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Research Article

Modeling of Gravitational Wet Scrubbers with Electrostatic Enhancement

Conventional gravitational wet scrubbers, which generally perform removal of fine particles with low efficiency, cannot meet new standards for pollution emissions. One way of improving the collection efficiency of fine particles is to impose additional electrostatic forces upon particles by means of particle-charging, or droplet-charging, or even opposite-charging of particles and droplets. A Monte Carlo method for population balance modeling is presented to describe the particle removal processes of gravitational wet scrubbers with electrostatic enhancement, in such a way that the grade collection efficiency and particle size distribution are calculated quantitatively. Numerical results show that, the grade collection efficiency of submicron particles is only ca. 5 % in conventional wet scrubbers. However, it reaches ca. 25 % in particle-charging wet scrubbers, ca. 70 % in droplet-charging wet scrubbers, and even above 99 % in opposite-charging wet scrubbers. Furthermore, population balance modeling is used to optimize the operational parameters of the droplet-charging wet scrubbers by means of the quantitative comparison of the grade collection efficiency. It is found that the operational parameters that are beneficial to the high-efficiency removal of fine particles are faster gas velocity, slower droplet velocity, larger liquid-to-gas flow ratio, larger charge-to-mass ratio of droplets, smaller geometric mean diameter and smaller geometric standard deviation of droplets.

Keywords: Dust-removal technique, Modeling, Monte Carlo method, Operation optimization, Particulate matter, Population balance

Received: July 25, 2008; *revised:* September 24, 2008; *accepted:* September 26, 2008

DOI: 10.1002/ceat.200800360

1 Introduction

Wet scrubbers are widely used to clean exhaust gas in the fields of metallurgy, mining and electric power plants [1]. These carrier particles are removed from a gas stream by conventional wet scrubbers through three main scrubbing mechanisms, i.e., Brownian diffusion, interception and inertial impaction [2, 3]. Generally speaking, small-scale particles (< 0.01 μm) and large-scale particles (> 5 μm) are effectively captured by droplets due to Brownian diffusion and inertial impaction, respectively; while most conventional wet scrubbers have low collection efficiency for intermediate-scale particles in the range of 0.1–1 μm, because all of the three wet scrubbing mechanisms have weak effects on these particles [2]. Unfortunately, these submicron particles are a recognized environmental problem since toxic substances, which pose the most difficulty for the respiratory system, are enriched in these fine particles [4]. One measure enhancing the fine particle precipitation is to reconstruct the conventional wet scrubbers as, e.g., a plate-column wet scrubber with gas-atomized spray [5]. Another measure to improve the grade collection efficiency of fine particles is to impose electrostatic forces upon the fine particles, e.g., smoke, dust, fly ashes, aerosols, etc., where either particles or droplets are charged [6–8], or even both particles and droplets are charged with opposite polarity [7–9] before entering the scrubber. The image force between charged-particles and neutral droplets, or the image force between charged-droplets and neutral particles, or the Coulombic force between charged particles and charged droplets will upgrade the grade collection efficiency of fine particles [10].

Empirical formulae and numerical simulation have been used to investigate the removal process of particles in wet scrubbers. In the fields of engineering, a series of empirical or semi-empirical expressions for the grade collection efficiency, overall mass collection efficiency and cut diameter of particles have been widely proposed to investigate the "macroscopical"

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effects of operation and running parameters on the performance of wet scrubbers. Meikap and Biswas [11] proposed an empirical correction of particulate collection efficiency in the modified multi-stage bubble column scrubber from detailed experimental results, considering thirteen factors including geometrical parameters, flow parameters and the physical properties of particles, gas, and droplets. These empirical expressions are not capable of quantitatively describing the detailed removal process of particles in wet scrubbers, and are not accurate from the point of view of scientific research. In order to obtain a clear understanding of the physical processes of particles and droplets in wet scrubbers, the two-phase turbulent models were further adopted. Adamiak et al. [12] proposed a three-dimensional, two-phase model to simulate the trajectories of charged dust particles moving horizontally in the vicinity of a free-falling, oppositely charged liquid droplet. Viswanathan [13] developed a two-dimensional efficiency model to simulate Venturi scrubbers, incorporating jet penetration and drop size distribution and investigating their effects on dust penetration. However, the complex models and expensive costs for simulating large particle numbers constrain its application. Population balance modeling (PBM), which only describes the dynamic evolution of particle size distribution through the numerical solutions of population balance equations (PBE), is capable of characterizing the removal process of particles in wet scrubbers. In addition, PBM has advantages over the two-phase turbulent model with respect to its simplicity and efficiency. Kim et al. [2] used the method of moments (MOM) and a priori lognormal size distribution of particles to solve the PBE. They investigated the particle removal efficiency, the particle size distribution, and the particle removal mechanisms of conventional gravitational wet scrubbers. However, the wet scrubbing mechanisms were modified or approximated in their method in order to make them suitable for the moment expressions.

This paper introduces a stochastic algorithm, i.e., the event-driven constant-volume (EDCV) method, for the solution of the PBE by keeping track of the numbers of particles and detailing the coagulation events between particles and droplets, i.e., the deposition events of particles. The Monte Carlo (MC) method is used to quantitatively describe the removal process of particles in conventional wet scrubbers, wet scrubbers with electrostatic enhancement through charging particles, or charging droplets, or charging particles and droplets to opposite polarity. The purpose of these numerical simulations is to find new dedusting techniques with a high removal efficiency of fine particles. The paper is organized in the following manner. In Sect. 2, the wet scrubbing mechanisms and their mathematical models of gravitational wet scrubbers with electrostatic enhancement, are presented. In Sect. 3, the event-driven constant-volume (EDCV) method is introduced briefly. Following this, the population balance modeling for gravitational wet scrubbers, with or without electrostatic enhancement is carried out in Sect. 4. Furthermore, Sect. 5 describes attempts to investigate the effects of the external operation conditions on the performance of gravitational wet scrubbers with droplet charging. The paper closes with an overall conclusion for gravitational wet scrubbers with electrostatic enhancement.

2 Theoretical Model of a Wet Scrubber with Electrostatic Enhancement

Fig. 1 shows a schematic diagram of a gravitational wet scrubber with electrostatics. It is assumed that the wet scrubbing process of particles is a steady-state one. Along with the particles that are scrubbed by the falling droplets, the size distribution function of the particle population, n_p, evolves with time, t, or the effective height of the wet scrubber, h[1]. Only collision events between droplets and particles, i.e., the wet scrubbing event of particles, are considered here. In addition, it is assumed that the size distribution of droplets is steady, although they collect amounts of particles and may evolve dynamically when they fall and are washed. The dynamic evolution of the particle size distribution is described mathematically by a population balance equation for particle wet scrubbing as follows, Eqs. (1) and (2):

$$\frac{\mathrm{d}n_\mathrm{p}(d_\mathrm{p},t)}{\mathrm{d}t} = -W(d_\mathrm{p})n_\mathrm{p}(d_\mathrm{p},t) \tag{1}$$

or

$$\frac{\mathrm{d}n_\mathrm{p}(d_\mathrm{p},h)}{\mathrm{d}h} = -\frac{W(d_\mathrm{p})}{U_\mathrm{p}}n_\mathrm{p}(d_\mathrm{p},h) \tag{2}$$

where $n_p(d_p,h)$ (μm^{-1} m^{-3}) is the size distribution function of particles with diameter d_p (μm), $n_p(d_p,h)dd_p$ represents the number concentration of particles whose size range is between d_p and $d_p + dd_p$ at the longitudinal distance h, U_p (m s^{-1}) is the velocity of the particle-laden gas stream, $h = U_p t$, $W(d_p)$ is the wet scrubbing kernel of particles with a diameter d_p, representing the collection rate of d_p-particles (s^{-1}).

The wet scrubbing kernel, $W(d_p)$, which can encapsulate any possible wet scrubbing mechanisms, is modeled by Eq. (3) [14]:

$$W(d_\mathrm{p}) = \int_{\mathrm{D_{d,min}}}^{\mathrm{D_{d,max}}} K(d_\mathrm{p},D_\mathrm{d})E(d_\mathrm{p},D_\mathrm{d})\mathrm{d}D_\mathrm{d} \tag{3}$$

where $K(d_p,D_d)$ is the collision kernel between d_p-particle diameter (μm) and D_d-droplet diameter (mm), describing the possibility of the collision event when the trajectory of the particle geometrically intercrossing that of the droplet. $K(d_p,D_d)$ is defined as Eq. (4) [14]:

$$\begin{aligned} K(d_\mathrm{p},D_\mathrm{d}) &= \pi D_\mathrm{d}^2|U(D_\mathrm{d}) - U(d_\mathrm{p})|n_\mathrm{d}(D_\mathrm{d})/4 \\ &= \pi D_\mathrm{d}^2[U(D_\mathrm{d}) + U(d_\mathrm{p})]n_\mathrm{d}(D_\mathrm{d})/4 \end{aligned} \tag{4}$$

in which $U(D_d)$ and $U(d_p)$ are the velocity of D_d-droplet diameter and d_p-particle diameter, respectively. It is assumed that the droplet falling velocity and the particle ascending velocity of all sizes are constant. It is considered that $U(D_d)$ is equal to the droplet spraying velocity of the nozzle, and $U(d_p)$ is equal to the velocity of the gas stream. $n_d(D_d)$ is the size distribution function of droplets, ($mm^{-1}m^{-3}$).

