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Invited review

Developments in the control of fine particulate air emissions*

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Abstract—A comprehensive review of emerging technologies and recent developments in air pollution control equipment and processes specifically addressing particulate removal is provided here. Emphasis is placed on approaches with a high degree of novelty and/or involving new modifications to conventional systems. Some emerging areas, such as waste incineration, have produced new particulate matter control needs which will be discussed. The subject and key problem areas are introduced, followed by a brief description of the various particle capture mechanisms and the principal technology groups which exploit these mechanisms to achieve particle capture. More details are then given for specific innovative projects, organized principally by technology, as well as by industry sector. Finally, alternatives to end-of-pipe treatment strategies are discussed. An extensive list of references is included, representative of a thorough literature survey.

1. INTRODUCTION

In the 1970s, it became widely recognized that fine particles from industrial processes and automobiles had a significantly more negative environmental impact than the relatively large particles of windblown dust regulated by the US Enviromental Protection Agency (EPA) as 'total suspended particulate matter' (TSP). In terms of air pollution control, particles with aerodynamic diameters less than 10 μm, referred to as PM10, have been targetted for removal. Studies in Canada and the US have typically identified sources such as fugitive dust, construction, agriculture and fuel combustion as the main contributors to PM10 loadings. At present in the US, PM10 is a guideline used for air quality standards. Pressure has been building to tighten the standard to PM2.5. With particles in this finer size fraction, impacts on human health are more pronounced due to an increased relative toxics concentration, as well as ready respirability.

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Advanced fine particle removal technologies are considered to be end of pipe systems capable of treating PM10 (or even PM2.5) material to produce gas stream emissions in compliance with air quality standards, and with some margin to be effective under tighter anticipated future regulations. Emission prevention strategies are also included.

In 1990 the US EPA produced a list of 189 Hazardous Air Pollutants (HAPs) under the Clean Air Act Amendments. This Act identifies specific chemical elements and compounds as harmful to health and environment, and places restrictions on the permissible emissions levels. The control of HAPs impacts particulate removal practice in that some HAPs are released in solid form (mostly metals), or in the case of some volatile organic compounds (VOCs), are adsorbed onto particulates also present in the emission stream.

The removal of particles (liquids, solids or mixtures) from a gas stream requires their deposition and attachment to a surface. The surface may be continuous, such as the wall and cone of a cyclone or the collection plates of an electrostatic precipitator, or the surface may be discontinuous such as spray water droplets in a scrubbing tower. Once deposited on a surface, a means must be provided to remove the collected particles continuously or at intervals without appreciable reentrainment into the gas stream.

The magnitude of the force to move a particle toward a collecting surface is influenced markedly by the size and shape of the particle. Gravity settling will be efficient only on large particles; 40–50 μm is the lower limit of effectiveness. Flow line interception and inertial impaction will be effective on particles down to 2–3 μm. Diffusional deposition and thermal precipitation become increasingly efficient with decrease in particle size and are highly efficient on particles smaller than 0.2 μm. Electrostatic forces are the strongest forces that can act on fine particles (loosely defined as particles smaller than 2–3 μm).

Control equipment for particulates fall into five general classes, i.e. gravity/inertial settlers; centrifugal separators (cyclones); electrostatic precipitators; fabric, packed bed or rigid barrier filters; and wet scrubbers. Such equipment must be matched to the particle characteristics as well as variables such as flow rate, temperature and required removal efficiency. It is well recognized that no universal particle removal method exists which will satisfy all problems and conditions. The choice is often based on a compromise between technical and economic factors.

This present review stems from participation in a techno-economic assessment of emerging air pollution control technologies [1]. Other overviews of the field of fine particle removal technology are available in a number of monographs having various perspectives [2–7].

This article first presents a brief overview of particle removal mechanisms, then a summary of the generic technology groups that have been developed to exploit these mechanisms. The bulk of the review will then focus on specific novel technologies, processes and fundamental mechanisms that have been identified from an extensive literature survey on the subject. The emphasis will be to highlight innovative pre-commercial systems as well as recent research findings with potential application to advanced fine particle removal technologies.

