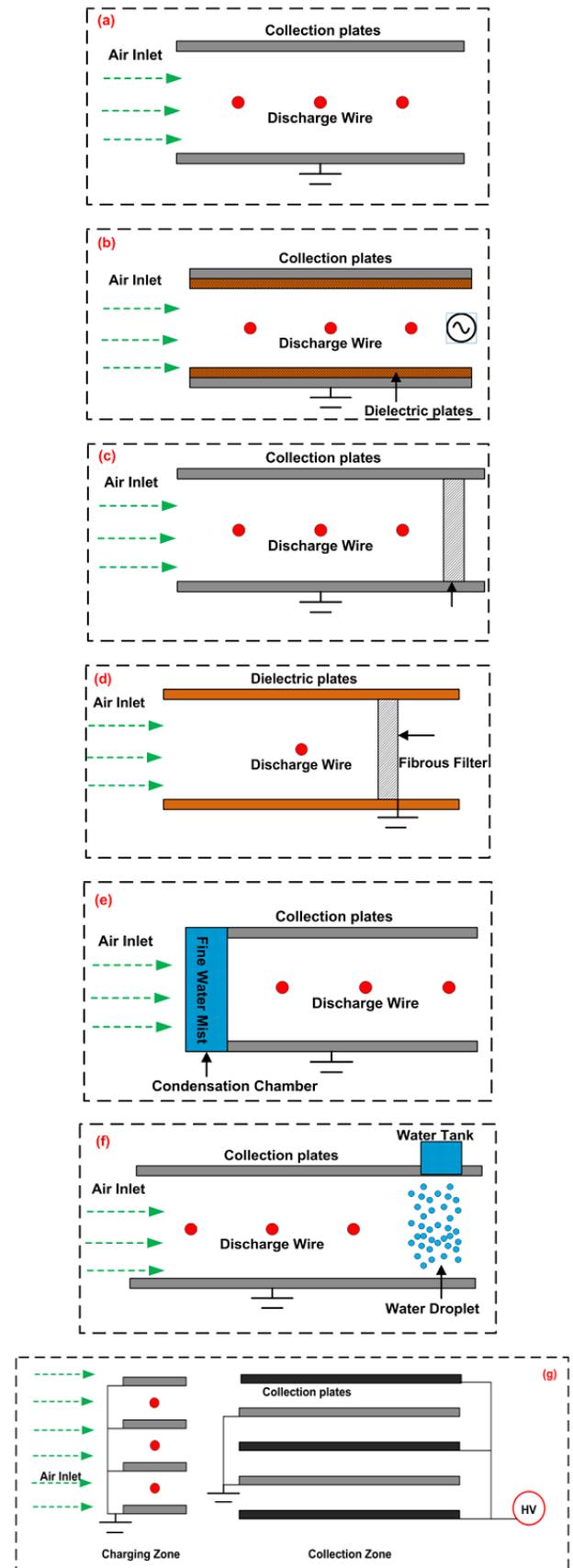

Fig. 1. Different types of electrostatic precipitators

The most challenging part is simulation of the electric field and the particle removal in the charged fibrous filter. Some recent studies presented a simplified mathematical model to simulate filter efficiency in HEFS [16, 17]. For the wet ESP shown in Figure 1(e), the particle condensation process is too difficult to be accurately modeled. The suitable particle coagulation model should be developed in future research. For the ESP described in

Figure 1(f), Jaworek et al. simulated the charged particle removal process by the liquid droplet [21]. Good agreement between the modeled and measured efficiency was observed.

Differently from the direct-current ESP simulation described above, the physical process in DBD-ESP is much more complex due to the alternating current excitation. Zouaghi et al. developed a simplified numerical model to simulate the particle efficiency in DBD-ESP [65]. This model included a lot of simplifying assumptions, such as ignoring the transient particle charging and using saturation particle charge. Some essential coefficients were fitted from the experimental data. Quasi-stationary numerical model of the dielectric barrier discharge was developed [19]. This model accurately simulated transient dielectric barrier discharge, including electric field, space ion concentration and charge accumulation on dielectric surface. However, the model was time and effort consuming because the time step needs to be very small (in ms or μs). It could be concluded that modeling the unsteady EHD flow field, particle charging and motion in DBD-ESP is also time consuming and very complex.
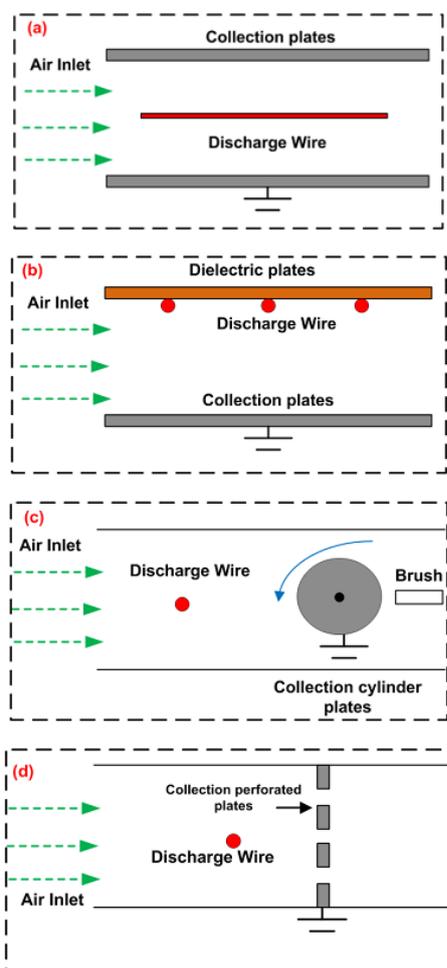

