Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.jzus.zju.edu.cn; www.springerlink.com
E-mail: jzus@zju.edu.cn

Review:

Recent advances in dust collection technology and ISO standardization in bag filtration*

Cheng-hang ZHENG[1], Chikao KANAOKA[†‡2]

[1]*State Key Laboratory of Clean Energy Utilization, State Environmental Protection Center for Coal-fired Air Pollution Control, Zhejiang University, Hangzhou 310027, China*

[2]*Kanazawa University, Kanazawa 920-1161, Japan*

[†]E-mail: kanaoka-4215@mail.bbexcite.jp

Received Feb. 10, 2017; Revision accepted Dec. 4, 2017; Crosschecked Dec. 15, 2017

Abstract: Dust collection technology is used not only as a countermeasure for air pollution, but also as removing technology for nano-particles, simultaneous removal of gas and dust, and facilitating the use of equipment in extreme conditions such as high and low pressures and temperatures. Particle concentration in the atmosphere, especially $PM_{2.5}$, has not decreased despite a reduction in the concentration of dust discharged from stationary sources. This is thought to be because of the formation of secondary particles following the discharge of condensable and/or reactive gaseous materials. Therefore, there needs to be an improvement in dust collection technology. In this paper, recent developments in dust collection technology, especially bag filtration and electrostatic precipitators, are described, and the ISO standards related to bag filtration are summarized. The future prospects for these technologies are outlined. This paper contributes to our understanding of the capture of particulate matter, which will support the improvement of particle removal technologies and the development of future applications.

Key words: Dust collection; Electrostatic precipitator (ESP); Bag filters; ISO standards
https://doi.org/10.1631/jzus.A1700072 **CLC number:** TU834.6

1 Introduction

Dust collection has been used and developed as a technology to separate particles from a gas stream enabling the recovery of valuable products from industrial processes. After air pollution became a serious social issue, dust collection has also been used extensively as a useful countermeasure to suppress the emission of air pollutants (Makino, 2015).

Particle separation equipment has been used in extreme circumstances, such as for the separation of nano-size particles, simultaneous separation of gas and particles, and particle separation at extremely high and low temperatures and pressures. Furthermore, dust collection has become an important technology for creating clean space for comfortable human life. Air pollution has become a severe and urgent issue in North-east Asia and other regions.

In this paper, current trends in particle separation technology and the ISO standardization of bag filters will be described.

2 Overview of dust collection technology

Various types of dust collectors are used for different purposes, but the dry type dust collectors are now the most widely used. Fig. 1 shows a rough sketch of the particle size and concentrations covered by typical dry type dust collectors. Although the

‡ Corresponding author

* Project supported by the National Key Research and Development Program of China (No. 2016YFC0203706), the National Natural Science Foundation of China (No. U1609212) and the Environmental Welfare Project of Ministry of Environmental Projection of China (No. 201509012)

ORCID: Cheng-hang ZHENG, https://orcid.org/0000-0003-0410-2007

coverage of each collector overlaps with those of others, air filters such as middle, high performance and high efficiency particulate air (HEPA) and ultra low penetration air (ULPA) filters are used at low dust concentration to purify the air and to create a very clean space, while cyclone, electrostatic precipitator (ESP), and bag filters are used at high dust concentration to recover products in a powder state, to prevent air pollution. Cyclone filters are used mainly as pre-dust collectors for ESP and bag filters because of their poor collection performance for fine particles. Cartridge filters are used to clean the air intake for internal combustion engines, to improve the work place environment, and to prevent emissions from machine tools, for example. However, each collector has quite a wide coverage which has tended to expand with time. For example, the coverage of bag filters and ESPs has been extended to lower particle concentration, while the use of cartridge filters has shifted to higher concentration. At the moment, bag filters and ESPs are popular as precision dust collectors at high dust concentration. At low dust concentration, air filters are mainly used. However, these have limited dust holding capacity due to their dust collection characteristics. For example, particles tend to collect inside the filter creating an increase in the pressure drop.

Nano-size particle collection is an important issue to be solved in nano-particle manufacturing and from a nano-safety point of view. When the particle concentration is very low and the gas treatment volume is small, air filters can handle this issue without any problem. However, when the gas treatment volume becomes large, air filters cannot be used for the reasons mentioned above.

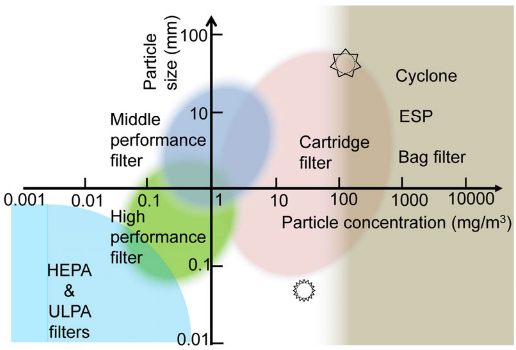


Fig. 1 Area map of dry type dust collectors in particle size and concentration space

3 Suppression of emission of $PM_{2.5}$

$PM_{2.5}$ arises not only from natural sources, but also from artificial sources. Despite significant reductions in the amount of dust discharged from artificial source, especially stationary sources, $PM_{2.5}$ concentrations have not shown a great reduction. This is thought to be because a fairly large proportion of $PM_{2.5}$ is generated by photochemical reactions in the gaseous exhaust from artificial sources. ESP and bag filters, which are the most popularly used dust collectors in stationary sources, exhaust not only particles, but also reactive or condensable gases. Hence, it is important to improve the removal performance of those collectors and/or develop new technologies effective for the reduction of $PM_{2.5}$ emissions.

3.1 ESP

Fig. 2 shows the experimental grade efficiency for removal of coal fly ash by a pilot scale ESP (Makino and Ito, 1987). Grade efficiency is very high, but is effective down only to a minimum particle size of 0.1–1 μm. This particle size range corresponds to the transition region of major charge mechanisms of diffusion and field charging. Hence, a major challenge for ESP development is to improve collection performance in the transition region. In general, the apparent resistivity of a particle is closely related to ESP performance, i.e. an ESP achieves high and stable performance for apparent resistivity ρ_d in 1×10^4–5×10^{10} Ω·cm, but performance drops significantly at smaller or higher resistivity ranges.

Ash from heavy oil combustion is an example of low resistivity dust. When low resistivity dust is collected by an ESP, collection efficiency increases

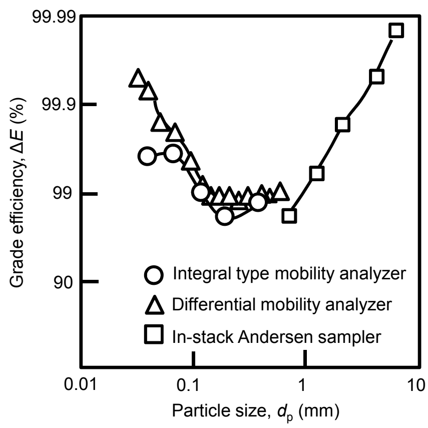


Fig. 2 Grade efficiency of a pilot scale ESP

with increasing temperature for a constant applied voltage, but decreases with temperature for a constant discharge current. However, collection efficiency increases with corona power (Fig. 3). Since corona power is the power consumption of ESP and is the product of applied voltage and discharging current, the collection efficiency of ESP can be estimated from power consumption (Watanabe et al., 1979).