1.1. Particle removal mechanisms

1.1.1. Sieving. When a gas stream containing particulate matter passes through a collection device (typically a screen) where the gaps between the collectors are smaller than the particle dimension, the solid is retained on the barrier. Generally, this mechanism is best suited for larger particles and is not common for industrial gas cleaning.

1.1.2. Gravity settling. All particles are subject to gravity and will attain a terminal settling velocity under quiescent conditions. Brownian motion, thermal, turbulent and convective forces may act on very small particles to stabilize their suspension in air. Generally, however, a net downward motion will arise for particles larger than 5 μm. The collector may be fibrous, a granular bed or simply the floor of a settling chamber. Gravity settling is not a common fine particulate matter removal mechanism.

1.1.3. Inertial impaction. Larger particles in a gas stream will possess enough momentum to deviate from the fluid streamlines and collide with a collecting obstacle in their path. These particles are separated by impaction. Collection efficiency is enhanced by larger particle diameter or conversely, a smaller collector dimension that will enhance contact. Certain types of fibre filters, packed beds, spray systems, impinging stream collectors and cyclones employ this removal mechanism.

1.1.4. Interception. A particle being carried by a fluid may experience a grazing collision with a collector, which is known as interception. This mechanism differs from impaction in the sense that the particle does not actually need to depart from the fluid streamline to contact the collector. The nature of the fluid flow is less important for this mechanism. Interception and impaction may operate simultaneously, although the latter becomes dominant at higher gas velocities. Internal tortuosity in a filter medium will cause numerous gas stream direction changes and will increase the probability that interception or impaction would occur.

Collection efficiency generally increases with increasing particle to collector size ratio. Examples include the collection of particles in fibrous or granular filter media.

1.1.5. Diffusion. Concentration gradients of particles in a gaseous medium will induce migration of particulate matter to regions of lower local concentration. The gas phase particle concentration next to collector surfaces is normally small, so that there is usually a diffusional force acting on the particles to cause them to approach the collector. Small gas phase velocities and particle diameters enhance collection by this mechanism. A large collector surface area is normally required for separations to be effected in this way. Fibrous and granular media and small liquid droplets can remove particulate matter by this mechanism.

1.1.6. Electrostatics. Inherently, particulate matter will possess some degree of surface electrical charge. Various ways of conditioning the feed stream can enhance this charging. An externally imposed electrical field will apply a force on charged matter and will set it in motion towards a collector of opposite electrical charge. Electrostatic collection is improved by increasing the magnitude of the electrical attraction, decreasing particle size and decreasing the flow rate of the gas stream.

Electrostatic precipitators are a technology employing this capture mechanism. The performance of other types of collectors such as fabric filters and some scrubbers is enhanced with electrostatic charging.

1.1.7. Other mechanisms. Other phenomena exist which cannot be used alone as capture mechanisms, but knowledge of their effects is constructive in designing advanced fine particle removal equipment. Particles suspended in a gas are known to descend thermal gradients, having a tendency to move towards cold surfaces or away from hot surfaces. This is known as *thermophoresis.* Basically, a cold collection system will enhance particle removal from a hot gas stream.

In a parallel fashion, any species of gas diffusing within a carrier stream will induce a flux. For example, particles would generally be carried toward a surface where condensation is occurring and away from a surface where evaporation is occurring.

1.1.8. General removal mechanism considerations. While all of the above particle removal mechanisms can act at the same time, they have more marked effects for specific particle sizes. Figure 1 shows schematically the effect of particle diameter on the efficiency of the various capture mechanisms [8]. It can be seen here that if the contributions of the various mechanisms are summed, there exists a particle diameter