Fig. 2. Different types of DC-ESP with various discharge and collection electrodes

Figure 2 compares four types of the DC-ESP with different discharge and collection electrodes. Figure 1(a) shows the wire to plate ESP. The wire is a discharge electrode and the plates serve as the collection electrodes. In order to improve the performance of the DC-ESP with two electrodes, the geometry and position of two electrodes were modified by many researches, as shown in Figure 2. Figure 2(a) presents the wire to plate ESP, but differently from the traditional version (Figure 1(a)), the wire direction is parallel to air flow. For such ESP type, the EHD flow pattern and filtration efficiency were investigated experimentally in [41, 42]. The PIV was used to measure the air flow field. However, there was no comparison between the two types of ESP for the efficiency, EHD flow pattern and electric energy

consumption. Moreover, there was no study focusing on the particle efficiency modeling.

Figure 2(b) shows another ESP with discharge wires attached to the dielectric plates. The air flow and particles could damage the wires placed in channel. If the wire is attached to a dielectric plate, it could be better protected. Li et al. conducted experimental and numerical study to compare the performance of this new type and the traditional one [29]. The new ESP type could have higher particle efficiency for small particles (0.01−1 μm), lower discharge current and ozone generation. Good agreement between the simulated and measured efficiency has been obtained. Figure 2(c) shows a type of ESP, which used a conductive cylinder as the collection electrode. The cylinder can rotate in precipitation process and the dust layer deposited on cylinder surface is uniform resulting in avoiding serious back corona discharge and efficiency decrease. The stationary brush could be placed closed to the cylinder and remove the dust layer [22]. This study also conducted numerical simulation for the wire-to-cylinder ESP and used the experimental data to validate the model.

Figure 2(d) shows a new type of ESP using a perforated plate as collection electrode [51], mounted perpendicularly to the air flow direction. The perforated plate could capture some particles even uncharged. Obviously, the corona discharge can improve the efficiency due to the Coulomb force acting on charged particles. The previous study investigated the filtration efficiency, particle layer distribution and electric energy experimentally [51]. However, there was no comparison between the wire-to-perforated plate ESP and the traditional type. Long and Yao modeled the wire to perforated plate ESP and provided some informative results, but the numerical results were not compared with the experimental data from literature [36].

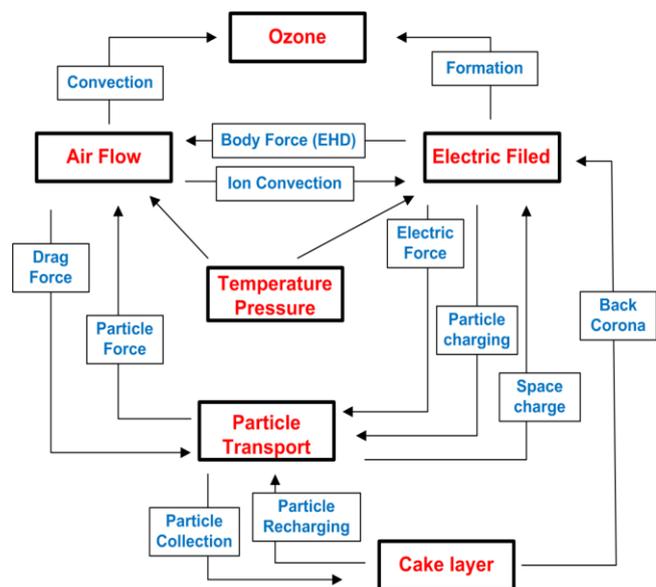## 2. The review of numerical model for ESP

Fig. 3. The physical phenomena and their mutual couplings in ESP

In any ESP, there are four basic physical phenomena: gas flow, ionized electric field, particle motion and ozone generation, as shown in Figure 3. Adamiak comprehensively reviewed the numerical study of ESP, but the ozone generation was not included [3]. The ozone generation in ESP is a very important factor for indoor environment application because this gas and its reactions with other chemical species have significant influence on human health. This Section summarizes the methods of ESP simulation, including the mathematical models, numerical techniques and the boundary conditions. All of the phenomena are mutually coupled, but some couplings are very weak and could be ignored. The simplest approach assumes that nearly all the couplings are neglected, except for the Coulomb force and air drag force acting on charged particles. This assumption can bring some

errors in the electric field, ion concentration, air flow pattern, ozone generation and particle removal efficiency calculations. If the couplings are not considered, the variables with superscript 'c' will be zero in the equations (1–5).