1) List of symbols at the end of the paper.

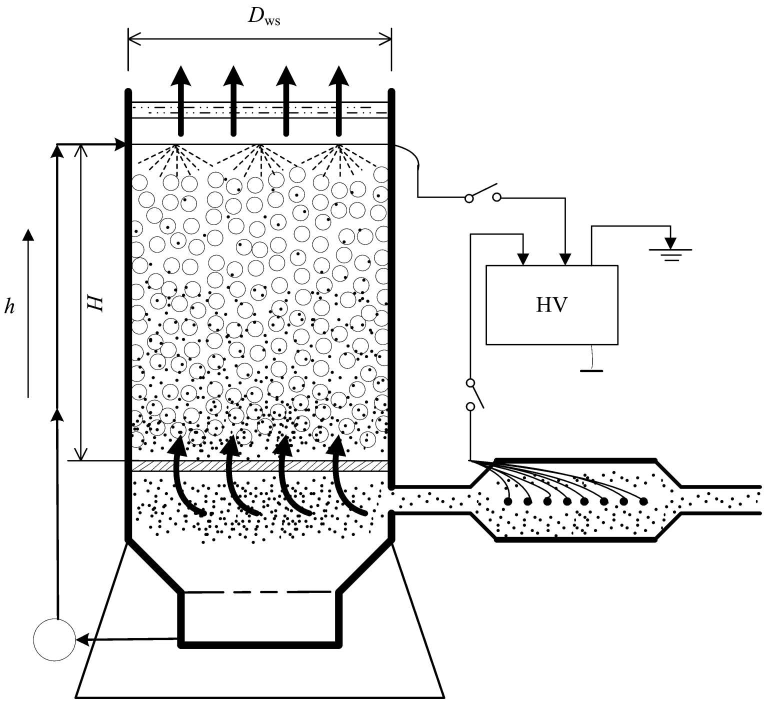

Figure 1. Schematic diagram of a gravitational wet scrubber with electrostatic enhancement.

are negligible, and no external electrostatic field is applied in the main body of the wet scrubbers. Therefore, only one kind of electrostatic mechanism, i.e., CDS, is considered in the paper. In addition, the most important non-electrostatic scrubbing mechanisms, i.e., Brownian diffusion, interception and inertial impaction, should also be considered [2]. It is generally assumed that the four mechanisms are independent and the four collision efficiencies are additive [2]. Therefore, the overall collision efficiency is described as:

$$E(d_p,D_d) = E_{diff} + E_{int} + E_{imp} + E_{elc} \quad (5)$$

where E_{diff}, E_{int}, E_{imp} and E_{elc} are collision efficiency of a single droplet due to Brownian diffusion, interception, inertial impaction and electrostatic forces, respectively. The three non-electrostatic collision efficiencies are respectively modeled by the expressions listed in Eq. (6) [16–18]:

$$\begin{aligned} E_{diff} &= 4.18\mathrm{Re}^{1/6}\mathrm{Pe}^{-2/3} \\ E_{int} &= \left(1+\frac{d_p}{D_d}\right)^2 - \frac{D_d}{D_d-d_p} \\ E_{imp} &= \left(\frac{St}{\mathrm{St}+0.7}\right)^2 \end{aligned} \quad (6)$$

$E(d_p,D_d)$ in Eq. (3) is the collision efficiency, representing the fraction of particles in the droplet sweep volume that are actually captured. Usually $E(d_p,D_d)$ is not constant, and $0 \le E(d_p,D_d) \le 1$. The collision efficiency takes account of the various attachment processes of interest, e.g., turbulent diffusion, Brownian diffusion and electrostatic attraction.

According to Melcher et al. [15] and Metzler et al. [10], the main collecting mechanisms due to electrostatics in wet scrubbers with electrostatic enhancement can be classified as: electrostatic precipitator (ESP, unipolar charged particles that migrate to the walls and are then collected under the influence of an external applied electrostatic field), self-agglomerators (SAG, particles that are charged to opposite polarities and agglomerate due to the force of electrostatic attraction), space-charge precipitator (SCP, unipolar charged particles that are precipitated on walls due to the field of their own space charge), charged droplet precipitator (CDP, charged particles that forcibly migrate to the walls by the space-charge field of likewise charged droplets), charged droplet scrubber (CDS, three cases of these types of particles are in existence, i.e., Case 1 – charged droplets collide with opposite charged particles due to the Coulombic force between particles and droplets, Case 2 – charged droplets collide with neutral particles due to the image force between particles and droplets, and Case 3 – neutral droplets collide with charged particles due to the image force between particles and droplets), and electrofluidized and electropacked beds (EFB and EPB, charged particles that are captured by the dipole momentum induced to uncharged droplets (or solid spheres) by an external applied field). In this paper, the space charge effect and the self-agglomeration effect

where Re and Pe are the Reynolds number and the Peclet number of a droplet, respectively, and St and D_{diff} are the Stokes number and the diffusion coefficient of a particle, respectively. These parameters are calculated by the expressions outlined in Eq. (7) as follows [14]:

$$\begin{aligned} &\mathrm{Re} = \frac{D_d U_d \rho_g}{\mu_g}; \mathrm{Pe} = \frac{D_d U_d}{D_{diff}}; \\ &\mathrm{St} = \frac{2\tau_p (U_d + U_p) C_c}{D_d}; D_{diff} = \frac{k_B T C_c}{3\pi\mu_g d_p}; \\ &\tau_p = \frac{\rho_p d_p^2}{18\mu_g \psi(\mathrm{Re}_p)}; C_c = 1 + 2.493\frac{\lambda}{d_p} + 0.84\frac{\lambda}{d_p}\exp\left(-0.435\frac{d_p}{\lambda}\right) \\ &\mathrm{Re}_p = \frac{d_p U_p \rho_g}{\mu_g}; \psi(\mathrm{Re}_p) = \begin{cases} 1, & \mathrm{Re}_p < 0.1 \\ 1 + 3\mathrm{Re}_p/16 & 0.1 < \mathrm{Re}_p < 1 \\ 1 + 0.15\mathrm{Re}_p^{0.687} & 1 < \mathrm{Re}_p < 1000 \\ 0.44\mathrm{Re}_p/24 & \mathrm{Re}_p > 1000 \end{cases} \end{aligned} \quad (7)$$

where ρ_g and μ_g are the density and viscosity of the gas stream, respectively, τ_p and Re_p are the relaxation time and the Reynolds number of particle, T is the absolute temperature of the gas stream, k_B is the Boltzmann constant, C_c is the Cunningham slip correction factor, and λ is the mean free path length of the gas molecules.

When particles and droplets are charged with the opposite polarity, they will attract each other due to Coulombic forces.

Davenport and Peters [19] provided the following expression for the electrostatic collision efficiency, Eq. (8):

$$E_{\mathrm{elc},1} = \frac{4C_c q_d q_p}{3\pi^2 \mu_g (U_d + U_p) \varepsilon_0 d_p D_d^2} \quad (8)$$

As for the interaction between charged droplets and neutral particles, the electrostatic collision efficiency due to the image force is given by Eq. (9) [20, 21]:

$$E_{\mathrm{elc},2} = \left\{ \frac{15\pi}{8} \left(\frac{\varepsilon_p - 1}{\varepsilon_p + 2} \right) \frac{2C_c \left[q_d / (\pi D_d^2) \right]^2 d_p^2}{3\pi\mu_g (U_d + U_p) \varepsilon_0 D_d} \right\}^{0.4} \quad (9)$$

With respect to the interaction between charged particles and neutral droplets, the semi-theoretical formula for the electrostatic collision efficiency due to the image force is obtained as Eq. (10) [20, 21]:

$$E_{\mathrm{elc},3} = 2.89 \times \left[\frac{C_c q_d^2}{3\pi^2 \mu_g (U_d + U_p) \varepsilon_0 d_p D_d^2} \right]^{0.353} \quad (10)$$

In the above three equations, ε_0 is the permittivity of free space, ε_p is the dielectric constant of particles, and q_d and q_p are the mean charges on the droplets and on the particles, respectively. It is considered in this study that the particles and droplets are charged by an external applied electric field. In field charging, the particle charge can be described by Cochet's charge equation, and the droplet's charge is considered to be the saturation charge. The charge models for q_d and q_p are given by the expressions in Eq. (11) [22, 23]:

$$\begin{aligned} q_d &= 3\pi\varepsilon_0 E_d D_d^2 \frac{\varepsilon_d}{\varepsilon_d + 2} \\ q_p &= \pi\varepsilon_0 E_p d_p^2 \left[\left(1 + \frac{2\lambda_i}{d_p} \right)^2 + \frac{2}{1 + 2\lambda_i / d_p} \frac{\varepsilon_p - 1}{\varepsilon_p + 2} \right] \end{aligned} \quad (11)$$

where E_d and E_p are the field strength applied in the droplets and in the particles, respectively, ε_d is the dielectric constant of droplets, and λ_i is the ionic mean free path.