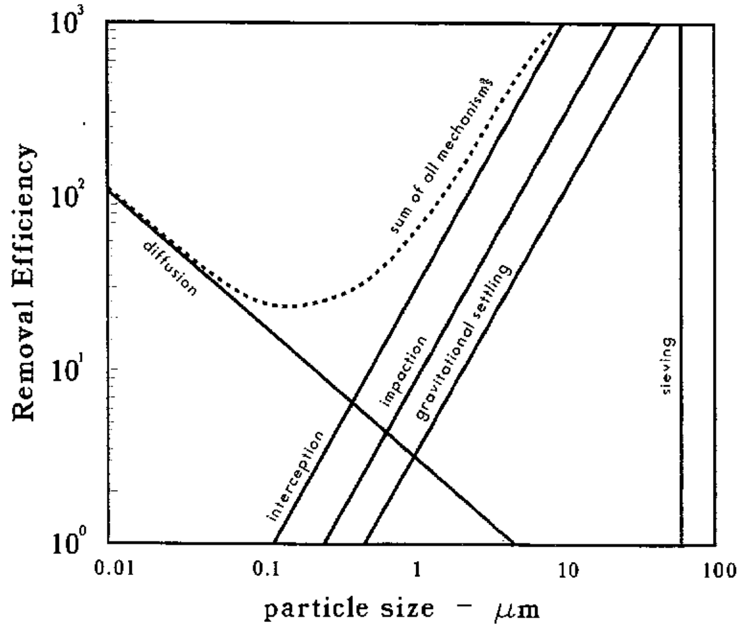

Figure 1. Relative extent of particulate removal mechanisms as a function of diameter. Adapted from [8].

for which the particulate matter removal is least efficient. In general, allowing for variations in the material of which the particulate matter is composed, the diameter range of 0.2–2 μm presents the most difficulty for air pollution control equipment. In Fig. 1, the removal efficiency on the y-axis is defined as the ratio of the particulate matter concentration in the gas stream entering a system to that leaving it.

1.1.9. Additional considerations. In addition to the technologies summarized above, there are a few more technical options to consider for the removal of airborne particulate matter. Process control equipment can be used to optimize the performance of almost all types of existing equipment.

Changes can be made to processes which generate particulate emissions. For example, cleaner burning fuels or combustor temperature controls can significantly reduce the amount of particulate matter created and carried by flue gases, thereby making its removal less difficult.

Modelling of unit performance can also be beneficial. An understanding of how all the relevant variables interact can point to system modifications which enhance particulate matter removal from gas streams. A review and analysis of various performance models for filters and electronic air cleaners was done by Lawless *et al.* [10]. Computational fluid dynamic (CFD) simulations have recently been made to evaluate dust laden gas stream two-phase flow patterns inside air pollution control equipment [11, 12].

2. RECENT ADVANCES IN UNIT OPERATIONS FOR AIRBORNE PARTICULATE CONTROL

Described below are the various conventional technologies that have been developed to remove particulate matter from gas streams. The capture mechanisms described previously are exploited in these units or processes.

Each unit operation will be treated in its own section. They will be introduced with a generic description of the process and equipment. This is then followed by a discussion of specific recent innovations and technology developments. The emphasis in this section is on the design and operation of the physical equipment. Section 3 discusses particulate emission control from a process perspective.

Figure 2 is a graphical guideline, mapping a suggested treatment method for a particle-laden gas stream defined by a desired particulate removal level and operating filtration velocity [3]. There is a rough monotonic correspondence between the filtration efficiency and the pressure drop across the filter for a given flux.

2.1. Cyclones

The general principle of inertial separation is that the particulate laden gas is forced to change direction. As the gas changes direction, the inertia of the particles causes them to continue in the original direction and be separated from the gas stream, exploiting the inertial separation mechanism.