2.1. Simulation of air flow

The EHD flows are governed by the well-known Navier-Stokes equation (1).

$$\rho(\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U}) = -\nabla p + \mu \nabla^2 \vec{U} + \vec{E}^c q^c \qquad (1)$$

where ρ is the air density (kg/m^3), t is the time (s), U is the air velocity (m/s), p is the pressure (Pa), μ is the air viscosity (Pa×s), E is the electric field intensity (V/m), q is the space charge density (C/m^3). In these equations, the variables with superscript 'c' should be used in the simulation including different physical processes couplings. If these couplings are not considered, these variables will be zero.

The EHD can generate many vortices upstream or downstream of the discharge wire. Moreover, it also increases the turbulence intensity. It is commonly assumed that the EHD flow in most of ESP cases is turbulent rather the laminar. If the inlet velocity is high enough, the flow in ESP is always turbulent. If the inlet velocity is very low, the flow in ESP without the corona discharge can be laminar. Once the applied voltage is turned on, the air flow in ESP becomes complex and changes from laminar to turbulent. The EHD could be modelled using DNS (direct numerical simulation) or a turbulence model. The DNS is not used widely in ESP due to considerable time consumption. Each turbulence model has its own application range: such as high turbulent flow, low turbulent flow or the transient flow. Therefore, the choice of the turbulence model would influence the EHD simulation results [56, 59]. Many papers utilized different turbulence models to simulate the EHD in ESP: standard k-ε model [7, 8, 64], RNG k-ε model [36, 43], Reynolds stress model [46]. The laminar model was also used in EHD modelling [25]. However, it is uncertain whether these models could provide the accurate results and their application ranges were unknown based on the available measured velocity results. The model assessment is necessary in the future.

2.2. Simulation of ionized electric field

Corona discharge is the most important physical phenomenon in ESP because it provides the space charge and electric field needed for charging the particles. In the corona discharge process, the ionization layer exists near the discharge cathode and it includes negative or positive ions and the electrons. Some studies tried to utilize numerical methods to model the complex physics of the corona discharge with ionization layer [10, 39]. In these models, the computing domain was very small compared to the practical ESP [12–15]. The modeling of ionization layer was also time-consuming. There were still some discrepancies between the simulated and measured results (such as the magnitude of current density or Trichel pulse frequency). For almost all ESP simulation studies, the ionization layer was neglected and steady-state ionic flow of just one species was considered, because the ionization layer is very thin [3]. This simple model can be used without any substantial changes in cases with different voltage polarities. The equations (2–3) could be used to simulate the ionized electric field in ESP based on the single ionic species assumption.

$$\nabla^2 V = -\frac{q + q_p^c}{\varepsilon_0} \qquad (2)$$

$$\nabla((k_i \vec{E} + \vec{U}^c)q_i + (k_p^c \vec{E}^c + \vec{U}^c)q_p^c) = 0 \qquad (3)$$

where V is the electric potential (V), ε_0 is the air permittivity (F/m), q_p is the space charge density of particles (C/m^3), k_i is the ion mobility (m^2/Vs) and k_p is the particle mobility (m^2/Vs).

Many numerical techniques were used to solve these two equations. The oldest one was the Finite Difference Method (FDM) [30]. However, FDM should work with a structured mesh

(such as 2D rectangular mesh). This disadvantage limits the use of FDM for ESP with complex geometries. The Finite Volume Method (FVM) and Finite Element Method (FEM) were much more popular in recent years because they allowed structured or non-structured meshes. In the ESP simulation, the most challenging part is solving the charge transport equation, as described by equation (3). A very small ion diffusion coefficient leads to the artificial numerical diffusion. Adamiak developed a hybrid BEM (Boundary Element Method) and MOC (Method of Characteristics) technique [4]. The advantage of MOC is that it does not introduce the numerical diffusion. However, the hybrid method needs more memory and usually leads to more complex codes, because the electric field and space ionic charge simulations need two different meshes. The BEM-MOC technique is also very difficult in 3-D cases. In order to avoid these problems, the Flux Corrected Transport (FCT) was developed to simulate the complex 3-D ESP [12–15]. Some studies utilized FEM directly to model the electric field and space charge distribution [22]. The FVM was also used in some studies [36, 40].

All of these numerical methods (BEM-MOC, FCT-FEM, FEM, FVM) can be implemented in commercial software (such as ANSYS-FLUENT, OpenFOAM, COMSOL). The COMSOL algorithm is based on FEM and different modules in this software could be used directly to model the ionized electric field without any external programming. The algorithms in ANSYS-FLUENT or OpenFoam are based on FVM. A usercan link his own code with these software packages [36, 40]. In ANSYS-FLUENT, the BEM-MOC and FCT-FEM can be attached using a concept of Used Defined Function (UDF). All other parameters (the air velocity, turbulence and temperature) can be modeled by FLUENT directly [12, 20].