3 The Event-Driven Constant-Volume Method for Particle Wet Scrubbing

When Monte Carlo (MC) methods are used for population balance modeling (PBM), the numbers of discrete particles are tracked directly to describe the dynamic evolution of its size distribution. As for wet scrubbers, the size distribution of droplets is considered to be steady-state, so that only the discrete particle population is simulated. A real particle population is usually represented by a simulation particle population in MC techniques, since a reasonably sized system contains too many real particles, e.g., 10^{15} m^{-3} particulate matter in pulverized-coal boiler [24]. Traditional MC methods of PBM simulate equally-weighted simulation particles [25–27]. However, the resolution of the edges of the particle size distribution in a traditional MC could be inadequate because there are very few simulation particles in these regimes, and thus, large statistical noise exists. In the present differentially-weighting MC method, real particles with the same or similar volume, i.e., real particles of the same size interval, are represented by some weighted simulation particles. Size intervals with low number concentration are assigned with some simulation particles with small weight, and size intervals with high number concentration are assigned with some simulation particles with larger weight. A pictorial representation for the differential weighting scheme of simulation particles is demonstrated elsewhere by Zhao and Zheng [28, 29]. Consequently, the differentially-weighting MC method is capable of reducing statistical noise for particles in those sections where the number density is low, e.g., the edges of the particle size distribution.

The MC method is based on an event-driven technique [30], i.e., special events are stochastically implemented with probabilities derived from the mean-filed rates of the corresponding dynamic processes, and then time is advanced by the waiting time between two successive events, which adjust themselves to the rates of various event processes. Furthermore, the computational domain is maintained, and the number of simulation particles is kept within prescribed bounds during the time evolution of the particle population. The MC method is known as the event-driven constant number (EDCV) method [31]. The EDCV method for particle wet scrubbing (or, particle-droplet collision) in wet scrubbers is briefly presented here.

The EDCV method describes the particle collection process in three steps, viz.:

I. Calculation of the Waiting Time between Two Successive Events

The interval of quiescence of two successive events after the ($k-1$) events, Δt_k, is calculated as following:

$$\Delta t_k = 1/(V R_{\mathrm{scr}}) = 1 \bigg/ \left(V \int_{d_p} W(d_p) n_p(d_p) \mathrm{d}d_p \right) = 1 \bigg/ \sum_{i=1}^{N_{ps}} W_i \quad (12)$$

where V is the volume of computational domain, R_{scr} is the real-time scrubbing rate per unit volume (s^{-1} m^{-3}), N_{ps} is the total number of simulation particles, and W_i is the wet scrubbing kernel of particle indexed by i. As for the wet scrubbers shown in Fig. 1, $V = \pi D_{ws}^2 H/4$, where D_{ws} and H are the inner diameter and effective height of the tower, respectively.

The calculation of the wet scrubbing kernel of particles with different sizes requires the definite integral over the droplet size distribution, as shown in Eq. (3). This operation of the definite integral will cost plenty of CPU time or generate some numerical errors, or it may not operate at all. In order to avoid the operation of the definite integral, the size distribution of the droplets is also discretized and differentially weighted simulation droplets are generated, which is similar to the above procedure for generating differentially weighted simulation particles. At this stage, the weight of the simulation droplet, j, is w_{dj} and the size is D_{dj}. If the total number of simulation droplets is N_{ds}, the wet scrubbing kernel of particles with a size d_p is calculated as outlined in Eq. (13) [14, 32]:

$$W(d_p) = \int_{D_{d,min}}^{D_{d,max}} \frac{\pi D_d^2}{4}\left[U(D_d) + U(d_p)\right] E(d_p, D_d) n_d(D_d) dD_d = \sum_{j=1}^{N_{ds}} \left[\frac{\pi D_{dj}^2}{4}\left[U(D_{dj}) + U(d_p)\right] E(d_p, D_{dj}) w_{dj}\right] \quad (13)$$

II. Selection of the Main Particle

The main particle, i.e., the particle that is collected by a droplet after the waiting time, is selected by the cumulative probabilities method [30] according to the following relationship, Eq. (14):

$$\sum_{m=1}^{i-1} W_m \Delta t_k < r \leq \sum_{m=1}^{i} W_m \Delta t_k \quad (14)$$

where r is a random number from a uniform distribution in the interval [0,1]. If Eq. (14) is satisfied, it is considered that the simulation particle i is the main particle and will be collected by a droplet.

III. Treatment of the Result of Particle Wet Scavenging and Restoration the Sample

If the simulation particle i is collected by a droplet, it will be discarded and not be tracked any longer in the simulation. A single wet scrubbing event means subtracting one from the total number of simulation particles. Along with the dynamic evolution of the simulation particle population, the total number of simulation particles will become smaller and smaller, which will lead to a deterioration of the statistical precision of the MC method. The EDCV method does not forcibly keep the total number of simulation particles constant throughout the simulation process, because the forcible maintenance of the particle number will disturb the ensemble and lead to the exhibition of an error associated with "sample restoration". The EDCV method adopts a so-called "stepwise constant number scheme" to restore the total number of simulation particles. When the number of simulation particles reaches $N_{ps,0}/2$ (where $N_{ps,0}$ is the initial number of simulation particles), the surviving particles are duplicated and added into the simulation particle array to restore the number of simulation particles. As a result, the weight of each simulation particle is halved. In the next time step, these new simulation particles are simulated. The halving of the weight always maintains the computational domain constant, while maintaining the total number of simulation particles within the prescribed bounds.

The MC method is used to indirectly solve the population balance in Eq. (2), and the dynamic evolution of particle size distribution along the longitudinal distance, h, in wet scrubbers is obtained.

4 Population Balance Modeling of Wet Scrubbers with Electrostatic Enhancement

4.1 Size Distributions of Particles and Droplets

Since particles with different sizes have the different formation and growth mechanisms, the size distributions of particle populations in engineering and nature fields are very complicated. As an example, fly ash particles from a pulverized coal boiler can be described as a tri-modal particle size distribution that includes a submicron fume region centered at ca. 0.08 μm diameter, a fine fragmentation region centered at ca. 2.0 μm diameter, and a bulk or supermicron fragmentation region for particles of ca. 5 μm diameter and greater [33]. The particle size distribution in this research is considered to be a sum of three lognormal functions, as outlined in Eq. (15):

$$n_p(d_p) = \sum_{i=1}^{3} \frac{N_{p,i}}{\sqrt{2\pi}\ln\sigma_{pg,i}} \exp\left[-\frac{\ln^2(d_p/d_{pg,i})}{2\ln^2\sigma_{pg,i}}\right]\frac{1}{d_p} \quad (15)$$

where $N_{p,i}$, $d_{pg,i}$, $\sigma_{pg,i}$ are the number concentration, geometric mean diameter, and geometric standard deviation of the i-th mode. The values selected in this work are listed in Tab. 1. In the paper, the range of particle size distribution is 0.08 μm ≤ d_p ≤ 20 μm when the initial particle number concentration at the inlet of wet scrubbers is $2.50 \cdot 10^{14}$ m^{-3}, and the initial mean diameter is ca. 0.11 μm. The initial particle mass fraction function distribution and initial particle number fraction function distribution are shown in Figs. 2a) and 2b), respectively. Obviously, the supermicron particles occupy the main mass quotas, but the number concentration of the submicron particles is far greater than that of the other particles at the inlet of the wet scrubber. The initial particle mass fraction function distribution is close to the experimental results of Markowski et al. [34]. The particle size distribution is divided into 100 bins between the largest and smallest particle size, which are logarithmically spaced. Every bin is represented by at least 100 simulation particles. The initial number of simulation particles is 27908.

In the current work, droplet size distribution is described by a unimodal lognormal function, Eq. (16):

$$n_d(D_d) = \frac{N_d}{\sqrt{2\pi}\ln\sigma_{dg}} \exp\left[-\frac{\ln^2(D_d/D_{dg})}{2\ln^2\sigma_{dg}}\right]\frac{1}{D_d} \quad (16)$$

Table 1. The characteristic parameters of particle size distribution function for a wet scrubber.