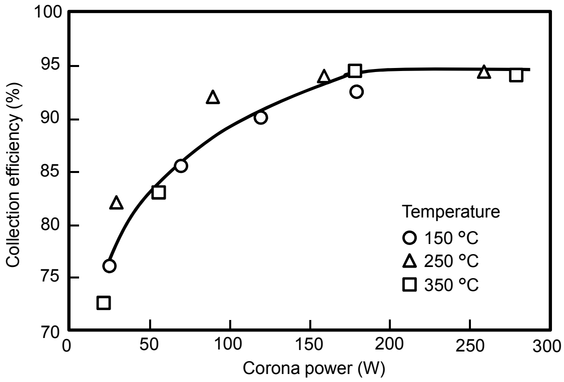


Fig. 3 Collection efficiency of ESP for low resistivity dust

Particles with $\rho_d<1\times10^4$ Ω·cm are easily captured on the collection electrode, but some are re-entrained to the gas flow, since captured particles release electrons very quickly and then are charged immediately by the electrostatic conductor to the same polarity as the electrode. They are then attracted in the direction of the discharging electrode, i.e. re-entrained to the gas stream. In other words, they flow down the ESP by repeatedly colliding with and bouncing into the collection electrode. As a result, the collection performance of the ESP drops significantly. Hence, it is necessary to have some suitable countermeasures to avoid performance degradation, such as the injection of additives to increase resistivity, injection of additives to enhance adhesive strength of particles to reduce re-entrainment, or the adoption of a water film to reduce re-entrainment (Kanaoka and Makino, 2013a).

Ash produced by the combustion of pulverized coal is an example of high resistivity dust. Fig. 4 shows the experimental collection efficiency of an ESP for high resistivity dust at different temperatures. Collection efficiency increases with corona power, but decreases as gas temperature increases, which differs from the trend shown for low resistivity dust. This is thought to be because the resistivity of coal ash decreases and the applicable voltage becomes lower as gas temperature increases (Makino et al., 1983).

In the case of $\rho_d>5\times10^{10}$ Ω·cm, it is difficult for dust particles to discharge on the collection electrodes and the electrons accumulate in the dust layer. Hence, the actual applied voltage decreases by the dust layer and the effective electric field strength becomes lower, and the collection efficiency decreases. If ρ_d becomes higher than 1×10^{13} Ω·cm, back discharge ensues and the collection efficiency decreases significantly. Hence, the lowering of the resistivity and stabilization of charging become important countermeasures (Kanaoka and Makino, 2013b). It has been found that ESP performance is improved significantly by operating at temperatures below the acid dew point of SO_3 (Fig. 5) (APPIE, 1997). ESPs of this type, called low-low-temperature ESPs, have become popular recently. Low-low-temperature ESPs allow ESPs to be compact, but special care has to be taken to avoid corrosion of equipment.

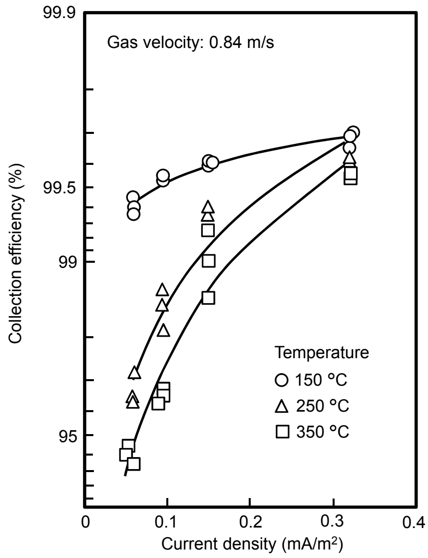


Fig. 4 Collection efficiency of ESP for high resistivity dust

High-temperature ESPs have also been studied in recent decades. High-temperature ESPs are a good solution for hot gas cleaning to ensure the long-term stability of the production system in many energy-consuming industries. In terms of pressurized fluidized bed combustion (PFBC) and integrated gasification combined cycle (IGCC), high-temperature ESPs are used to remove dust to avoid damaging downstream equipment, e.g. heat exchangers and gas turbines (Leibold et al., 2008; Brown et al., 2009; Yan et al., 2015). For example, the dust content of inlet gas should be less than 5 mg/m^3 for gas turbines. In this case, gas cleaning must be conducted at 900–1200 K (Smid et al., 2004). Fly ash also contains several hazardous heavy metal elements which could poison the catalysts and lead to their deactivation. Hence, it is necessary to place a high-temperature ESP in front of the selective catalytic reduction (SCR) system for certain types of flue gas (for example, the gas in a glass furnace) (Caputo and Pelagagge, 1999; Prabhansu et al., 2015).

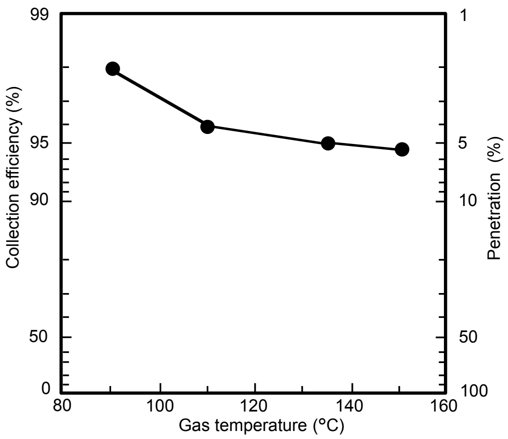


Fig. 5 Collection performance of low-low-temperature ESP

The feasibility of high-temperature ESP technology has been extensively verified. A laboratory-scale ESP can work at temperatures of up to 1366 K under a pressure of 3550 kPa (Brown and Walker, 1971; Bush et al., 1979). The characteristics of the corona discharge are fundamental for high-temperature ESPs because ion concentration and electric field strength play important roles in particle charging (Darcovich et al., 1997; Mizuno, 2000).

Research has gradually become focused on the collection characteristics of different particles at high temperature (You et al., 2010; Xu et al., 2016). Particle collection efficiency in an experimental wire-cylinder ESP for high-temperature, high-pressure biomass syngas purification was 100% at 783 K and 96% at 953 K (Villot et al., 2012). As a supplement to the experimental research, Fulyful (2008) simulated the performance of an ESP at 1–4 standard atmospheric pressure from 293 K to 700 K. The ESP operating parameters were found to be the significant factors affecting particle removal. Xu et al. (2015) studied the effects of voltage/current, particle concentration, and gas velocity through an ESP on collection efficiency from 300 K to 900 K. To enhance particle removal at high temperature, Zheng et al. (2017a, 2017b) proposed a method of enhancement through particle conditioning which increased particle collection efficiency from 65.8% to 87.6% at 623 K in a lab-scale high-temperature ESP.