Formulating the boundary conditions is another challenge in simulating ionized electric field. For the electric potential, the value on discharge cathode is equal to the applied voltage and the value on collection plate is zero. The boundary condition for the space charge density on cathode is more difficult to be formulated. The easiest and simplest method is to use the experimental voltage-current characteristics [36]. However, this method would not work, if the measured data are not available. The most popular method, which doesn't require experimental information, is based on the so-called Kaptzov's hypothesis. The electric field value on surface of discharge electrode can be assumed constant at a value calculated from an experimental Peek's formula. However, this formula exists only for the cases with relative simple cathode geometry (such as sphere or cylinder). For more complex geometries (such as a spiked electrode), the approach is strictly speaking not valid.

2.3. Simulation of particle charging, motion and removal

The Eulerian and Lagrangian models were two popular methods for the simulation of particle motion in ESP. Equations (4–5) describe both of them. The Eulerian method regards the particle phase as a continuum and solves an additional species transport equation [5, 58]. The Lagrangian method calculates the particle trajectories from the Newton second law of motion. Although both of the models could give reasonable results, the choice of a suitable method should be based on the characteristics of the problem (particle size, unsteady or steady state). Chen and Zhao studied the particle motion in a narrow channel [60]. The results indicated that both Eulerian and Lagrangian models could provide accurate results for 0.4–1.0 μm particles. The Lagrangian model was not very accurate for particles smaller than 0.1 μm as it was not able to correctly represent the effect of the Brownian diffusion. Accurate modeling of the Brownian diffusion is critical and challenging for the Lagrangian model.

$$\frac{d\vec{U}_p}{dt} = F_D(\vec{U} - \vec{U}_p) + \vec{g}\frac{(\rho_p - \rho)}{\rho_p} + \vec{E}q_p \qquad (4)$$

$$\frac{\partial C}{\partial t} + (C \cdot \nabla)\vec{U} + \nabla(\vec{E}kC) = D\nabla^2 C \qquad (5)$$

where ρ_p is the particle density (kg/m³), k is the effective mobility (m²/Vs), U_p is the particle velocity (m/s), F_D is the inverse of relaxation time (1/s), g is the gravity of acceleration (m/s2). C is the particle concentration for a certain particle diameter. D is the particle diffusion coefficient, which is the sum of Brownian diffusion coefficient and turbulent diffusion coefficient.

For the particle removal in the Lagrangian model, almost all published studies assumed that the particles were captured once the particle trajectory and collection plate surface intersected. The particle collision and rebound were ignored. For the Eulerian model, the particle concentration on collection plate surface was regarded as zero. The particle flux from polluted air to collection plate can be obtained from solving the species transport equation. Due to the local turbulence flow or back corona effect, the deposited particles could re-entered into the air flow. Zhang et al. developed a new method to model the particle capture in wire-to-plate ESP [57] Based on the comparison between the surface energy and the kinetic energy of the charged particle, it is determined whether the charged particle adheres to or rebounds off the collecting plate.

Particles in ESP are captured by electrostatic forces. Therefore, the particle charge is an essential parameter determining the precipitation efficiency. Accurate prediction of particle charge is of fundamental importance in ESP efficiency modelling. The particle charging mechanisms includes the field charging by ion bombardment and charging by ion diffusion. Long and Yao summarized nine particle charging models, and used measured data (such as particle charge amount, particle traverse velocity and precipitation efficiency in ESP) from literature to test the performance of different particle charging models [35]. The computing time was also compared. They found that it was difficult to select the optimum model because the model performance was case dependent. Each model had its own advantages or disadvantages. However, these particle charging models are widely used in ESP simulation [6, 26]. Lin and Tsai found that these models described above could predict the ESP efficiency for particles larger than 100 nm [31]. However, they failed for ultrafine particles (< 100 nm). If the particle size is very small, the partial charging effect can occur. A fraction of small particles remain uncharged and penetrates through the ESPs, resulting in the increased penetration ratio when the particle diameter increases from 5 nm to 30 nm. Therefore, this study tested other particle charging models based on the measured ESP efficiency for ultrafine particles [18, 39]. For the particles with 30 < dp < 100 nm, the Fuchs charging model can provide relative accurate ESP collection efficiency results [18]. For the particle smaller than 20 nm, the charging model from Marlow and Brock can model ESP efficiency more accurately [39].

If the particle charging models for ultrafine particles were used, only the Eulerian model could be adopted to model particle motion, because these models regards the particles as a continuum [18, 39]. For other models, only the Lagrangian model could be used, because in these particle charging models the particle charge accumulates along the particle trajectory [35]. The Eulerian model is not able to predict the trajectory for certain particles. In a summary, the choice of particle charging and motion models is related to the particle size captured by ESP.