Parameters	$N_{p,1}$ (m^{-3})	$d_{pg,1}$ (μm)	$\sigma_{pg,1}$	$N_{p,2}$ (m^{-3})	$d_{pg,2}$ (μm)	$\sigma_{pg,2}$	$N_{p,3}$ (m^{-3})	$d_{pg,3}$ (μm)	$\sigma_{pg,3}$
Values	$5 \cdot 10^{14}$	0.08	1.5	$1 \cdot 10^{11}$	2.0	2.0	$1 \cdot 10^{9}$	10.0	1.5

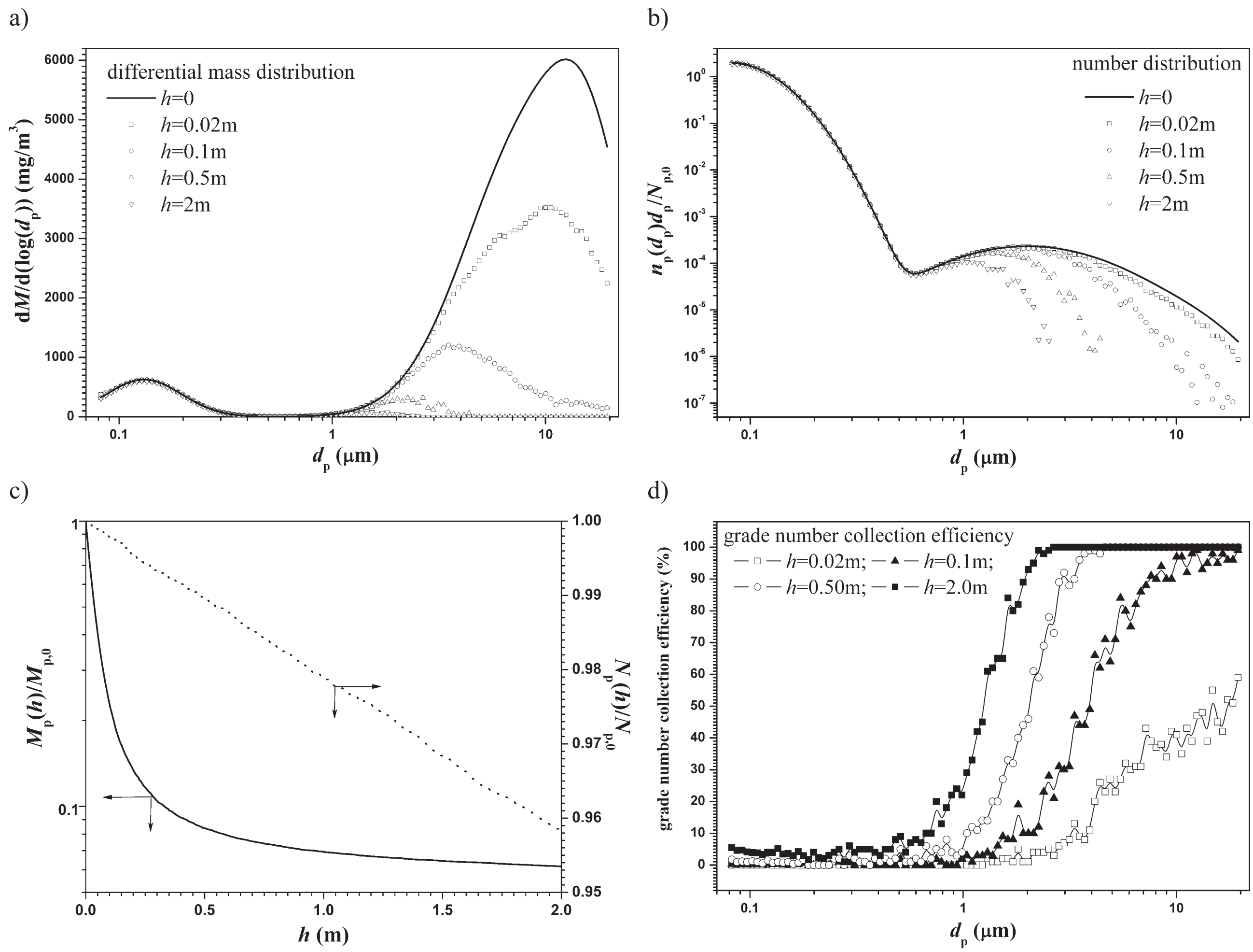

Figure 2. The dynamic evolution of particle size distribution in a conventional gravitational wet scrubber: (a) Particle mass fraction size distribution, (b) Particle number fraction size distribution, (c) Particle number concentration and particle mass concentration, and (d) Grade collection efficiency.

where N_d is the total number concentration (m^{-3}), D_{dg} is the geometric mean diameter (mm), and σ_{pg} is the geometric standard deviation of droplets. In the section, D_{dg} = 1 mm and σ_{dg} = 1.25.

The flux of the particle-laden gas stream, Q_g (m^3h^{-1}), depends on the gas velocity, u_g (m s^{-1}), and the inner diameter of the tower, D_{ws} (m), i.e., $Q_g = 900\pi D_{ws}{}^2 u_g = 900\pi D_{ws}{}^2 U_p$. The performance of all kinds of wet scrubbers is associated with the effective total height of the wet scrubber, H (m).

With respect to the log-normal droplet size distribution, the total number concentration of real droplets, N_d, is related to the flux of water, Q_d (m^3h^{-1}), or, the liquid-to-gas flow ratio, Q_d/Q_g, by the flowing expression, Eq. (17):

$$N_d = \frac{w_1}{\rho_d \pi d_{dg}^3 \exp\left(9\ \ln^2 \sigma_{dg}\big/2\right)\big/6} = \frac{Q_d \rho_d\big/\left(\pi D_{ws}^2 U_d/4\right)}{\rho_d \pi d_{dg}^3 \exp\left(9\ \ln^2 \sigma_{dg}\big/2\right)\big/6} = \frac{Q_d/Q_g \times U_p/U_d}{\pi d_{dg}^3 \exp\left(9\ \ln^2 \sigma_{dg}\big/2\right)\big/6} \quad (17)$$

where w_1 is the water content (kg m^{-3}), and represents the total mass of droplets per unit volume.

All parameters used in the models are listed in Tab. 2. If there is no specific indication, these parameters are the same in all simulations.

Table 2. Parameters used in the current model for web scrubbers.

Parameters	D_{ws} (m)	H (m)	u_g (m s^{-1})	U_p (m s^{-1})	U_d (m s^{-1})	ρ_d (kg m^{-3})	ρ_p (kg m^{-3})	ρ_g (kg m^{-3})	μ_g (kg m^{-1} s^{-1})
Values	6	2	0.6	0.6	1.2	997.45	2270	0.8288	$2.4 \cdot 10^{-5}$
Parameters	Q_g (m^3 h^{-1})	Q_g/Q_d (L m^{-3})	T (K)	ε_p	ε_d	ε_0 (F m^{-1})	λ (m)	λ_i (m)	k_B (J K^{-1})
Values	61072.56	20	433	5	80	$8.85 \cdot 10^{-12}$	$6.5 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	$1.38054 \cdot 10^{-23}$

4.2 Conventional Gravitational Wet Scrubbers

In conventional gravitational wet scrubbers, only three non-electrostatic mechanisms, i.e., Brownian diffusion, interception, inertial impaction, are considered. Therefore, the following expression applies, Eq. (18):

$$E(d_p, D_d) = E_{diff} + E_{int} + E_{imp} \tag{18}$$

The particle wet scrubbing in conventional gravitational wet scrubbers is similar to the particle wet scavenging by precipitation in a natural environment [14, 32].

Fig. 2a) shows the particle mass fraction size distribution at several specified heights. The differential mass distribution, $dM/d(\log(d_p))$, is calculated in the MC by Eq. (19):

$$\frac{dM}{d(\log(d_p))} = \frac{N(d_p)\pi\rho_p d_p^3 / 6}{\log\left(d_p^+\right) - \log\left(d_p^-\right)} \tag{19}$$

where $N(d_p)$ represents the number concentration of a particle bin with a respective size of d_p, d_p^+ and d_p^- are the upper and lower limit of the size interval with respective sizes, d_p. Fig. 2b) shows the particle number fraction size distribution at different heights. The number distribution, $n_p(d_p)d_p/N_{p,0}$, is calculated in the MC by using Eq. (20):

$$\frac{n_p(d_p)d_p}{N_{p,0}} = \frac{N(d_p)d_p / \left(d_p^+ - d_p^-\right)}{N_{p,0}} \tag{20}$$

It is clear from Figs. 2a) and 2b), that as the effective scrubbing height increases, the mass fraction and number fraction of supermicron particles are occupying smaller and smaller quotas, which indicates that these supermicron particles are effectively scrubbed by droplets. In fact, as shown in Fig. 2c), the overall mass collection efficiency, $1 - M_{p,h=2m}/M_{p,0}$, reaches 93.84 %, which is attributed to the effective collection of supermicron particles. However, the overall number collection efficiency, $1 - N_{p,h=2m}/N_{p,0}$, is only 4.18 % in the case shown in Fig. 2c). This is because the submicron particles that occupy the highest number fraction are difficult to scrub by a conventional wet scrubber. Consequentially, the size distributions of submicron particles are almost maintained constant against the incremental effective scrubbing height, as shown in Figs. 2a) and 2b).

The grade collection efficiency is usually used to evaluate the performance of wet scrubbers. There have been numerous theoretical and experimental studies undertaken on the model of collection efficiency [11, 35]. The grade collection efficiency can be obtained by counting the simulation particles tracked by the MC, as shown in Fig. 2d). The simulation results of the EDCV method exhibit some fluctuations. The fluctuations originate from the inevitable statistical error of MC. As shown in Fig. 2d), the grade collection efficiency of all particles more or less increases, when plotted against the incremental effective scrubbing height. However, the grade efficiency of submicron particles is only ca. 5 % at the outlet of the wet scrubber, i.e., at $h = 2$ m. If the collection efficiency of fine particles is too low, then the new standard of pollution emissions cannot be achieved, since these fine particles have a notorious impact on human health.