Wet electrostatic precipitators (WESPs) have also been developed to avoid dust re-entrainment and increase dust removal efficiency. WESPs are widely used in industry for removal of micron-sized particles from effluent gases, and have been shown to achieve a better collection performance than dry ESPs for long-term operations (Parker, 1997; Lin et al., 2010; Dey and Venkataraman, 2012). A WESP operates in a three-step process: (1) charging the particles under non-uniform, high electric field strength, (2) collecting the charged particles on the wet collecting surface, and (3) cleaning the collected particles by washing the collecting electrode with liquids (Saiyasitpanich et al., 2006). The spraying of water can avoid back-corona discharge and dust re-entrainment, and is also helpful for particle coagulation, which may also occur in dry ESPs when dealing with submicron particles or ultrafine particles (Yang et al., 2017). A water film formed on the collection electrode surfaces greatly improves the collection efficiency of submicron particles and significantly promotes the removal of large particles. The effect of the water film on the collection efficiency of WESPs is a combined result of thermophoresis, vapor, and water flushing (Wang and You, 2013). The collection efficiency of a field WESP can be higher than 90% even against fine particles including mists. This resulted in a total particle collection efficiency of 99.98% for the gas cleaning system of a 0.7 MW pilot plant when wet and dry ESPs were used simultaneously (Kim et al., 2014). Industrial applications show that dust emissions can be lower than 5 mg/m^3 downstream of a WESP, and in some demonstrations, the emissions are lower than 2 mg/m^3.

WESPs are also used for sulfuric acid aerosol removal from wet flue gas (Jeong et al., 2013; Pan et al., 2017). The removal efficiency increased with increasing specific surface area (SCA) and electric field intensity, and also with decreasing gas temperature (Chang et al., 2011). For high sulfur content fuel, WESPs may suffer decreasing collection efficiency when dealing with corona discharge suppression (Beltran, 2008; Bologa et al., 2009). With this type of WESP installation, the performance of the WESPs can be guaranteed by carefully choosing gas velocity (Fujishima and Nagata, 2004).

The electrodes of WESPs can produce electronic corona, and free radicals like O and OH by gas discharge. These free radicals are highly reactive towards other substances. Thus, Hg^0 can be oxidized into Hg^{2+} by free radicals, and the Hg^{2+} formed can be subsequently removed by a WESP. WESP systems also remove Hg by capturing fine particles, in which the concentrations of Hg are distinctively high (Zhang et al., 2017; Zheng et al., 2017c).

3.2 Bag filters

Recently, pulse jet type bag filters have been most commonly used because they can operate at a relatively high filtration velocity and bag filter systems can be compact in size. Operation of this type of bag filter involves repetition of the stages of particle collection and cleaning of accumulated particles. The capturing stage is further divided into two stages, one "without" and one "with" a dust layer on the medium. Hence, the filtration operation can be divided into three stages. This repetition pattern can be clearly seen from Fig. 6 (Yoneda, 2001) which shows the change of outlet dust concentration over time from a pilot scale test bag filter system during the three stages. Since the cleaning pulse jet is injected impulsively (Stage 3), its duration cannot be shown in the figure, but it can be recognized at the time when the outlet dust concentration jumps up. The dust concentration increases very sharply and then drops down in a short time (Stage 1). Then it stays low until the next cleaning pulse of air is injected (Stage 2).

Features of each stage can be summarized as follows:

Stage 1: Dust collection without dust layer. This stage can be defined as the time from just after the dust cleaning process until when the filter becomes clogged. The duration is very short, but the total gas flow rate and dust concentration are much higher than those during the steady filtration period because of low flow resistivity and blow-back of the pulsed air. Furthermore, only a few particles remain on and in the medium so that incoming particles are captured and accumulate inside the medium and finally clog the filter. In other words, particles emitted from the filter and the amount of emitted dust in this stage comprises a large portion of the total emitted dust during dust bag filtration (Fig. 6). However, the number of particles remaining in the fabric at the beginning of this stage increases with the number of cleaning cycles, and thus grade collection efficiency of the fabric improves (Fig. 7) (JEMAI, 2017).

Stage 2: Dust collection with dust layer. In this stage, dust particles are captured by the sieving effect of the dust layer, which is composed of the same dust

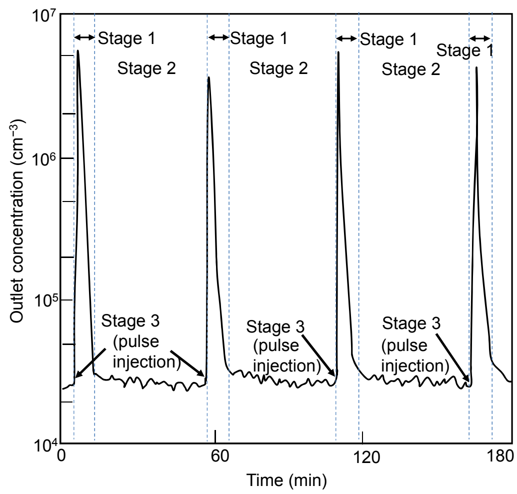


Fig. 6 Operation stage of bag filtration and outlet particle concentration from a pilot scale bag filter (Yoneda, 2001)

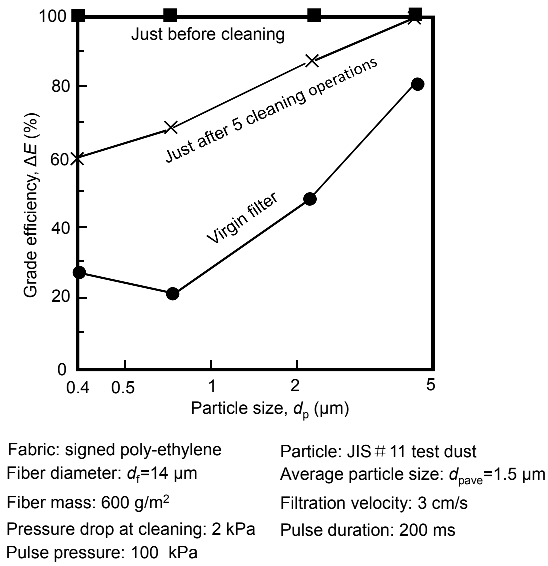


Fig. 7 Grade efficiency of non-woven fabric (JEMAI, 2017)

particles as those captured before, so fraction collection efficiency of any particle size is almost 100%, as seen from data labelled "just before cleaning" in Fig. 7. This stage lasts until the cleaning air pulse is injected. In this period, outlet particle concentration becomes extremely low. This is confirmed from the change in outlet dust concentration against dust load (Fig. 8) (Dennis and Klemm, 1979a, 1979b). The dust concentration decreases sharply with dust load *m* at the beginning, but stays constant at large *m* despite the increasing dust layer thickness, which disagrees with the theoretical prediction, i.e. that dust concentration decreases continuously. So far, no clear explanation has been found, but some leakage of dust related to uneven packing of fibers in the medium (Fig. 9) (Kanaoka and Bao, 2016), pinhole formation or seams may be contributing to this effect. However, outlet particle concentration at large *m* is several orders of magnitude lower than that just after pulse cleaning.