2.4. The coupling between different physical processes in ESP

The most important is the coupling between ionized electric field and air flow. The electric field and space charge generate electrostatic body force and modify the air flow, which is the so-called electrohydrodynamic flow. In equation (1), the E_q term is the electric field body force which affects the air flow field. On the other side, the external air flow and EHD can influence the ion motion in corona discharge zone [61]. The drag force between the air and the ions can modify the space current density, as described

by equation (3). The U_q term in equation (3) represents the ion convection flux. If the coupling between air flow and ionized electric field is not considered, the results of air flow and corona discharge will be different. The results of particle motion and removal efficiency will also be affected by the coupling between corona discharge and air flow field.

The second coupling occurs between the ionized electric field and particles. The corona discharge charges the particles and the electric field force acting on charged particle drags them onto the collection plates. The reverse coupling also takes place: the particles affect the ionized electric field. Increasing the particle concentration modifies the total space charge due to the charged particle, as described by equation (2). The voltage-current relationship will also be affected by increasing particle concentration. Once the ionized electric field varies, the air flow and the particle removal efficiency would also be changed. Therefore, the particle concentration can influence all the physical processes in ESP.

The third coupling occurs between air flow and particle motion. The air drag force acting on particles makes them follow the gas streamlines. The reverse coupling is the effect of particle phase on gas phase. If the particle concentration is high enough, this effect could not be ignored. However, the available numerical studies focusing on high particle concentration in ESP did not include the direct influence of particle concentration on air phase [55]. In the numerical simulation, coupling between different physical processes will consume much more time and effort. Therefore, it is necessary to investigate the influence of different couplings on simulation results and determine the conditions when some coupling should be included.

3. The numerical results of ESP simulation

3.1. The results of ionized electric field

Based on the numerical models described above, the electric potential and space charge density can be calculated. Adamiak simulated the two dimensional ionized electric field in a wire-to-plate system using the MOC-BEM method [4]. The simulated electric potential and voltage-current relationship agreed well with the measured data from literature. Adamiak and Atten simulated the ionized electric field in a point to plate system using the FEM-MOC-BEM method [2]. The simulated voltage-current relationship was also validated by the experimental data. In addition, the numerically computed current density distribution along the collection plate agreed with the experimental data and Warburg formula prediction.

For the three-dimensional wire-to-plate system, Farnoosh et al. simulated the electric potential and space charge concentration. The results indicated that the electric field intensity and space charge distribution were very high in the area near the discharge wire [12]. Farnoosh et al. simulated three dimensional ionized electric field in a spike-to-plate system using the FCT-FEM method [15]. The two assumptions for the boundary space charge density on the discharge spike were used: uniform or non-uniform. The latter was close to a realistic physical behavior, but it needed more computing effort. The simulated results indicated that the ion distribution near the spike tip was different for the cases with uniform or non-uniform boundary distributions. In the zone far away from the spike, the difference in ion distribution for both cases could be ignored. The number of particles entering the zone very close to the spike tip was limited, so that the particle collection efficiency could not be influenced significantly by different boundary charge assumptions.

Zhao and Adamiak simulated the ionized electric field in pin-to-plate system [62]. The electric potential, space charge density and volume Coulomb force decreased from the pin tip to the collection plate. The numerically predicted voltage-current relationship was also compared with the measured data and good agreement existed. Long et al. simulated the ionized electric field in a 2D wire-to-plate ESP system [34]. The calculated distribution

of electric potential and current density along the collection plate agreed well with experimental data from literature. Long et al. simulated the ionized electric field in a 3D advanced hybrid particulate collector [33]. A cylinder was used as the discharge wire. Three flat plates including one solid metal plate, one conductive perforated plate and one dielectric bag filter were considered as the collection plates. The electric field and ion distribution inside this system was analyzed. The computed and measured voltage-current characteristics agreed well. Overall, the numerical method from literature could provide relatively accurate and informative results for the ionized electric field in ESP.

The air flow and charged particles can modify the electric potential or space electric charge distribution in ESP, if the values of air velocity or particle concentration are high enough. Zhao and Adamiak studied the effect of inlet velocity on the ion trajectory and current density distribution along the collection plate in a typical wire-to-plate ESP [64]. If the inlet velocity was high enough (3 m/s), the effect of external flow on current density was visible. Actually, the external air flow can modify the corona discharge and particle efficiency at the same time. However, the particle motion and removal were not considered in this study. Zhao and Adamiak used numerical method to study the effect of air flow (including EHD and external flow field) on the ionized electric field, as described in equation (3) [61]. The pin-to-ground mesh system was considered. The external flow direction was parallel to the discharge pin and vertical to the mesh. If the external air velocity was zero, the influence of EHD on corona discharge could be ignored. If the external velocity increased to 10 or 30 m/s, this influence was clearly visible. However, this geometry was quite different from the traditional wire-to-plate ESP. The results from this study could not be used directly for other ESP types. In the wire-plate ESP, the electric field was very strong near the wire. Therefore, the ion velocity was much higher than the gas velocity. However, in the region remote from the wire, the ion velocity may be comparable to the gas velocity due to a weak electric field. Neglecting the influence of ion convection in the region near the collection plate can cause some errors in simulation. There have been no research studies focusing on this issue.