4.3 Droplet-Charging Wet Scrubbers

In the case of droplet-charging wet scrubbers, the droplets are applied in an electric field with strength of 5 kV cm^{-1}. Hence, for a droplet of diameter 1 mm, the charge-to-mass ratio of the droplet is $7.79 \cdot 10^{-5}$ C kg^{-1} according to Eq. (11). For this case, the electrostatic collection efficiency, $E_{elc,2}$, is calculated using Eq. (9), and the overall collision efficiency is given by Eq. (21):

$$E(d_p, D_d) = E_{diff} + E_{int} + E_{imp} + E_{elc,2} \tag{21}$$

As shown in Figs. 3a) and 3b), the mass fraction and number fraction of both supermicron and submicron particles decrease when plotted against the incremental effective scrubbing height. In comparison to the conventional wet scrubber, the droplet-charging wet scrubber removes any sized particles, which is attributed to the image forces between charged droplets and neutral particles. Accordingly, the grade collection efficiency of submicron particles reaches ca. 70 %, as shown in Fig. 3d). With respect to the droplet-charging wet scrubber, the overall mass collection efficiency is still high at 98.62 %, and it is worth noting that the overall number collection efficiency reaches 72.01 %, as shown in Fig. 3c). Therefore, the droplet-charging wet scrubbers should provide a feasible route to removal of fine particles from a gas stream.

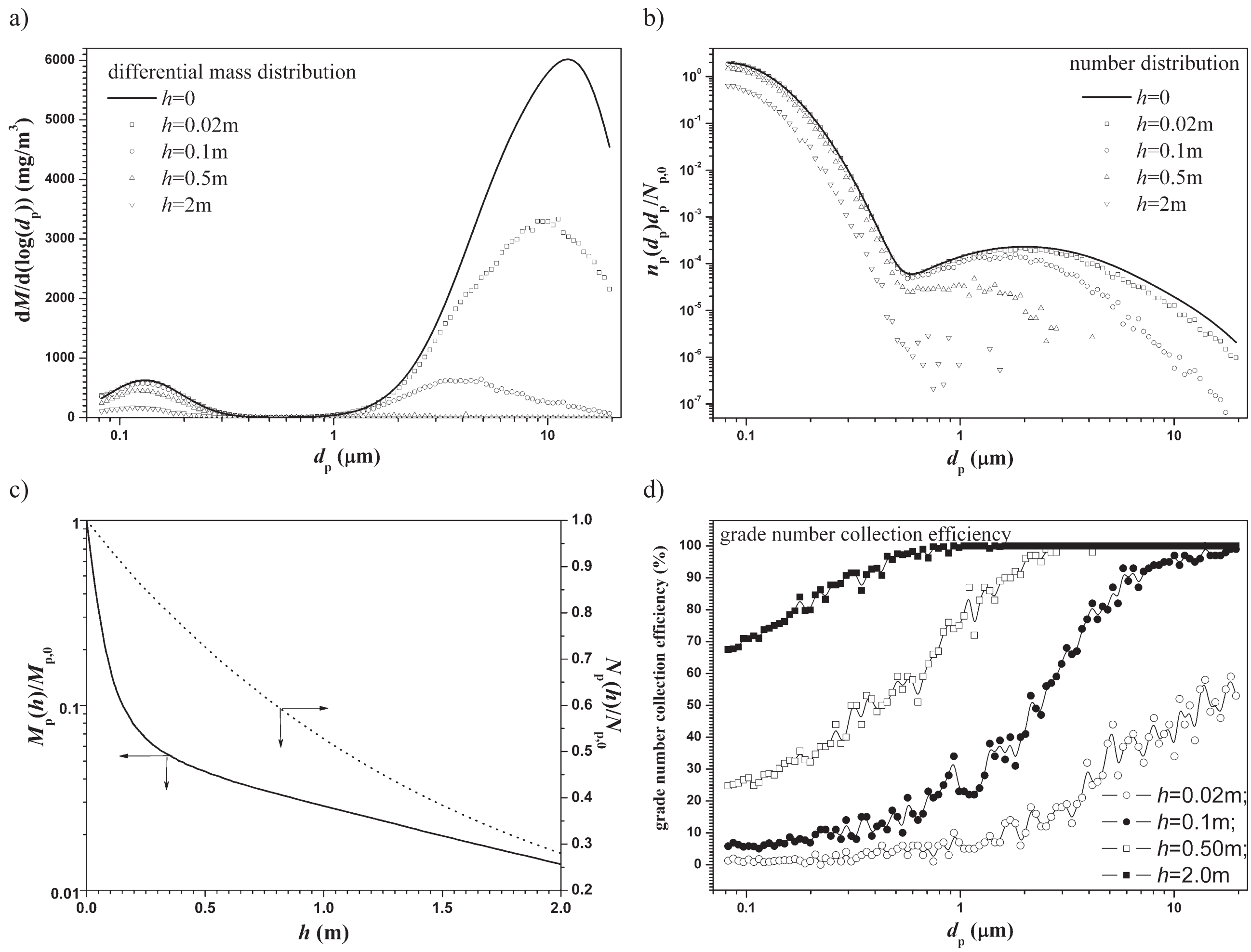

Figure 3. The dynamic evolution of particle size distribution in a droplet-charging gravitational wet scrubber: (a) Particle mass fraction size distribution, (b) Particle number fraction size distribution, (c) Particle number concentration and particle mass concentration, and (d) Grade collection efficiency.

4.4 Particle-Charging Wet Scrubber

If only particles are charged, the image force between charged particles and neutral droplets will also help droplets collect particles. In this case, the electrostatic collection efficiency, $E_{\text{elc},3}$, is given by Eqs. (10) and the overall collision efficiency is given by Eq. (22):

$$E(d_{\text{p}},D_{\text{d}}) = E_{\text{diff}} + E_{\text{int}} + E_{\text{imp}} + E_{\text{elc},3} \tag{22}$$

In addition, the electric field strength for the charging particles is 5 kV cm^{-1}.

From Fig. 4, the particle-charging wet scrubber also collects the supermicron particles effectively and enhances the collection efficiency of submicron particles to a certain extent. The grade collection efficiency of submicron particles reaches 25 %, and the overall mass and number collection efficiencies are 95.41 % and 25.08 %, respectively. However, the droplet-charging wet scrubber performs better than the particle-charging wet scrubber when either droplets or particles are applied in an external electric field with the same strength. In fact, the particle size is usually smaller than the droplet size, i.e., the particle surface area is usually smaller than the droplet surface area. Therefore, the charge of a particle with a typical size, e.g., a mean particle diameter of 0.11 μm, is smaller than that of a droplet with a typical size, e.g., a mean droplet diameter of 1 mm, which results in smaller image forces between the particle and the droplet, and hence, a smaller electrostatic collision efficiency. The particle-charging wet scrubbers require higher external electric field strength to improve the grade collection efficiency of fine particles.

4.5 Opposite-Charging Wet Scrubbers

In the case of opposite-charging wet scrubbers, particles and droplets are charged with opposite polarity. Here, the electric field strength is 1 kV·cm^{-1} for particle charging, and 5 kV cm^{-1} for droplet charging. It is assumed that the repulsion of droplets or particles of the same electric charge is not considered.