Stage 3: Cleaning of accumulated particles. In this stage, clean compressed air is injected into the bag filter in a very short time (several hundred ms). During the air injection, the filter, which is initially bent inwards, expands outward and the dust cake is removed (Fig. 10). Then the filter is drawn back inside by the filtration gas flow.

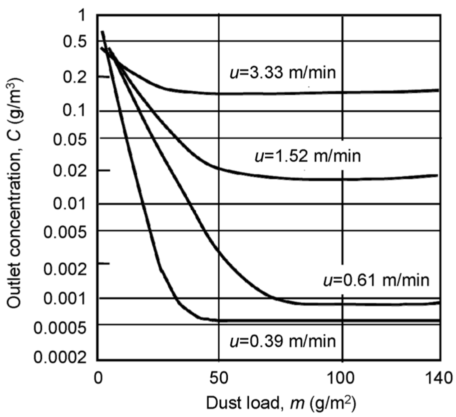


Fig. 8 Outlet concentration *C* by dust load *m* at different filtration velocities *u* from a glass fiber fabric filter

$PM_{2.5}$ is thought to be emitted mostly just after pulse cleaning, and thus deduction of particle emissions after pulse injection is the most important issue for the effective collection of $PM_{2.5}$. Hence, it is necessary to develop an effective filter medium with sufficiently high collection efficiency for $PM_{2.5}$ and to improve the operation to reduce the amount of emissions.

Pulse jet type bag filters are now popular, which simultaneously collect particles and clean filter elements in the same housing. Filter elements in the baghouse are grouped into several cleaning blocks and the elements in each block are cleaned by injecting high pressure air in a very short time. As a result, since flow resistance of cleaned filters becomes very low, gas flow concentrates to those cleaned filters and their dust load increases steeply at the beginning and slows down later. Fig. 11a schematically shows the change with time of the pressure drop of the bag house, dust load on the filter, and outlet dust concentration (Kanaoka and Makino, 2013c). Figs. 11b and 11c show the behavior of dust released just after cleaning and after the restart of filtration. Dust released by cleaning falls down into the dust bin, but re-collection of released dust might occur if it falls down against the gas flow.

This means that improvement or innovation in operations not directly related to particle collection, such as the cleaning operation method, control of gas flow in the cabin, and the operation pattern of the equipment, is a very important issue for the suppression of dust emission. For this reason, numerical simulation of gas flow in the baghouse and development of pulsed air for cleaning will be adopted for the design of bag filter systems (Sasakura et al., 2014).

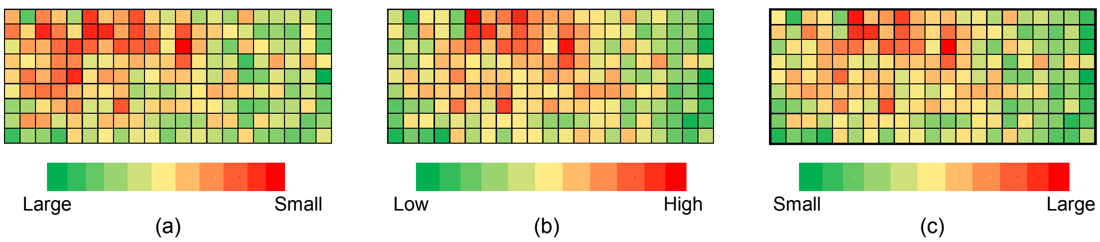


Fig. 9 Effect of un-evenness of fiber mass on permeability and emitted particles from a non-woven filter medium
(a) Surface distribution of fiber mass; (b) Permeability distribution; (c) Distribution of emitted particles at filtration velocity of 1 m/min. Fiber material: polytetrafluoroethylene, manufacturer's specifications; mass: (700±70) g/m^2; thickness: (1.2±0.3) mm

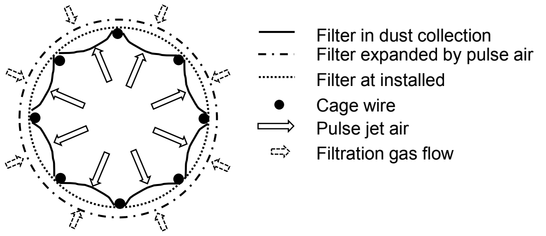


Fig. 10 Cross-sectional view of bag filter accompanying filtration and cleaning process

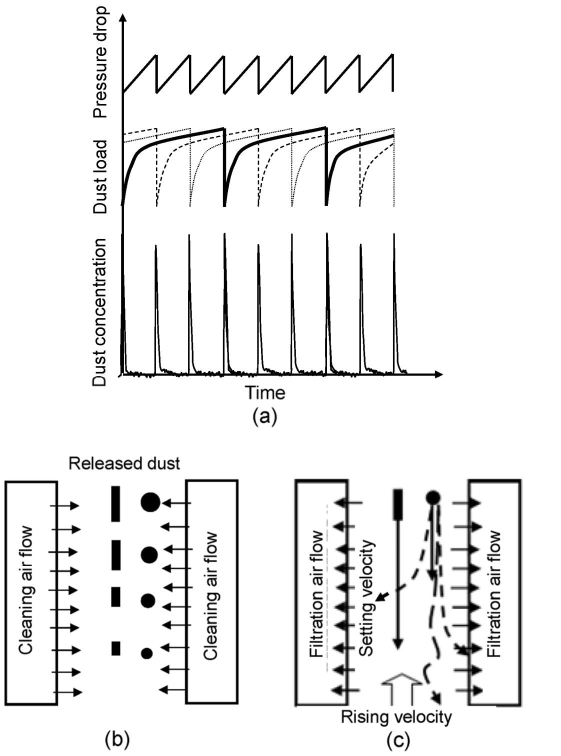


Fig. 11 Behavior of parameters with filtration operation
(a) Time change of pressure drop, dust load, and emitted dust concentration; (b) Just after cleaning operation; (c) After restart of filtration

3.3 Simultaneous removal of particles and hazardous gases

Dirty gas to be removed by dust collectors often contains small amounts of hazardous or toxic gases, like SO_x, NO_x, and HCl, and the vapor of heavy metals, such as Hg. Although they can be removed in the gaseous state, they can be removed by changing to "particles" by some means like a reaction and/or adsorption onto particles. For example, HCl gas forms solid $CaCl_2$ particles by reaction with $CaCO_3$. Such particles can then be removed by a bag filter. Fig. 12 shows the removal efficiency of HCl gas from flue gas (Yoneda and Hirai, 1997). This requires more than the stoichiometric ratio of 3 to achieve a removal efficiency of 90% when hydrated lime powder is dispersed, but a ratio of about 1 when injected in a slurry state. Hence, lime consumption needs to be reduced by developing innovative techniques to reduce the consumption of non-reacted lime (Kishima et al., 2016).

3.4 Development of a high performance filter medium

Fig. 13 shows the experimental penetration of various filters such as bag filters, HEPA, and nanofiber filters (SCEJ, 1988; Kim et al., 2007, 2009; Yun et al., 2007; Wang et al., 2011). Maximum penetration appears in particle sizes ranging from 100 nm to 1000 nm and declines as fiber diameter reduces.

