Separation and Purification Technology 136 (2014) 27–35

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

An efficient wet electrostatic precipitator for removing nanoparticles, submicron and micron-sized particles

Tzu-Ming Chen [a,b], Chuen-Jinn Tsai [a,*], Shaw-Yi Yan [b], Shou-Nan Li [b]

[a] Institute of Environmental Engineering, National Chiao Tung University, No. 1001 University Road, Hsinchu 30010, Taiwan
[b] Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Rm. 109, Bldg. 64, No. 195, Sec. 4, Chung Hsing Rd., Chu Tung, Hsinchu 31040, Taiwan

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form 20 August 2014
Accepted 27 August 2014
Available online 6 September 2014

Keywords:
Wet electrostatic precipitator
Deutsch–Anderson equation
Heterogeneous condensation
Particle control

ABSTRACT

An efficient wire-to-plate single-stage wet electrostatic precipitator (WESP) was designed and tested to control nanoparticles, submicron and micron-sized particles emitted from semiconductor manufacturing processes. Tungsten-wires of 0.36 mm in diameter were used as discharge electrodes and a fixed voltage of −15 kV was supplied to generate the electric field and corona ions. Fine water mist at room temperature was used to quench the high temperature exhaust gas 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 WESP was operated with fine water mist. A predictive method was developed to calculate the particle collection efficiency equation $\eta(\%)$ in the form as $\eta(\%) = [1 - \exp(-\alpha(N_{De})^{\beta} + \gamma)] \times 100\%$, in which α, β and γ are regression coefficients and N_{De} is the Deutsch number. Good agreement was obtained between present predictions and experimental data. For longer term operation, the periodic wall-cleaning water was used to clean discharge electrodes and collection electrodes regularly. In the field tests, the total collection efficiencies ($40 \leqslant d_p \leqslant 8100$ nm) of the WESP were found to maintain greater than 98.7% and 97.3% for continuous operation for 35 and 22 day at fab A and fab B, respectively.

1. Introduction

Silicon-containing chemicals including silane (SiH_4), tetraethyl orthosilicate (TEOS) and dicholorsilane (DCS) etc. are used as chemical precursors for silicon (Si) film in chemical vapor deposition (CVD) processes [1–3]. Residual SiH_4, TEOS and DCS and byproducts such as SiF_4 in the processes are emitted and treated by the local scrubbers of electric thermal or combustion types. Numerous SiO_2 nanoparticles (diameter < 100 nm) and fine particles (diameter < 2.5 μm) are formed in these local scrubbers [4,5]. These sticky and corrosive particles are emitted into the discharge gas of the local scrubbers at a temperature higher than 200 °C but without being properly treated. When emitted to the workplaces and the atmosphere, they may pose adverse effects on human health, ecology and the environment [6–10].

Electrostatic precipitators (ESPs) are used widely in the industry to remove suspended particles from the exhaust gas because of the advantages of low pressure drop and high operating flow rate. They can also be operated at high exhaust temperature while achieving high particle collection efficiency. However in dry ESPs, the accumulation of dust cake on the discharge and collection electrodes results in the decrease in the electrical field strength [11–13], particle re-entrainment caused by rapping [14–16] and back corona [17], which all lead to reduction in particle collection efficiency. In addition, dry ESPs are not suitable to collect particles that are sticky, corrosive, or have high dust cake resistivity. Wet electrostatic precipitators (WESPs) are designed and developed to eliminate the above-mentioned problems by using periodic or continuous scrubbing water to remove deposited particles on the collection electrodes [13,18].

ESPs have a high collection efficiency for fine particles. However, contrary to theory, experimental studies found that collection efficiency decreased with decreasing particle diameter for particle smaller than about 60 nm [19,20]. The low capture efficiency was primarily attributed to partial charging of ultrafine particles [21,22]. Although using the soft X-ray [23] and increasing the applied voltage of the ESPs [20,24] can minimize the partial charging effect and increases the nanoparticle collection efficiency, it may increase power consumption and operation cost.

Nucleated or heterogeneous condensation was applied in condensation particle counters (CPCs) [25] and many air pollution control devices. According to Tsai et al. [26], when the exhaust gas with a temperature higher than 200 °C was quenched with fine

* Corresponding author. Fax: +886 3 5731880.
E-mail address: cjtsai@mail.nctu.edu.tw (C.-J. Tsai).

http://dx.doi.org/10.1016/j.seppur.2014.08.032
1383-5866/

water mist at room temperature in front of the venturi scrubber, the exhaust gas could reach the super-saturation condition. Nanoparticles and submicron particles were grown to micron-sized and the collection efficiency was enhanced. Their results showed that the particle collection efficiency of the venturi scrubber with the water mist system could be enhanced to 40–80% for particles from 50 to 100 nm in diameter and 80–90% for particles larger than 100 nm. Huang et al. [27] added steam before the venturi scrubber and mixed it with waste stream at room temperature. The collection efficiencies of SiO_2 particles from 70 to 500 nm in diameter were enhanced significantly from 50% to 90%. Yang et al. [28] improved a wet flue gas desulfurization (WFGD) system by adding steam into the gas stream at room temperature to remove particles. The collection efficiency of the WFGD system for particles was improved from 25–45% to 45–70% for $CaCO_3$ particles from 70 to 10,000 nm in diameter. The results of these studies indicate that the collection efficiency of submicron particles can be enhanced by nucleated condensation but the enhancement of nanoparticles collection efficiency is not very obvious.