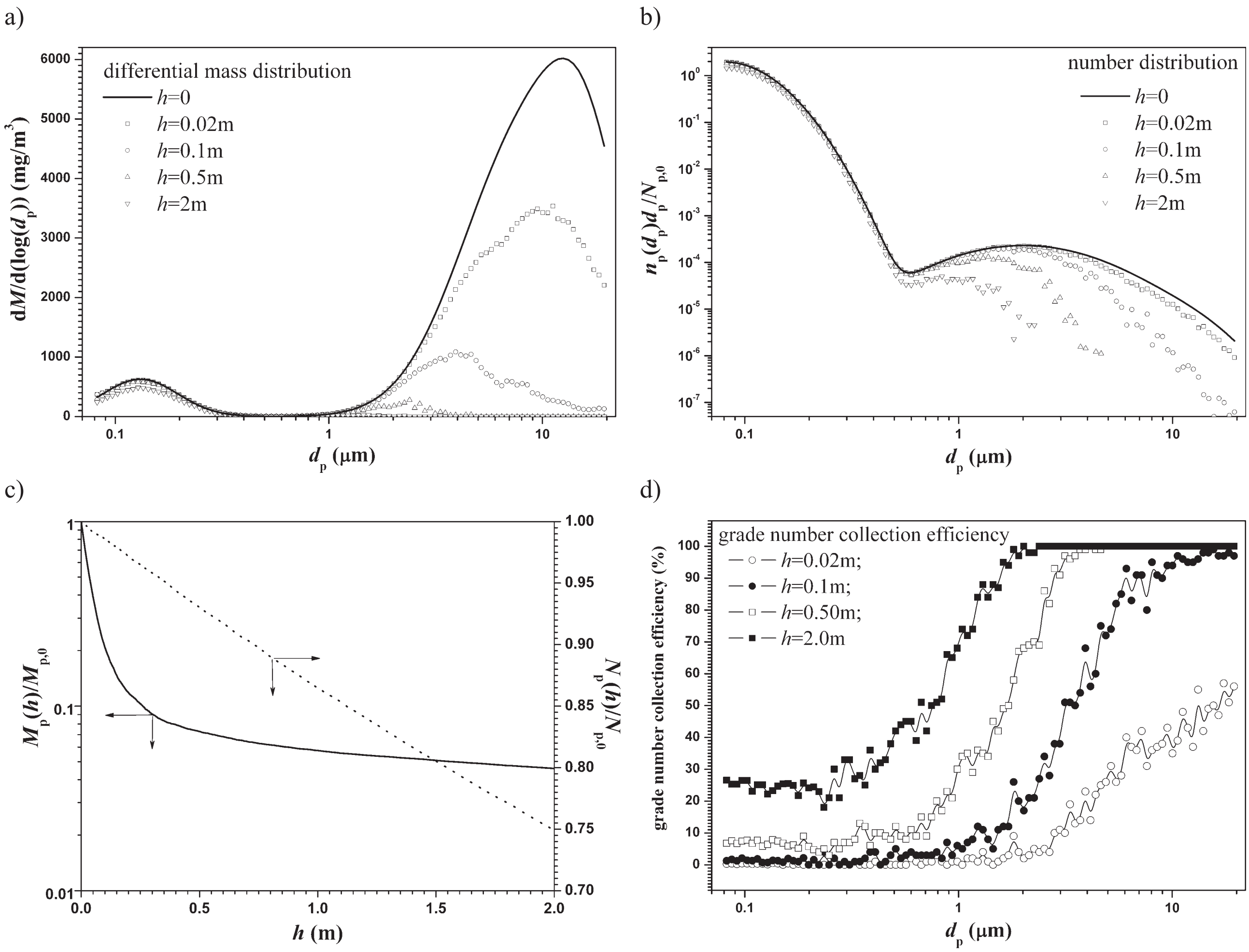

Figure 4. The dynamic evolution of particle size distribution in a particle-charging gravitational wet scrubber: (a) Particle mass fraction size distribution, (b) Particle number fraction size distribution, (c) Particle number concentration and particle mass concentration, and (d) Grade collection efficiency.

The Coulombic force between charged particles and oppositely charged droplets will significantly improve the collision efficiency. The electrostatic collection efficiency, $E_{\mathrm{elc},1}$, is calculated by using Eqs. (9) and the overall collision efficiency is given by Eq. (23):

$$E(d_{\mathrm{p}},D_{\mathrm{d}}) = E_{\mathrm{diff}} + E_{\mathrm{int}} + E_{\mathrm{imp}} + E_{\mathrm{elc},1} \quad (23)$$

As shown in Fig. 5, both supermicron particles and submicron particles are removed effectively in the droplet-charging and particle-charging wet scrubbers. The grade collection efficiency of all sized particles reaches almost 100 %, and the overall collection efficiencies based on mass and number are 99.99 % and 99.93 %, respectively. These results show that the electrostatically enhanced wet scrubbers perform better for the removal of fine particles than the three wet scrubbers described above.

5 Discussion

5.1 Wet Scrubbing Kernel and Collision Efficiency

The wet scrubbing kernel, $W(d_{\mathrm{p}})$, represents the wet scrubbing rate of a particle with size d_{p}. $W(d_{\mathrm{p}})$ is directly related to the grade collection efficiency by Eq. (3), and also characterizes the dynamic evolution of particle size distribution in wet scrubbers by the population balance expression in Eq. (2). Fig. 6 shows the relation between particle size and the wet scrubbing kernel in the four kinds of different wet scrubber. With respect to a submicron particle with a specific size, e.g., 0.1 μm, its wet scrubbing kernel in the opposite-charging wet scrubber is greater than the kernel in the droplet-charging wet scrubber, the kernel in the particle-charging wet scrubber, and the kernel in the conventional wet scrubber (in that order). Therefore, the opposite-charging wet scrubber removes fine particles more effectively than the other three wet scrubbers. For a supermicron particle with a specific size, e.g., 10 μm, its

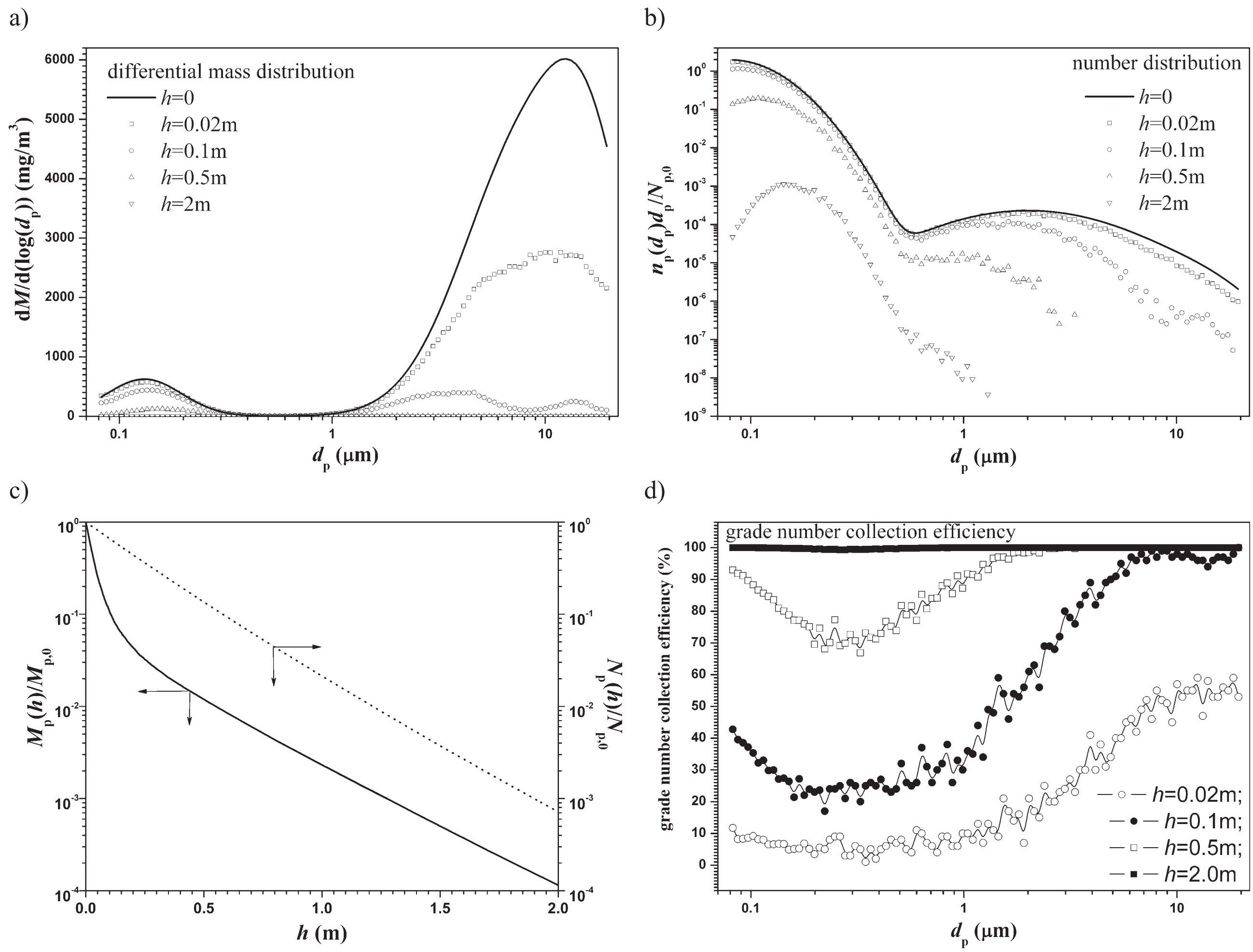

Figure 5. The dynamic evolution of particle size distribution in an opposite-charging gravitational wet scrubber: (a) Particle mass fraction size distribution, (b) Particle number fraction size distribution, (c) Particle number concentration and particle mass concentration, and (d) Grade collection efficiency.

wet scrubbing kernel is nearly the same in the four wet scrubbers, and is far greater than that of a given submicron particle. Therefore, the four kinds of wet scrubber are seen to remove the supermicron particles with high efficiency.