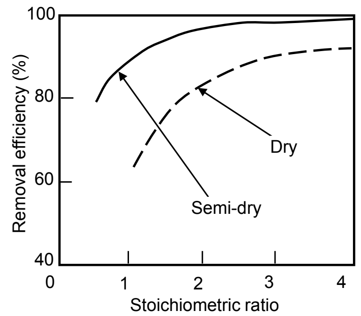


Fig. 12 Removal efficiency of HCl (Yoneda and Hirai, 1997)

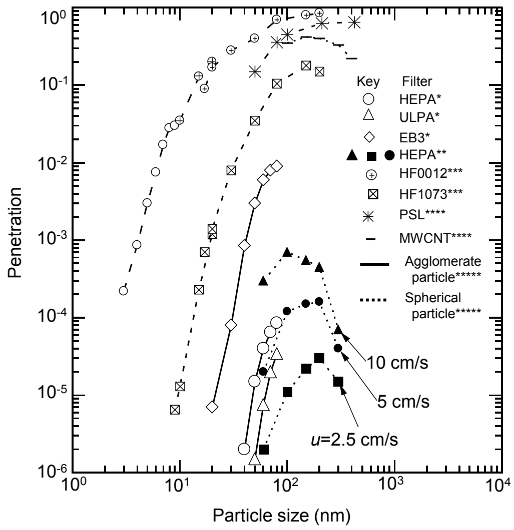


Fig. 13 Penetration of particles from various filters
Modified from (SCEJ, 1988; Kim et al., 2007, 2009; Yun et al., 2007; Wang et al., 2011). *: Yun et al. (2007); **: SCEJ (1988); ***: Kim et al. (2007); ****: Wang et al. (2011); *****: Kim et al. (2009)

Furthermore, the finer the fiber diameter, the higher is the filtration velocity and the smaller is the maximum size of penetrating particles. Furthermore, in the nano-fiber range, Cunningham's correction factor for gas slip increases greatly, and thus fluid drag acting on the fiber becomes small, i.e. the pressure drop of the filter becomes low.

From this viewpoint, various aspects of nano-fiber filters have been investigated (Wang et al., 2008; Bao et al., 2015; Nemoto et al., 2016).

4 Demand from users for innovation of bag filter technology

Since bag filters are used by various industries, the purpose and application of their use can vary among users. The Dust Collector Committee of the Association of Powder Processing Industry and Engineering (APPIE), Japan has studied uses, difficulties, and demands of users related to bag filters in different industrial sectors through factory visits and questionnaire surveys among member companies of APPIE (JSIMM, 2008). The most popular bag filter was found to be the so-called small size filter system of less than 100 m^3/min flow rate. Demands for technical improvements were similar regardless of the sectors, i.e. improvement in cleaning performance, a high filtration velocity, and a low pressure drop of the system (Table 1). Furthermore, users would like to see the unification and visualization of performance tests and results.

5 ISO standards related to bag filtration

Although many types of dust collector are used in every industry and country, there are only a few

Table 1 Summary of survey results (user demands for improvements in bag filtration technology)

Item	Demand from various areas	Demand from particular area
Bag filter system	Improvement of cleaning performance; Stabilization of flow rate; Downsizing of the system, energy saving; Reduction of initial/running costs; Unification of evaluation method of the system performance and indication method of the measured results	Height limit to enable visibility around the factory (automobile industry); Reduction of air supply to equipment distributed in the factory (automobile industry)
Filtration velocity; pressure drop	Downsizing the system even at high filtration velocity but low pressure drop and stable operation	
Collection performance	Establishment of collection technology for nano-particles; Operation under emission standard	Development of HEPA filter class bag filter systems in nano-particle industry
Safety measure	Improvement of safety measures against fire, combustion, and explosion; Participation of user in system design;	Reduction of nano-risk due to the secondary re-entrainment of particles (nano-industry)
General information	International standardization of system design, safety measure, ducting, etc.	
Filter medium	Operation and maintenance cost cut by extended filter service life; Recycle use, reuse of medium	Effective countermeasures against dew condensation (forging industry) and multi-functionalized medium including those effective for dioxin (iron industry); Washable filter medium
Functionalization		Recovery of energy, deodorization, etc. (iron industry); Contamination free (nano-particle production)
Maintenance	Visualization and standardization by formalization of the system such as central control of operation	
Improvement of working environment	Improvement of hooding for effective dust collection; Rational air conditioning	Reduction of air flow rate of dust collector in an air conditioned factory; Reduction of nano-risk by reducing emission dust from dust collector

ISO standards related to dust collectors, i.e. ISO 11057 “Air quality–test method for filtration characterization of cleanable filter media” (ISO, 2011) and ISO 16891 “Test methods for evaluating degradation of characteristics of cleanable filter media” (ISO, 2016). Both standards provide test methods to evaluate medium performance such as collection and pressure drop, and degradation by corrosive gases using an acceleration test. Two standards relating to the evaluation method of dust collector systems are discussed, i.e. ISO/PWI 16313-1 “Laboratory test of dust collection systems utilizing filter media online cleaned using pulses of compressed gas–Part 1: systems not utilizing integrated fans” and ISO/PWI 16313-2 “Laboratory test of dust collection systems utilizing filter media online cleaned using pulses of compressed gas–Part 2: system utilizing integrated fans.”

5.1 ISO 11057

This international standard describes a standard reference test method for a pulse-jet cleanable flat filter medium for dry gas cleaning applications. The main purpose of testing is to gain information about both the operation performance and the particle emissions of a cleanable filter medium. The results obtained from this method cannot be used for predicting the absolute performance of full scale filter facilities. However, they will be helpful for the selection and development of appropriate cleanable filter mediums and the identification of suitable operating parameters.

Fig. 14 is a sketch of test apparatus shown in ISO 11057. Pural NF is used as the test powder and is fed at a constant rate from the top of the apparatus. It is dispersed by compressed air and the resulting dirty gas flows vertically down the duct. Then a part of the dirty gas penetrates into a test filter medium, which is attached vertically on the vertical duct. Test powder is collected on the filter medium. When the pressure drop of the filter medium reaches a pre-determined value, the filter is cleaned by means of a pulse of compressed air.

In this standard, a test is required to be performed in the listed sequence shown in Table 2 and with operating parameters listed in Table 3.

Fig. 15 shows an example of the change in residual pressure drop against time given in ISO 11057.