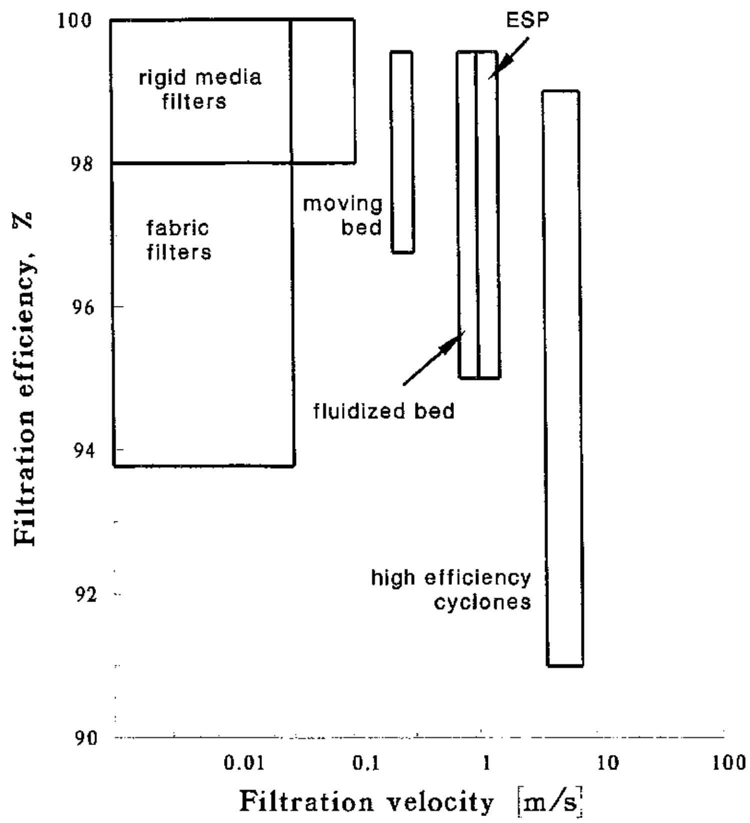

Figure 2. Unit operation map for airborne particulate treatment, with parameters of filtration efficiency and filtration velocity. Adapted from [3].

Cyclones, where the gas is forced to spin in a vortex through a tube, are the most common types of inertial separators. A typical cyclone configuration is shown in Fig. 3.

Inertial separators are widely used for the collection of medium-sized and coarse particles. Their relatively simple construction, low pressure drops and absence of moving parts mean that both the capital and the maintenance costs are lower than for alternative methods. In general, however, cyclone efficiency drops if the fines content of the particulate matter is significant. They are typically used as precleaners upstream of other devices to reduce particulate loadings and to remove larger, abrasive particles.

Conventional cyclone separators are seldom capable of the necessary removal efficiencies for an entire particle size range of an industrial gas cleaning application under present PM10 guidelines, if designed according to standard elementary cyclone theory [13]. The deviation between prediction and performance arises from the presence of secondary currents within the cyclone body, which disturb the predicted process of separation. Primary flow character can be restored by attention to the detailed design of the cyclone, including the geometry of the separation chamber, the position of openings, use of flow guides within the cyclone, the dimensions and the geometry of the hopper, bleeding and bypassing of the gas, use of multicyclones, and means for dust agglomeration. Alternatively, a 'dust strand' cyclone can be designed, exploiting

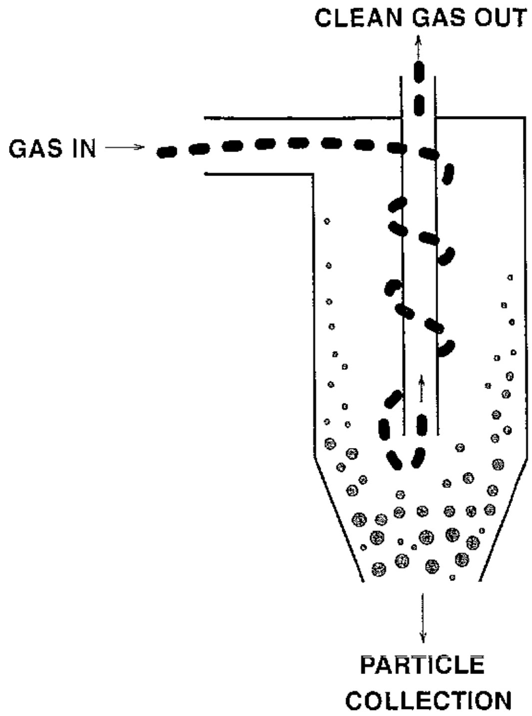

Figure 3. Simplified schematic of a cyclone.

the secondary flows (Dean vortices) which attain higher local solids concentration, enhancing particle removal [14].