Adamiak and Atten numerically studied the influence of particle concentration on the ionized electric field in ESP. A single wire-to-plate 2-D ESP was analyzed [1]. The particle size was assumed to be equal to 0.3 μm and the reference particle concentration was $2E+12$ (#/m^3). Based on the equations (1–3), the charged particles can simultaneously modify the ionized electric field and air flow. Higher particle concentrations will result in a lower discharged current value because the space charged particle density or ion density had the same effect on the electric field. If the particle concentration increased 20 times, the discharge current decreased by 40%. Farnoosh et al. also studied the effect of particle concentration on corona discharge in ESP in the single wire-to-plate 3-D ESP configuration [13]. A polydispersed particle composition was assumed with the particle diameters ranging from 0.3 to 90 μm. Similarly to the 2-D case [1], a higher inlet particle concentration resulted in a lower discharged current. If ionized electric field was modified by a high particle concentration, the particle efficiency and EHD flow were also affected.

3.2. The results of EHD flow in ESP

The EHD flow in ESP was widely investigated by numerical simulation. The electric field intensity and space charge density could generate electric body force resulting in the EHD flow. The ionized electric field would result in several vortices, oscillation and turbulence in EHD flow field. If there was no corona discharge in ESP, the air flow was very easy to measure or simulate due to its simple geometry. Once the corona discharge occurred, the EHD simulation or velocity measurement became much more complex.

Farnoosh et al. simulated 3D EHD flow pattern in a spike-to-plate system by the FCT-FEM method [14, 15]. This study compared the air velocity and charged particle velocity. For 0.25 μm particles, the values of air or particle velocity were approximately the same. For larger particles with 1.5 um diameter, the two velocities differed a lot due to significant electric force acting on the charged particles. Two vortices were formed in the vicinity of the discharge electrode with the flow circulating in the opposite directions. A higher applied voltage resulted in a higher vortex size. For the different sections with or without discharge spike tip, the vortex structure and size was quite different. This study also provided the simulated turbulence intensity distribution. The corona discharge could increase the turbulence intensity from 3% to 65%. The turbulence intensity in the area of upstream spike was higher than the in the downstream area. Farnoosh et al. also simulated 3D EHD flow pattern in a wire-to-plate system by the FCT-FEM method [12]. This study investigated the influence of the inlet velocity on the EHD flow pattern, if the applied voltage was same. When inlet velocity was lower than 0.1 m/s, four big vortices existed in the vicinity of discharge wire. The vortices had blocked the main flow and driven them towards the collection plates. Increasing inlet velocity resulted in a smaller vortex size and more obvious vortex deformation. When the inlet velocity was higher than 0.4 m/s, only two vortices existed near the plates. If the inlet velocity was high enough, no vortex could be observed.

Chun et al. used the standard k-ε model to model the EHD flow in a single wire-to-plate ESP [8]. The study investigated the influence of inlet velocity and applied voltage on EHD flow patterns. It also provided basic information about the turbulence intensity, but the detailed analysis was not conducted. The conclusions were formulated, that the attachment of EHD wakes to the ESP collection electrode would enhanced the particle removal efficiency. However, the particle motion in ESP is a very complex process and this assumption should be verified by numerical simulation.

Zhao and Adamiak simulated the influence of ionized electric field on air flow field in a single wire to plate ESP by a hybrid FEM-MOC algorithm with the corona discharge modifying the air flow field [64]. This study used two dimensionless parameters (Reynolds and EHD numbers) to describe the external air flow and ionized electric field. The results show that by increasing the EHD number or decreasing the Re number, the significance of electrohydrodynamic flow increases. If the Re number was high or the EHD number was lower, the main external flow dominated the channel. This paper also developed an entire EHD flow map in ESP for different Re or EHD numbers and grouped all the air flow patterns into eight different types based on flow streamline patterns. The difference of each type is the size, number or position of vortices. This study only classified the electrohydrodynamic flow patterns by qualitative analysis (such as observing the vortex number and size). The essential quantitative classification method was not developed. Otherwise, the effect of EHD flow on particle motion and precipitation efficiency was not investigated. The corona discharge can enhance the turbulence intensity, which is an important factor determining small particle motion. However, the results of turbulence intensity were not given in this study. As seen in Figure 1, there are so many different types of ESP. The entire EHD flow map of a traditional single wire to plate ESP would be quite different than in the other types.