In the standard, although one test apparatus and operating method has been chosen, other apparatuses are acceptable if results (residual pressure drop, cleaning cycle time, residual dust mass, and clean gas

Table 2 Sequence of the standard test phases

Measuring phase	Condition	Determination of clean-gas concentration
Phase 1: conditioning	30 loading cycles with differential pressure controlled pulse-jet cleaning and a cleaning set point of 1000 Pa	Yes
Phase 2: ageing	2500 pulse-jet cleaning cycles at an interval of 20 s each	No
Phase 3: stabilizing	10 loading cycles with differential pressure controlled pulse-jet cleaning	No
Phase 4: measuring	30 cleaning cycles but at least 2 h measuring time with differential pressure controlled pulse-jet cleaning set point of 1000 Pa	Yes
Phase 5: optional measuring	2 h loading cycles with raised cleaning set point of 1800 Pa	Yes

Table 3 Primary test parameters and tolerances

Parameter	Value	Tolerance
Filter face velocity (m/min)	2	±3%
Dust concentration presented to the sample filter (g/m^3)	5	±7%
Pressure drop prior to pulse-jet cleaning (Pa)	1000	±1%
Tank pressure (MPa)	0.5	±3%
Valve opening time (electric) (ms)	60	

Test dust: Pural NF (aluminum oxide hydroxide γ-AlO(OH)), average particle size in mass basis χ_{50}≈4.5 μm

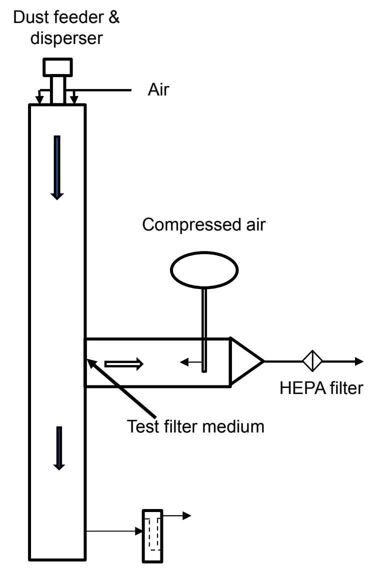


Fig. 14 Test apparatus shown in ISO 11057

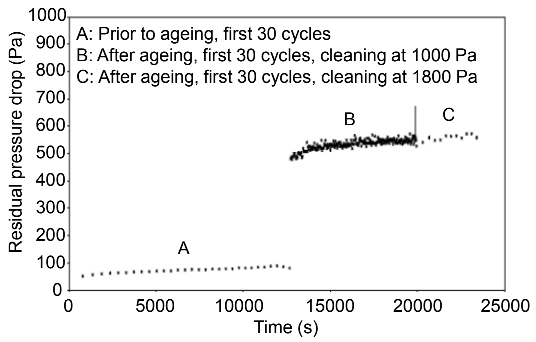


Fig. 15 Development of residual pressure drop vs. time before and after ageing

dust concentration) of a candidate apparatus agree with the reference apparatus within 10% accuracy.

5.2 ISO 16891

This international standard specifies a standard reference test method useful for assessing the relative degradation characteristics of cleanable filter media for industrial applications under standardized simulated test conditions. The main purpose of testing is to obtain information about the relative change in the properties of the filter media due to exposure to the simulated gas conditions for a long time. The main target of this international standard is the change in the properties of non-woven fabric filters because they are frequently used under similar circumstances to the test gas conditions described in this standard.

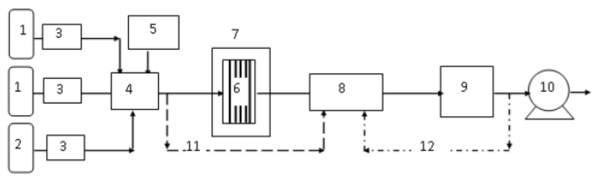
The physical performance of filter media usually degrades with time because of long time exposure under severe gas conditions, such as hot and/or corrosive gas conditions. When filter media are exposed to hot and/or corrosive gas atmospheres, those gases are considered to interact with materials in the fiber resulting in irreversible damage to the media and a weakening of physical performance, including tensile strength and elongation. The tensile strength after filter media are exposed to corrosive gases and/or high temperature can be expressed by the following equation, assuming that the degradation reaction between the corrosive gas and some reactive component in a fiber is pseudo linear:

$$\tau(0)-\tau(t)=\Delta\tau=F(A)\left[1-\exp(-Kt)\right],$$

where $\tau(t)$ is the tensile strength of filter media at time t, $F(A)$ is the unknown constant related to total surface area of filter media A, and K is the effective reaction constant and is related to the degradation of media.

The degradation process is very slow and thus measurable change appears only after filter media have been exposed for a very long time. Hence, in this international standard, degradation is accelerated by exposing the filter media to a higher corrosive gas concentration and higher gas temperature. The test is specified to be carried out in the following three steps: (1) preparation of filter sample sheets for gas exposure, (2) exposure of sheets, and (3) tensile test.

A test specimen with similar permeability is first selected and then exposed to test gases at high temperature by the system shown in Fig. 16. A corrosive gas could be chosen to suit the purpose of the filter media from Table 4, but the test gas and its concentration could also be chosen by negotiation among



1: test gas; 2: balance gas; 3: mass flow controller; 4: mixing box; 5: moisture generator; 6: expose chamber with filter sample sheets; 7: heating system; 8: gas analyzer; 9: gas treatment device; 10: pump; 11: gas line for inlet gas concentration measurement; 12: gas line for gas concentration measurement for exhaust gas

Fig. 16 Example of continuous flow through type setup for exposure test

stakeholders. Parameters such as tensile strength, elongation, and mass loss are then measured. Fig. 17 shows an example of a test result shown in ISO 16891.

Table 4 Gas composition for exposure

Exposing gas	Gas composition
N_2	N_2: 100% (only for thermal exposure)
NO_x	NO_2: 0.1%, O_2: 10%, N_2: balance
SO_x	SO_2: 0.1%, N_2: balance;
	SO_2: 0.1%, moisture: 20%, N_2: balance
HCl	HCl: 0.2%, N_2: balance;
	HCl: 0.2%, moisture: 20%, N_2: balance
Mixed gas 1	NO_2: 0.1%, SO_2: 0.1%, HCl: 0.2%, O_2: 10%, N_2: balance
Mixed gas 2	NO_2: 0.1%, SO_2: 0.1%, HCl: 0.2%, O_2: 10%, moisture: 20%, N_2: balance

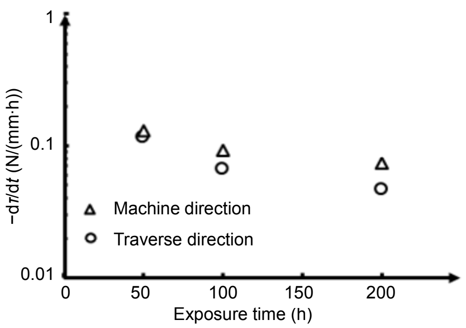


Fig. 17 Tensile strength vs. exposure time

6 Conclusions

Suppression of $PM_{2.5}$ is a very difficult but urgent issue to be solved in relation to global warming, especially in North-east Asia. To accomplish this, dust collectors, especially ESPs and bag filters, play an important role.

In this paper, we reviewed the state-of-the-art of dust collectors and surveyed the development of dust collection technology, especially bag filtration, wet ESPs, and high-temperature ESPs. ISO standards related to bag filtration were also described. In the future, technologies for improving the performance of dry ESPs, wet ESPs, and high-temperature ESPs will be applied in different areas and industries. Bag filters with high cleaning performance, high filtration velocity, and a low pressure drop will still be widely demanded. This paper contributes to our understanding of the capture of particulate matter, and provides a basis for the improvement of particle removal technologies and the development of future applications.

References

APPIE (Association of Powder Processing Industry and Engineering), 1997. Shuujin no Gijutsu to Souchi. Nikkan Kogyo, Japan, p.125 (in Japanese).