The question now arises as to why the different wet scrubbers have different wet scrubbing kernels? As shown in Figs. 6 and 7, the curves of the collision efficiency are very similar to the corresponding curves of the wet scrubbing kernel, which indicates that the different wet scrubbing kernels in different wet scrubbers can be mainly ascribed to the different collision efficiencies, if the same external operation conditions (including the velocity of gas stream and the droplet spraying operation) are applied. Furthermore, the contributions of the different wet scrubbing mechanisms to the overall collision efficiency are separately analyzed in Fig. 8, where the droplet size is 1 mm. It is obvious that the collision efficiencies dominated by Brownian diffusion, interception, inertial impaction, i.e., E_{diff}, E_{int} and E_{imp}, are similar in the four wet scrubbers. However, the electrostatic collision efficiencies in the various wet scrubbers are different. With respect to any specified particle size, the electrostatic collision efficiency due to the Coulombic force between the charged particles and oppositely charged droplets, $E_{elc,1}$, is greater than the electrostatic collision efficiency due to the image force between charged droplets and neutral particles, $E_{elc,2}$, and the electrostatic collision efficiency due to the image force between charged particles and neutral droplets, $E_{elc,3}$, in that order. Therefore, the different electrostatic collision efficiencies result in different overall collision efficiencies and wet scrubbing kernels, and consequently, this leads to different scrubbing performances of fine particles in the different wet scrubbers.

5.2 Operational Optimization of Droplet-Charging Wet Scrubbers

The collection performance of wet scrubbers is closely related to external operating conditions, e.g., gas flux, atomization operation of nozzles and charging operation of electrostatic fields. From analysis of the influences of the different operating

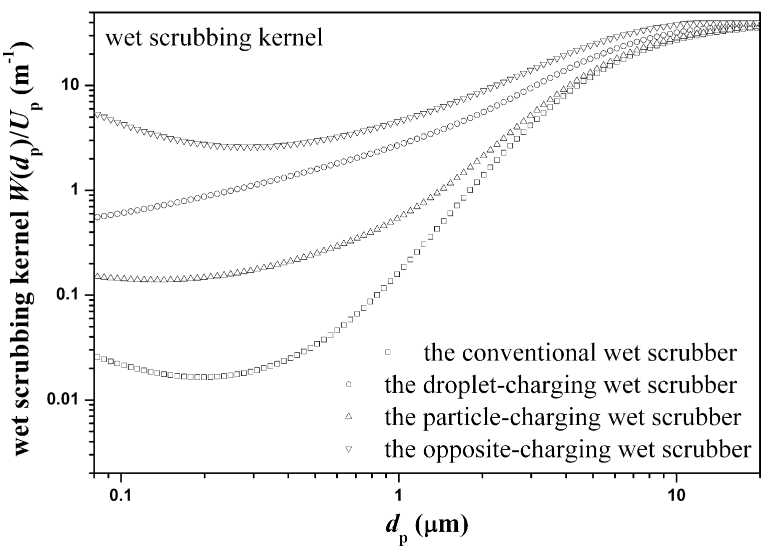

Figure 6. The wet scrubbing kernels in different wet scrubbers.

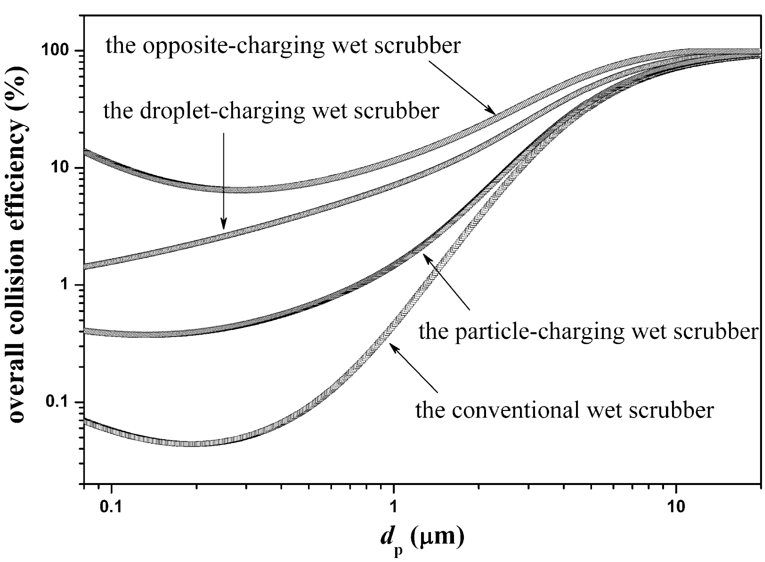

Figure 7. The collision efficiency between particle and droplet (D_d = 1 mm) in different wet scrubbers.

conditions on the grade collection efficiency, one is capable of investigating the influences of the different operating conditions on the collection performances of wet scrubbers, where the typical operation conditions in Sect. 4 are considered as a reference. The key operation parameters include the velocity of the gas steam, the spraying velocity of the droplets, the size distribution of the droplets, the charge-to-mass ratio of the droplets, and the liquid-to-gas flow ratio. Only the droplet-charging wet scrubbers are considered here since they perform the high grade collection efficiency of fine particles and are more feasible compared to the particle-charging wet scrubbers, which usually require voluminous and expensive electrostatic devices, e.g., electrostatic precipitators (ESPs).

Fig. 9 shows the influence of the different gas velocities and droplet spraying velocities on the collection performance of wet scrubbers. As the gas velocity increases, the grade number collection efficiency at the outlet increases. In fact, increases in the gas velocity result in increased values of E_{imp} and the collision kernel $K(d_p,D_d)$. As a consequence, the wet scrubbing kernels of any sized particles will increase. On the other hand, the decrease of the velocity of droplet spraying results in the effective collection of any sized particles, especially that of fine particles. The droplet spraying velocity influences the collision efficiency due to Brownian diffusion, E_{diff}, the collision efficiency due to inertial impaction, E_{imp}, the collision efficiency due to electrostatic collection, $E_{elc,2}$, and the collision kernel, $K(d_p,D_d)$. As the droplet spraying velocity decreases, E_{diff} and $E_{elc,2}$ increase, while E_{imp} and $K(d_p,D_d)$ decrease. These several nonlinear factors together mean that the wet scrubbing kernel and the grade collection efficiency increase with decreases in the velocity of droplet spraying.

From Fig. 10, it is clear that the grade number collection efficiency at the outlet increases as the charge-to-mass ratio of droplets and the liquid-to-gas flow ratio increase. When the external electric field strengths for the charging of droplets are 1, 5 and 10 kV cm^{-1}, the consequential charge-to-mass ratios of a droplet with diameter 1 mm are $1.56 \cdot 10^{-5}$, $7.79 \cdot 10^{-5}$ and $1.56 \cdot 10^{-4}$ C kg^{-1}, respectively. It is obvious that the incresing strength of the electric field results in increased charge-to-mass ratio of a specified sized particle, and the increase of $E_{elc,2}$. When the liquid-to-gas flow ratio, Q_d/Q_g, is considered, increaqses in Q_d or decreases in Q_g mean that more droplets wash less particles carried by the gas stream. According to Eq. (3), the wet scrubbing kernel of a given particle size will increase as Q_d/Q_g increases. This result agrees qualitatively with the results of Kim et al. [2] and Leith et al. [36].

The size distribution of droplets also has important influence on the performance of wet scrubbers. As shown in Fig. 11, smaller geometric mean diameters and geometric standard deviations of droplets, i.e., fine and uniformly-sized droplets, result in increased grade collection efficiency of fine particles. In this case, several factors influence the wet scrubbing performance. The collision efficiency is analyzed as follows. Firstly, the electrostatic collision efficiency, $E_{elc,2}$, increases as the droplet size decreases according to Eq. (9). Secondly, smaller values of D_{dg} and σ_{dg} result in larger values of N_d, and consequently, a larger total surface area of droplets under the condition of similar water consumption, which also agrees with Eq. (17). The increased surface area of the droplets will increase the collision efficiency due to Brownian diffusion; Thirdly, the collision efficiency due to the interception mechanism, E_{int}, depends on the radio of particle size and droplet size, d_p/D_d. Smaller values

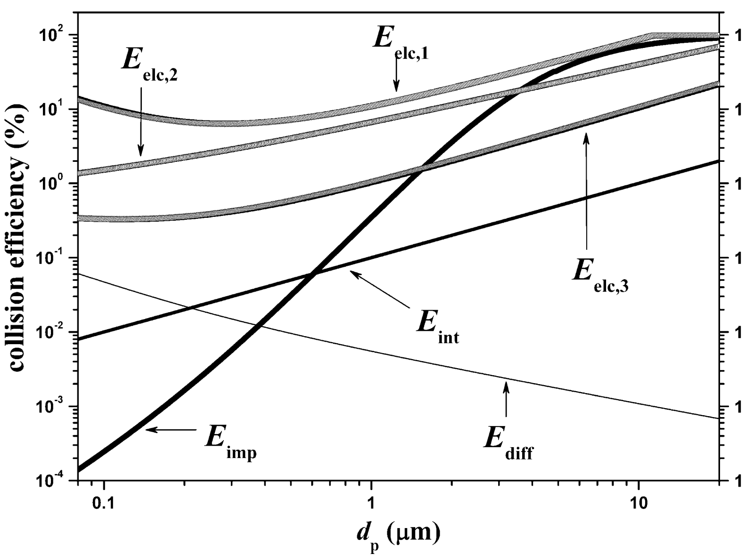

Figure 8. The contribution of several wet scrubbing mechanisms to collision efficiency.