Lancereau et al. used a laminar model to investigate the EHD flow in ESP [25]. In this study, the discharge wire was parallel to the collection cylinder, which is quite different from that analyzed in other papers [64]. The vortices existed near the wire cusp and collection plate. Based on observing the flow distribution and vortex structure, the study grouped the EHD patterns into four regimes. Differently from the previous study, this paper investigated the EHD flow map quantitatively. The parameter a, as defined in equation (6), was used to determine the limit between the two regimes. The 3-D relationship between the pressure drop, electric Reynolds number (Re_e) and hydrodynamic Reynolds number (Re_a) were analyzed. The limit function of the two

Reynolds numbers to calculate the interface of two regimes could be obtained based on the simulated pressure drop data because the pressure drop is very sensitive to the EHD flow pattern. However, this paper did not consider the turbulence in their EHD flow simulation. Although the inlet velocity was low, the EHD could generate vortices and increase the turbulence intensity. Therefore, choosing a suitable turbulence model is essential in the future study.

$$a_A = \frac{dV_z}{dr} \qquad (6)$$

where V_z is the velocity parallel to the wire direction, r is the distance between one point to discharge wire.

As it can be observed, there were many studies focusing on the EHD flow in ESP. However, only a few study used experimental velocity or turbulence data to validate the numerical results [36, 62]. The utilization of turbulence model has significant influence on EHD flow in ESP because the electric body force could generate vortices and turbulence, but the evaluation of suitable turbulence model depended on the accurate measurement. The most accurate and time consuming method was the direct velocity measurement, such as hot wire or hot sphere sensors [32]. In ESP, it was impossible to place the hot wire sensor into the channel because the sensor would be damaged due to corona discharge. Zhao and Adamiak used the hot wire sensor to measure the EHD velocity in pin to metal grid system [62]. The hot wire sensor was installed downstream of the metal mesh to measure the EHD induced air velocity. The hot wire sensor would not be damaged because it was not exposed to the corona discharge field. The measured velocity magnitude was reliable for numerical simulation validation and model evaluation.

Differently from the direct velocity measurements, the Particle Image Velocimetry (PIV) method is an indirect method and it can determine the velocity distribution in a certain section. The PIV measures the particle velocity. If there is no electric force acting on particles and the particle size is small enough, the particle follow the air streamline, so that the particle velocity equals to air velocity. In ESP, both of the electric force and air drag force act on the charged particle resulting in the charged particle velocity, which is different from the air velocity. Therefore, utilizing the PIV to obtain the EHD flow field could bring some errors. Although there were many ESP publications focusing on the PIV method [41, 42, 44], only a few study used the measured data to validate their numerical simulation [36]. Actually, the direct or indirect velocity measurement has its own error [32]. Theoretically, the direct numerical simulation (DNS) could provide accurate velocity and turbulence results because there was no turbulence assumption in modelling. However, the disadvantage is that the time and space discretization resolution is very high resulting in considerable computing effort. However, the DNS was feasible for the narrow channel ESP. There were some researches using DNS to model the EHD flow in corona discharge field [19, 47, 48, 50]. Using DNS results to evaluate different turbulence model performance was promising in the future study.

The direct effect of ionized electric field on air flow field was investigated by some studies mentioned above. Nearly all of the studies assumed that the direct influence of particle motion on EHD flow in ESP should be ignored even if the particle concentration was high enough [1]. However, this assumption should be verified by the future study. High particle concentration could indirectly influence the EHD flow. The charged particles can affect the ionized electric field, then the modified corona field can influence the EHD flow in ESP. Adamiak and Atten studied the indirect influence of particle concentration on the air flow pattern in the single wire-to-plate 2-D model of ESP [1]. The direct influence of particle motion on air flow was not considered. Based on the equations (1–3), the charged particles could modify both ionized electric field and air flow. If there are no particles in ESP, the EHD pattern generated by corona is symmetrical. The presence of charged particles in ESP also contributed to the EHD and non-symmetrical EHD pattern existed. The particles located upstream of discharge wire were not fully charged. In this situation, the electric body force upstream of the wire was smaller than in the downstream region, where particles were fully charged and stronger EHD could be observed. Therefore, the non-symmetrical electric body force in ESP resulted in the non-symmetrical EHD pattern. In the presence of charged particle, the flow was unsteady and obvious oscillation occurred. Farnoosh et al. numerically studied the effect of particle concentration on EHD flow [13]. The single wire-to-plate 3-D ESP model was analysed with the poly-dispersed particle sizes in the range of 0.3 – 90 μm. The high particle concentration (20 times the reference value) could cause obvious flow fluctuation. These 3D results were very similar to the 2D results of previous study [1].

3.3. The results of particle motion and removal in ESP

The particle removal in ESP could be easily estimated from the mathematical models described above [12–15, 20, 22, 29, 35–37]. The effect of applied voltage, air flow rate, ESP structure and air temperature on particle collection efficiency was analyzed numerically. Long and Yao, and Lu et al. compared the simulated and measured particle collection efficiency in typical wire-to-plate ESP analyzed by previous study [35, 37]. Good agreement with experimental data was obtained. However, the inlet velocity (2 m/s) was so high that EHD flow could be ignored. The influence of EHD on particle removal efficiency was very limited. Therefore, the experimental ESP efficiency results could not be used to check the accuracy of EHD modeling. Also, the particle size (4 μm) was rather large in the experiment. Li et al. simulated the particle precipitation efficiency in an advanced ESP with discharge wire attached to the dielectric plate for particles ranging from 10 nm–1000 nm [29]. Good agreement between the modeled and measured efficiency was observed. The inlet velocity varied from 0.25 m/s to 0.5 m/s. However, this study didn't provide the detailed analysis of EHD flow pattern and its effect on efficiency. Lin and Tsai modeled the nanoparticle efficiency (< 100 nm) in a2D wire to plate ESP. The modeled efficiency agreed well with the measured data.