In the literature, there are no studies to enhance the collection efficiency of fine and nano-sized particles by condensational growth in the WESP. In this study, a wire-in-plate WESP employing particle condensational growth method was designed and tested. The fine and nano-sized particle collection efficiency of the WESP was examined with or without fine water mist using laboratory generated particles. For continuous operation, wall-cleaning water was further used to clean collection and discharge electrodes periodically to maintain a high collection efficiency. Long-term field tests of the WESP were further conducted for more than 3 weeks at two semiconductor fabrication plants (or called fabs) where lots of fine and nano-sized SiO_2 particles were emitted.

To facilitate the design of the WESP, a modified equation based on the empirical equations of Lin et al. [21] and Ortiz's et al. [29] was used to predict the particle collection efficiencies which were then validated by present and previous experimental data.

2. Experimental methods

Fig. 1 shows the schematic diagram and dimensions of the present WESP made of stainless steel with a condensation chamber at the inlet. In the condensation chamber, fine water mist (average droplet diameter is 15–20 μm) is generated by atomizer nozzles (Model SU1A, Spraying System Corp., USA) and the mixing ratio is kept at 0.9–0.11 to ensure that nanoparticles and fine particles can grow to 0.8–1.75 μm [26,27].

There are total of four channels in the WESP and four tungsten-wire discharge electrodes of 0.36 mm in diameter in each channel. The channel width is 0.048 m. The surface area of each collection electrode is 0.034 m^2. To generate the electric field and corona ions, −15 kV was supplied on the discharge electrodes by using a high voltage power supply (Model PT-10, Taiwan-ep Corp., Taiwan). The distances of discharge wire to the collection electrode and the wire to wire are 24 and 56 mm, respectively. In order to clean collection and discharge electrodes, two spray nozzles (Model Flat Jet K, Spraying System Corp., USA) were installed at the top of each collection electrode to spray clean water on the wall and wires at a wide-angle of 115–120°. For water saving, the cleaning duration was 10 s for every 10 min at the water flow rate of 0.6 L/min for each collection electrode. During cleaning, high voltage power was disconnected to avoid short circuiting.

Fig. 2 shows the experimental setup for the tests in the laboratory and at field. An electrical low pressure impactor (ELPI, Dekati Ltd., Finland), which combines the well-known impactor technology with particle charging and electrical detection and enables real-time particles size distribution measurements (size range of

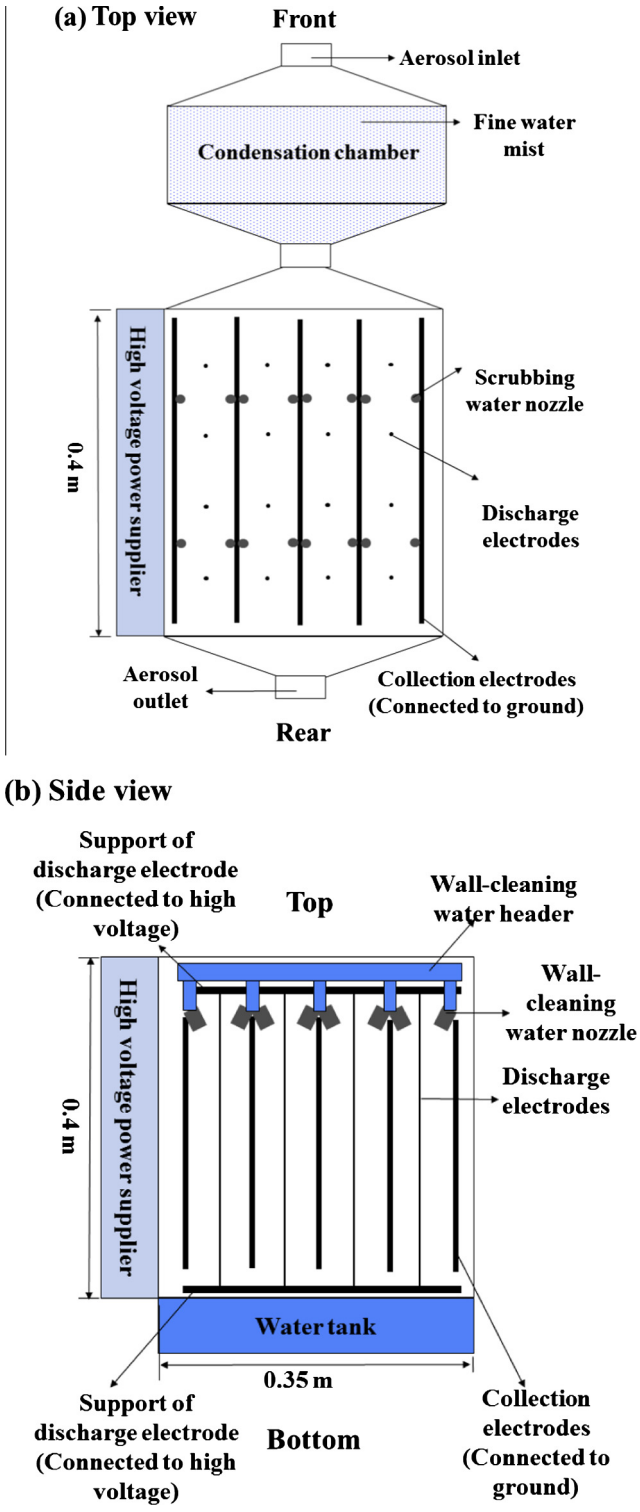

Fig. 1. Schematic diagram of the present WESP. (a) Top view and (b) side view.

30–10,000 nm), was employed to measure the size distributions at the WESP inlet and outlet. The particle collection efficiency (η_{dp}) is calculated by the following equation:

$$\eta_{dp}(\%) = \frac{C_{in}(d_p) - C_{out}(d_p)}{C_{in}(d_p)} \times 100\% \quad (1)$$

where $C_{in}(d_p)$ is the inlet particle concentration and $C_{out}(d_p)$ is the outlet particle concentration for particles with the diameter d_p.