Bao L, Kiyotani H, Chaen S, et al., 2015. Investigation of HEPA filter media for energy saving. 32nd Annual Meeting on Air Cleaning and Contamination Control, p.125-126 (in Japanese).

Beltran MR, 2008. Wet ESP for the collection of submicron particles mist and air toxics. 11th International Conference on Electrostatic Precipitation.

Bologa A, Paur HR, Seifert H, et al., 2009. Novel wet electrostatic precipitator for collection of fine aerosol. *Journal of Electrostatics*, 67(2-3):150-153. https://doi.org/10.1016/j.elstat.2009.01.059

Brown D, Gassner M, Fuchino T, et al., 2009. Thermo economic analysis for the optimal conceptual design of biomass gasification energy conversion systems. *Applied Thermal Engineering*, 29(11-12):2137-2152. https://doi.org/10.1016/j.applthermaleng.2007.06.021

Brown RF, Walker AB, 1971. Feasibility demonstration of electrostatic precipitation at 1700 F. *Journal of the Air Pollution Control Association*, 21(10):617-620. https://doi.org/10.1080/00022470.1971.10469576

Bush JR, Feldman PL, Robinson M, 1979. High-temperature, high-pressure electrostatic precipitation. *Journal of the Air Pollution Control Association*, 29(4):365-371. https://doi.org/10.1080/00022470.1979.10470802

Caputo AC, Pelagagge PM, 1999. Cost-effectiveness analysis of waste gas treatment plants for the glass industry. *Journal of the Air & Waste Management Association*, 49(12):1456-1462. https://doi.org/10.1080/10473289.1999.10463971

Chang J, Dong Y, Wang Z, et al., 2011. Removal of sulfuric acid aerosol in a wet electrostatic precipitator with single terylene or polypropylene collection electrodes. *Journal of Aerosol Science*, 42(8):544-554. https://doi.org/10.1016/j.jaerosci.2011.05.006

Darcovich K, Jonasson KA, Capes CE, 1997. Developments in the control of fine particulate air emissions. *Advanced Powder Technology*, 8(3):179-215. https://doi.org/10.1016/S0921-8831(08)60463-X

Dennis R, Klemm HA, 1979a. Fabric Filter Model Format Change. Vol. I. Detailed Technical Report; Vol. II. User's Guide. Report No. EPA/600/7-79/043a-b, Environmental Protection Agency, USA.

Dennis R, Klemm HA, 1979b. A model for coal fly ash filtration. *Journal of the Air Pollution Control Association*, 29(3):230-234.

Dey L, Venkataraman C, 2012. A wet electrostatic precipitator (WESP) for soft nanoparticle collection. *Aerosol Science and Technology*, 46(7):750-759. https://doi.org/10.1080/02786826.2012.664295

Fujishima H, Nagata C, 2004. Experiences of wet type electrostatic precipitator successfully applied for SO_3 removal in boilers using high sulfur content fuel. Ninth International Conference on Electrostatic Precipitation.

Fulyful FK, 2008. High temperature-high pressure effect on performance of an electrostatic precipitator. *Journal of Kerbala University*, 6(2):84-92.

ISO (International Organization for Standardization), 2011. Air Quality–Test Method for Filtration Characterization of Cleanable Filter Media, ISO 11057. ISO.

ISO (International Organization for Standardization), 2016. Test Methods for Evaluating Degradation of Characteristics of Cleanable Filter Media, ISO 16891. ISO.

JEMAI (Japan Environmental Management Association for Industry), 2017. Shin Kogaiboushi no Gijutu to Houki. Taikihen, Maruzen, Japan, p.298 (in Japanese).

Jeong SH, Shim SH, Song DK, et al., 2013. Performance of a pilot-scale wet electrostatic precipitator for the control of sulfuric acid mist and fine particulates. *Polish Journal of Environmental Studies*, 22(2):409-415.

JSIMM (Japan Society of Industrial Machinery Manufacturers), 2008. Study on the Extraction of Subjects Necessary for Bag Filter System for Environmental Protection Use. JSIMM Report.

Kanaoka C, Makino H, 2013a. Hajimete no Shuujin Gijutsu. Nikkan Kogyo, Japan, p.75 (in Japanese).

Kanaoka C, Makino H, 2013b. Hajimete no Shuujin Gijutsu. Nikkan Kogyo, Japan, p.79-85 (in Japanese).

Kanaoka C, Makino H, 2013c. Hajimete no Shuujin Gijutsu. Nikkan Kogyo, Japan, p.139 (in Japanese).

Kanaoka C, Bao LM, 2016. Packing density distribution of fiber in a nonwoven filter media. Preprint of the 33rd Annual Meeting on Air Cleaning and Contamination Control, p.96-99 (in Japanese).

Kim HJ, Han B, Woo CG, et al., 2014. Performance evaluation of dry and wet electrostatic precipitators used in an oxygen-pulverized coal combustion and a CO_2 capture and storage pilot plant. *Journal of Aerosol Science*, 77: 116-126. https://doi.org/10.1016/j.jaerosci.2014.07.003

Kim SC, Harrington MS, Pui DYH, 2007. Experimental study of nanoparticles penetration through commercial filter media. *Nanotechnology and Occupational Health*, 2006: 117-125. https://doi.org/10.1007/978-1-4020-5859-2_12

Kim SC, Wang J, Emery MS, et al., 2009. Structural property effect of nanoparticle agglomerates on particle penetration through fibrous filter. *Aerosol Science and Technology*, 43(4):344-355. https://doi.org/10.1080/02786820802653763

Kishima T, Wada Y, Iio Y, et al., 2016. Reduction of consumption amount of chemicals used in a bag filter system for hazardous gas (HCl) removal in a municipal waste incineration gas. Preprint of the 27th Annual Meeting of Japan Society of Material Cycles and Waste Management, p.361-362 (in Japanese).

Leibold H, Hornung A, Seifert H, 2008. HTHP syngas cleaning concept of two stage biomass gasification for FT synthesis. *Powder Technology*, 180(1-2):265-270. https://doi.org/10.1016/j.powtec.2007.05.012

Lin GY, Tsai CJ, Chen SC, et al., 2010. An efficient single-stage wet electrostatic precipitator for fine and nanosized particle control. *Aerosol Science and Technology*, 44(1): 38-45. https://doi.org/10.1080/02786820903338298

Makino H, 2015. Development tendency and future prospect of dust collection technology for environmental protection. *Funtai Gijutsu*, 7:105-112 (in Japanese).

Makino H, Ito S, 1987. Emission control of sub-micron particles in pulverized coal combustion flue gas. *Kagaku Kogaku*, 51:523-526 (in Japanese).

Makino H, Sato M, Ninomiya T, 1983. Evaluation of Collection Characteristics of Electrostatic Precipitore from Coal and Coal Ash Properties. CRIEPI Research Report No. 283023, Central Research Institute of Electric Power Industry, Japan (in Japanese).

Mizuno A, 2000. Electrostatic precipitation. *IEEE Transactions on Dielectrics and Electrical Insulation*, 7(5):615-624. https://doi.org/10.1109/94.879357

Nemoto J, Soyama T, Saito T, et al., 2016. Preparation of nanocellulose containing air filter media. 33rd Annual Meeting on Air Cleaning and Contamination Control, p.117-118 (in Japanese).