Some innovative modifications have been made to conventional cyclone units. The application of an external electric field to a cyclone unit filtering low resistivity silica roughly doubled the collection efficiency of particles less than 5 μm in diameter at low flow rates [15]. Built-in particulate matter removal capability was considered with the design of a cyclonic suspension combustor for the burning of pulverized coal or coal-water slurry [16]. Cyclonic separators are also being considered as diesel soot collectors. A unit designed by Kudos Corp. in the UK involves spinning a gas through a tube while also spinning the tube itself, to separate particles down to 0.1 μm. This system exploits secondary flows (Rankine vortices) and operates at rotation rates of 60 000 r.p.m. [17]. It has yet to be field tested. A competing system makes use of a spray electrode which charges (presumably, neutralizes) particles so that they agglomerate and are captured by a cyclone. Between 75 and 90% of the particulate emissions, down to diameters of about 0.6 μm, were captured by this system during tests with a Peugeot diesel engine [18].

2.2. *Electrostatic precipitators* (*ESPs*)

ESP is a particle control device that uses electrical forces to move particles out of the flowing gas stream and onto collector plates. The particles are given an electric charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that attracts the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow channel. This arrangement is shown schematically in Fig. 4. Chapter 10 of [4] contains a number of good illustrations showing the construction and configuration of entire ESP units.

Once the particles are collected, they must be removed from the plates without any appreciable reentrainment into the gas stream. This is usually accomplished by knocking them loose from the plates, allowing the collected layer of particles to slide down into a hopper. Some precipitators remove the particles by intermittent or continuous washing with water.

ESPs have enjoyed very widespread use for fine particulate matter removal applications. They are a mature, established technology and the move for innovation in the ESP area appears somewhat less urgent than elsewhere. Nevertheless, there is still significant and interesting activity for updating ESP technology for the improved collection of ultrafine particulates. Quite extensive reporting on recent work appears regularly [19, 20].

In view of the present large number of ESP installations, a considerable market exists for retrofit opportunities. The tightening of emissions standards for SO_2 and NO_x and sub-10 μm particulate matter may impact on the capabilities of the ESP infrastructure. An overview of some of the issues facing the ESP user community, and an introduction to some of the basic types of retrofit options was given by Offen and Altman [21]. Beyond the need to condition the flue gas, typical upgrade options include enlarging the ESP, sectionalizing the ESP (dividing flue gas passages into a greater number of segments which can individually be operated at more optimum levels), spacing the collector plates further apart, implementing process control and/or improved rapping and collection equipment [22]. Two independent studies, focussing on the techno-economics of ESP use found that with the increasing use of high-resistivity coals, ESPs cannot compete with pulse-jet fabric filter systems when particulate emissions regulations allow only 0.01 lb/MBtu [23, 24].

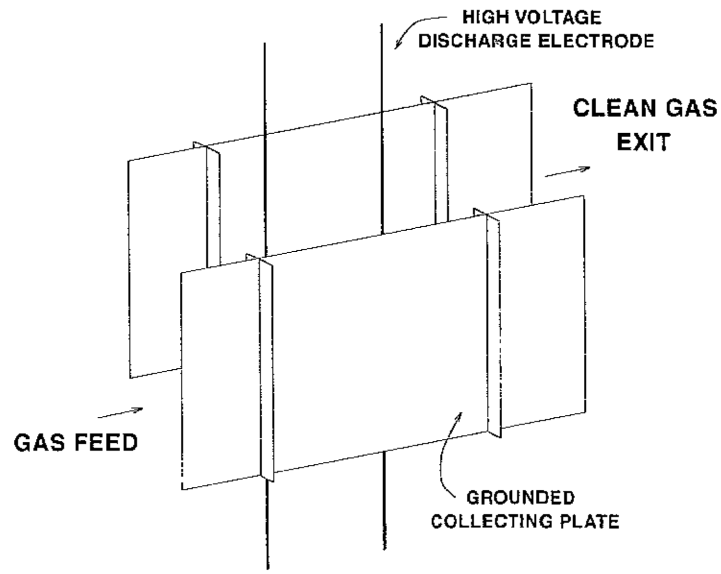

Figure 4. Schematic of a typical electrode and collector arrangement found inside an electrostatic precipitator.