Farnoosh et al. simulated the precipitation efficiency in a spike-to-plate ESP. For 0.25–1.50 μm particles, the predicted efficiency was lower than the experimental values [14]. The authors speculated that electrostatic agglomeration of suspended charged particles after collisions was the main reason for the difference. However, simulation of particle agglomeration in ESP is very challenging. This study also compared the ESP efficiency assuming different spike positions. The efficiency of ESP with spike on upstream side of electrode was higher than that with spike on downstream side. The reason was in different EHD vortex structures. For the ESP with spikes on both sides of the corona electrode, the efficiency was highest, but the consumed electric energy was double as compared with the ESP only with spikes on one side of the electrode. This numerical research also investigated the particle deposition pattern on collection plates.

The EHD flow influenced the particle collection efficiency. Farnoosh et al. proved that the EHD flow can enhance the collection efficiency [13]. However, the numerical results of Xing et al. show that the EHD had negative effect on typical wire to plate ESP [55]. Therefore, it was essential to conduct complete study to investigate the influence of EHD on the collection efficiency. For some ESP patterns if the effect of EHD on efficiency could be ignored, EHD should not be included in simulation of engineering designs because EHD consideration increases computing time. If the air flow pattern affects the ionized electric field, then the ionized electric field also influences the particle motion and efficiency. However, this indirect coupling was not analyzed in detail in the published literature.

Based on the equations (1–3), the charged particles can modify the ionized electric field and air flow. Then, the charged particle motion and removal is also indirectly influenced by the high particle concentration. Adamiak and Atten studied the effect of particle concentration on the particle precipitation efficiency in

ESP [1]. The single wire-to-plate 2-D ESP was assumed. In the zone downstream of the discharge electrode, the region with negligible particle concentration spreads out with an increased particle concentration. However, the electric force had much weaker effect on particle motion than air drag force in this study. If the electric force is increased, the results may be quite different. Also, this study only considered the 3 μm particle; the results can be different for other particle sizes. Farnoosh et al. studied the effect of particle concentration on ESP efficiency for the single wire to plate configuration assuming polydispersed particles [27]. The high particle concentration (20 times of the reference value) caused visible flow fluctuation. However, this study focused on the one type of poly-dispersed particles only. The effect of particle concentration assuming a different particle size distribution was not investigated. This study also modeled the effect of inlet particle concentration on the ESP filtration efficiency. For small particles (0.3 μm in diameter), a higher inlet particle concentration resulted in a higher collection efficiency. For large particles (10 μm in diameter), a higher inlet particle concentration caused a lower efficiency. When the particle size was even larger (15 μm in diameter), an increased inlet particle concentration did not have any influence on efficiency, because in all the cases all particles were collected (100% efficiency).

Although many studies utilized the experimental ESP efficiency data to validate their numerical model, there are still some issues not solved. For example, the particle efficiency of ESP with a lower inlet velocity and a strong EHD flow was not investigated experimentally. Therefore, it was difficult to evaluate the EHD induced particle precipitation simulation results due to the absence of measured results. The numerical studies indicated that a high inlet particle concentration have obvious effect on corona discharge, EHD flow pattern and precipitation efficiency. These predictions were not validated by the measured data obtained for high particle concentrations. Most of the numerical investigations described above focused on the traditional wire-to-plate ESP. Meantime, a lot of advanced ESP were developed and investigated by experimental study in recent years (such as two staged ESP or DBD-ESP). These new ESP should be numerically studied, too.

4. Conclusions

This review summarized different numerical models for simulating performances of ESP, including ionized electric field, EHD flow field, particle charging and motion. Based on the results described above, the following conclusions could be drawn:

1) The available models can accurately simulate the traditional wire-to-plate ESP. Many experimental results of corona discharge validated the numerical models. For the EHD flow, the accurate and sufficient model validation is still unavailable. The predicted particle collection efficiency for different particle size was also verified by measured data.

2) However, there are still some deficiencies in the available models. Choosing the suitable turbulence model in EHD simulation is still difficult. An optimum numerical model, which could model the particle efficiency in ESP with strong EHD effect, is not known due to the absence of suitable experimental data. Considering the coupling between different physical processes in ESP could yield more accurate results. The criteria for determining necessary couplings in simulation are still unavailable.

3) In recent years, many new types of ESP were developed with high collection efficiency and low by-product generation. Most of the new types need to be simulated with acceptable accuracy. The most difficult problem is related to the DBD-ESP device. The unsteady modeling for electric field, air flow and particle motion with very small time step is more complex and time consuming.

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