Pan D, Yang L, Wu H, et al., 2017. Removal characteristics of sulfuric acid aerosols from coal-fired power plants. *Journal of the Air & Waste Management Association*, 67(3):352-357. https://doi.org/10.1080/10962247.2016.1202155

Parker KR, 1997. Applied Electrostatic Precipitation. Blackie Academic & Professional, London, UK.

Prabhansu, Karmakar MK, Chandra P, et al., 2015. A review on the fuel gas cleaning technologies in gasification process. *Journal of Environmental Chemical Engineering*, 3(2):689-702. https://doi.org/10.1016/j.jece.2015.02.011

Saiyasitpanich P, Keener TC, Lu M, et al., 2006. Collection of ultrafine diesel particulate matter (DPM) in cylindrical single-stage wet electrostatic precipitators. *Environmental Science & Technology*, 40(24):7890-7895. https://doi.org/10.1021/es060887k

Sasakura S, Hamada N, Kishima T, 2014. New pulse jet bag filter: ECO pulser. *Nihon Spindle Technical Report*, 54:5 (in Japanese).

SCEJ (Society of Chemical Engineers, Japan), 1988. Chemical Engineering Handbook, 5th Edition. Maruzen, Japan, p.793 (in Japanese).

Smid J, Peng CY, Lee HT, et al., 2004. Hot gas granular

moving bed filters for advanced power systems. *Filtration & Separation*, 41(10):32-35.
https://doi.org/10.1016/S0015-1882(04)00380-5

Villot A, Gonthier Y, Gonze E, et al., 2012. Separation of particles from syngas at high-temperatures with an electrostatic precipitator. *Separation and Purification Technology*, 92:181-190.
https://doi.org/10.1016/j.seppur.2011.04.028

Wang J, Kim SC, Pui DYH, 2008. Investigation of the figure of merit for filters with a single nanofiber layer on a substrate. *Journal of Aerosol Science*, 39(4):323-334.
https://doi.org/10.1016/j.jaerosci.2007.12.003

Wang J, Kim SC, Pui DYH, 2011. Measurement of multi-wall carbon nanotube penetration through a screen filter and single-fiber analysis. *Journal of Nanoparticle Research*, 13(10):4565-4573.
https://doi.org/10.1007/s11051-011-0415-y

Wang X, You C, 2013. Effects of thermophoresis, vapor, and water film on particle removal of electrostatic precipitator. *Journal of Aerosol Science*, 63:1-9.
https://doi.org/10.1016/j.jaerosci.2013.04.003

Watanabe M, Nagayama T, Matsuda H, et al., 1979. Collection Efficiency of High Temperature Electrostatic Precipitation for Oil Burning Boiler (Part II). CRIEPI Research Report No. 279004, Central Research Institute of Electric Power Industry, Japan (in Japanese).

Xu X, Gao X, Yan P, et al., 2015. Particle migration and collection in a high-temperature electrostatic precipitator. *Separation and Purification Technology*, 143:184-191.
https://doi.org/10.1016/j.seppur.2015.01.016

Xu X, Zheng C, Yan P, et al., 2016. Effect of electrode configuration on particle collection in a high-temperature electrostatic precipitator. *Separation and Purification Technology*, 166:157-163.
https://doi.org/10.1016/j.seppur.2016.04.039

Yan P, Zheng C, Xiao G, et al., 2015. Characteristics of negative DC corona discharge in a wire-plate configuration at high temperatures. *Separation and Purification Technology*, 139:5-13.
https://doi.org/10.1016/j.seppur.2014.10.026

Yang Z, Zheng C, Chang Q, et al., 2017. Fine particle migration and collection in a wet electrostatic precipitator. *Journal of the Air & Waste Management Association*, 67(4):498-506.
https://doi.org/10.1080/10962247.2016.1260074

Yoneda T, 2001. Dust collection technologies by fabric filters. *Journal of the Society of Powder Technology, Japan*, 38(6):436-445 (in Japanese).
https://doi.org/10.4164/sptj.38.436

Yoneda T, Hirai S, 1997. Exhaust gas treatment system using bag filters and dioxins reduction technology. *Journal of the Japan Institute of Energy*, 76:963-970 (in Japanese).

You C, Wang X, Liu R, et al., 2010. Simultaneous effects of electrostatic field and thermophoresis on inhalable particulate matter removal. *Powder Technology*, 202(1-3): 95-100.
https://doi.org/10.1016/j.powtec.2010.04.022

Yun KM, Hogan CJ, Matsubayashi Y, et al., 2007. Nanoparticle filtration by electrospun polymer fiber. *Chemical Engineering Science*, 62(17):4751-4759.
https://doi.org/10.1016/j.ces.2007.06.007

Zhang Y, Yang J, Yu X, et al., 2017. Migration and emission characteristics of Hg in coal-fired power plant of China with ultra low emission air pollution control devices. *Fuel Processing Technology*, 158:272-280.
https://doi.org/10.1016/j.fuproc.2017.01.020

Zheng C, Shen Z, Chang Q, et al., 2017a. Experimental study on electrostatic precipitation of low-resistivity high-carbon fly ash at high temperature. *Energy & Fuels*, 31(6):6266-6273.
https://doi.org/10.1021/acs.energyfuels.7b00107

Zheng C, Shen Z, Yan P, et al., 2017b. Particle removal enhancement in a high-temperature electrostatic precipitator for glass furnace. *Powder Technology*, 319:154-162.
https://doi.org/10.1016/j.powtec.2017.06.017

Zheng C, Wang L, Zhang Y, et al., 2017c. Partitioning of hazardous trace elements among air pollution control devices in ultra-low-emission coal-fired power plants. *Energy & Fuels*, 31(6):6334-6344.
https://doi.org/10.1021/acs.energyfuels.7b00894

中文概要

题　目： **除尘技术研究进展和袋式除尘 ISO 标准**

目　的： 分析当前最新的针对烟气中颗粒物的高效脱除技术，包括静电除尘和袋式除尘的提效方法、原理以及所能达到的效果等；对研究现状进行评述和对未来发展做出展望，并介绍袋式除尘的相关 ISO 标准。

创新点： 1. 总结了各参数对静电除尘器（包括低低温静电除尘、高温静电除尘和湿式静电除尘等）除尘效率的影响；2. 分析比较了不同结构形式的滤袋并总结了适应更高过滤要求的新型过滤材料。

方　法： 1. 通过数据分析，比较不同粒径、比电阻和温度对静电除尘器除尘效率的影响，并提出相关改进措施；2. 比较不同形式滤袋的收尘特点，结合 ISO 标准和当前工业需求，对袋式除尘进行展望。

结　论： 1. 为保证除尘效率，对于不同特性的粉尘，可采取不同形式的静电除尘器增效技术；2. 为满足更高的过滤要求，在袋式除尘器方面，急需开发新型过滤材料和优化清灰技术，以适应更高的温度和满足更高的清灰要求。

关键词： 除尘；静电除尘器；滤袋；ISO 标准