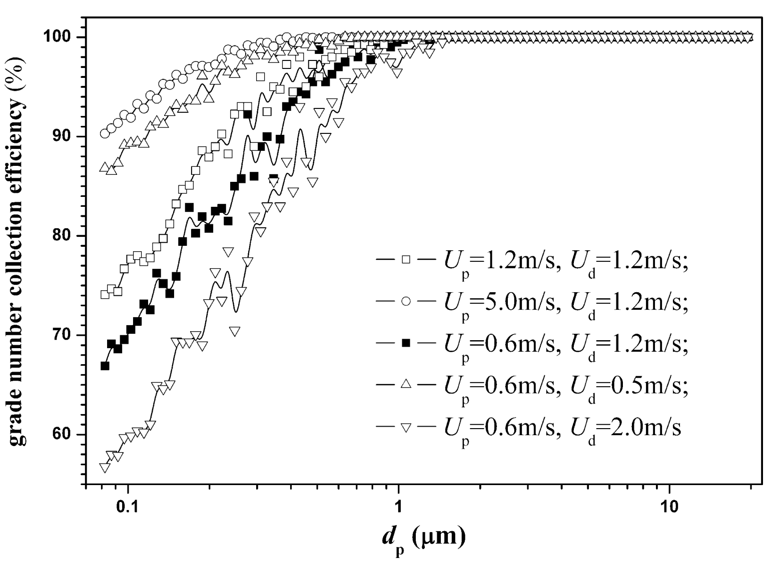

Figure 9. The influence of gas velocity and droplet velocity on the wet scrubbing kernel.

of D_{dg} and σ_{dg}, result in larger d_p/D_d ratios, and therefore, larger values of E_{int}. Fourthly, the collision efficiency due to inertial impaction, E_{imp}, correlates positively with the Stokes number for the particles, St. The value of St correlates negatively with D_d, and thus, E_{imp} also correlates negatively with D_d. Therefore, smaller values of D_{dg} and σ_{dg} result in a larger E_{imp}. Finally, smaller values of D_{dg} and σ_{dg} result in larger values of N_d and $K(d_p, D_d)$. As a result, the wet scrubbing kernel, $W(d_p)$, will increase, as indicated by Eq. (3). The above factors result in the smaller values of D_{dg} and σ_{dg} being useful for the wet scrubbing of particles of any size.

6 Conclusions

The event-driven constant-volume method for population balance modeling is used to quantitatively describe the removal of particles in wet scrubbers. Particular attention is paid to methods for enhancing the collection performance of fine particles with the help of electrostatic forces. Therefore, the droplet-charging wet scrubbers, the particle-charging wet scrubbers, and the opposite-charging wet scrubbers are simulated by means of population balance equations. The results show that wet scrubbers with electrostatic enhancement increase the collection efficiency of fine particles on the inclusion of electrostatic forces. Among the three electrostatic enhanced wet scrubbers, the wet scrubbers in which the particles and droplets are charged with opposite polarity result in the highest collection efficiency of fine particles. This type of scrubber is followed by the droplet-charging wet scrubbers and the particle-charging wet scrubbers in order of efficiency for fine particle removal.

With regard to the droplet-charging wet scrubbers, the influences of the external operating conditions on their collection performance were analyzed, and show that faster gas velocity or slower droplet velocity, smaller geometric mean diameter or geometric standard deviation of droplets, and larger liquid-to-gas flow ratio or charge-to-mass ratio of droplets, can all increase the efficiency of removal of fine particles.

Acknowledgements

The authors were financially supported by the National Natural Science Foundation of China (Grants No. 20606015 and 50721005), the National Key Basic Research and Development Program (Grants No. 2006CB705800 and 2006CB200304), and the Fok Ying Tung Education Foundation (Grant No. 114017). H. Zhao was also supported by a postdoctoral fellowship from the Alexander von Humboldt Foundation.

Symbols used

C_c	[–]	Cunningham slip correction factor
d	[μm]	particle diameter
D	[mm][m]	droplet diameter / inner diameter of wet scrubber
D_{diff}	[–]	diffusion coefficient of aerosol
E	[–][kV·cm^{-1}]	collision efficiency / electric field strength applied in droplets or in particles

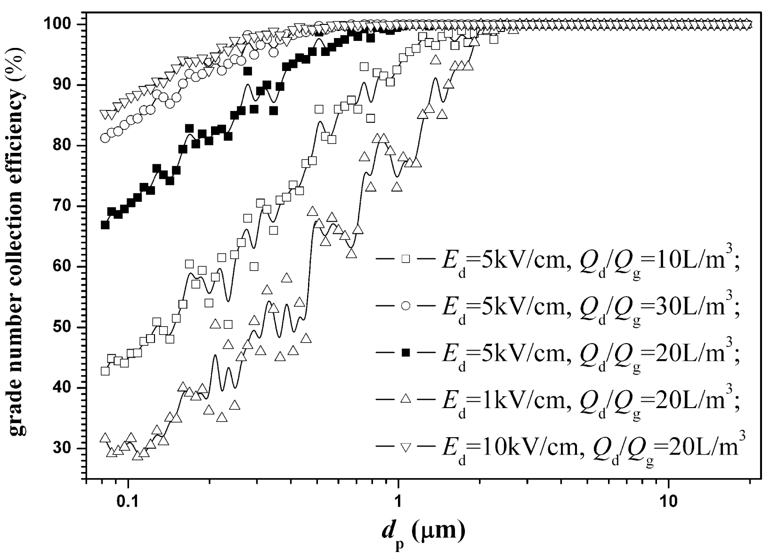

Figure 10. The influence of the liquid-to-gas flow ratio and the charge-to-mass ratio of the droplet on the wet scrubbing kernel.

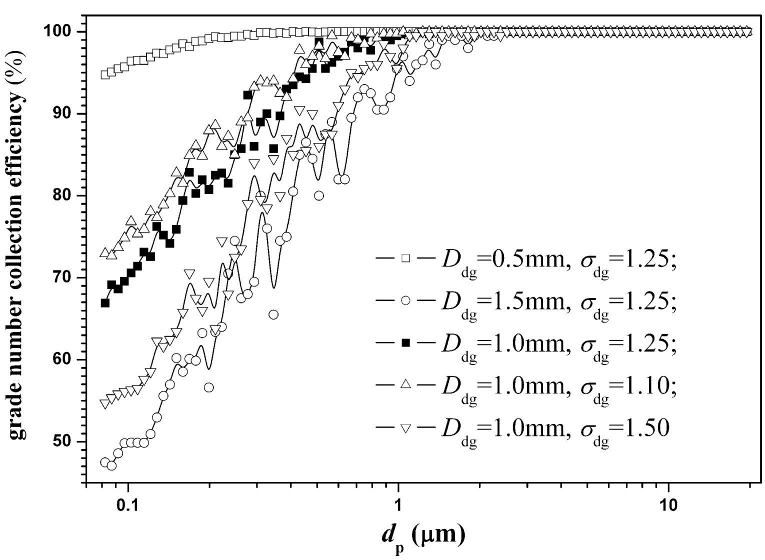

Figure 11. The influence of droplet size distribution on the wet scrubbing kernel.

h	[m]	effective scrubbing height of wet scrubber
H	[m]	total effective scrubbing height of wet scrubber
i	[–]	index of simulation particles or droplets
K	[m^{3}s^{-1}]	collision kernel
k_b	[J K^{-1}]	Boltzmann constant
M	[kg·m^{-3}]	mass concentration
n	[μm^{-1}m^{-3}][mm^{-1}·m^{-3}]	size distribution function of particles / size distribution function of particles droplets
N	[–][m^{-3}]	number of real/simulation particles or droplets / the number concentration of particles or droplets
Pe	[–]	Peclet number
q	[C]	mean charges on the droplets or on the particles
Q	[m^{3}s^{-1}][L·s^{-1}]	flux of gas stream / flux of water
r	[–]	random number
Re	[–]	Reynolds number of a particle or a droplet
Sc	[–]	Schmidt number of a particle
St	[–]	Stokes number of a particle
t	[s]	time
T	[K]	absolute temperature of the air
u, U	[m·s^{-1}]	velocity
V	[m^3]	domain volume
w	[–]	weight
W	[s^{-1}]	wet scrubbing kernel
w_1	[kg·m^{-3}]	water content

Greek symbols

ε	[–]	dielectric constant of particles or droplets
ε_0	[F·m^{-1}]	permittivity of free space
λ	[m]	mean free path length of the gas or ion
μ	[kg m^{-1}s^{-1}]	viscosity
ρ	[kg m^{-3}]	density
σ	[–]	geometric standard deviation
τ	[s]	relaxation time
Δt	[s]	time step

Subscripts

0	initial condition
a	air
d	droplets
diff	Brownian diffusion mechanism
elc	electrostatic collection mechanism
g	gas or the geometric meaning
int	interception mechanism
imp	inertial impaction mechanism
p	particles
s	simulation particles

scr wet scrubbing event
ws wet scrubber

Superscripts

+ upper limit of particle size bin
− lower limit of particle size bin

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