A number of recent papers detail specific physical modifications to ESPs to handle high-resistivity flyash. Case studies are discussed where existing ESP installations were rebuilt to house large plate heights and wider plate spacings [25]. The ESP can be placed downstream of a non-leaking, high dust load gas-gas heater (with water as the heat exchange medium) to reduce the gas temperature through the ESP to the 90–100°C range rather than the conventional 130–140°C range [26]. Pilot testing has shown that the decreased temperature decreases the electrical resistivity of the dust, improving collection efficiency. Hitachi has introduced two new configurations for ESPs [27]. The moving electrode ESP has the plates sectioned into short panels that circulate like a vertical conveyor belt. The dust is collected by rotating brushes in a hopper zone where no gas flows and particulate matter reentrainment is minimal. They have also developed a 'saw-edged' wire that shows superior static discharge characteristics, useful for rapidly charging submicron particulate matter which is more abundant when the boiler fuel is oil instead of coal. Operating experience with intermittent energization of the ESP to suppress back corona and thus increase ESP efficiency for the capture of high-resistivity particulate matter was reported [28, 29]. Examples were cited on gas stream treatment from coal-fired boilers, oil-fired boilers, Kraft pulp boilers and iron-ore sintering plants.

A novel two-stage ESP with an electrostatic agglomerator between the stages has been tested at the laboratory scale [30]. A quadrupole AC electric field is applied to the remaining fines after the first ESP stage, inducing oscillatory motion and electrical polarization, which have been shown to increase submicron mean diameters by 400% and increase collection efficiency from 95 to 98%. A system has been designed with flow diversion during rapping to minimize fines entrainment [31]. Cost estimates for this technology show that this technique provides benefits for emissions limits below 50 $mg/N\,m^3$. Special horizontal strip collectors without baffles have been shown to increase ESP performance on large installations [32]. Seoul-Sharp-CED has developed what they term a 'SUPER-ESP' [33]. By separating the charging and collecting functions, both steps can be done independently in a more consistent and optimized way. A high particle charge can be imparted for any level of resistivity, and then these particles can be subjected to the appropriate electric field for collection. The temperature can be controlled in the separate charging area to modify the resistivity. Instead of an ESP with several long conventional sections, a smaller ESP results from this configuration when a number of charging and short collector pairs are used. For low-resistivity particulate matter this design can provide a unit about one-third the physical size of a conventional ESP and the size is further reduced to one-sixth for high-resistivity particulate matter.

The electrical nature of precipitators make them especially suitable for digital control. A recent expert system controller employing fuzzy logic allows some of the more difficult operations to be run in a more optimized fashion, such as diagnosing faults, start-up and shutdown routines as well as controlling the operating efficiency [34]. Field testing has shown significant emissions reductions as well as lowered energy consumption. Other types of controllers for spark rate and spark anticipation can better enable existing ESP units to handle flue gas and flyash variability in an energy efficient manner [35].

Wet ESP systems continue to play a key role for specialized particulate matter removal applications. For certain lower temperature applications (below the dew-point) only wet electrostatic systems can be used. Dissolving chemical agents in the wash liquid can provide a means to fix unwanted gaseous components along with the suspended particulate matter [36]. In Japan, Mitsubishi Heavy Industries Ltd have developed and tested a 'high velocity' wet ESP, capable of working at face velocities of 10 m/s, thereby allowing its installation within existing plant configurations in some cases [37]. Wet ESPs are well suited to applications such as coal-fired magnetohydrodynamic systems where the fines content in the flue gas is substantial [38]. As a retrofit option for waste incineration plants, wet ESPs have been added after a wet scrubber to treat particulate matter and acid gas. A unit known as the SonicKleen wet ESP system consists of a bundle of hexagonal (to save space) downflow tubes made of a conducting steel alloy, which contain discharge electrodes [39]. Condensed liquids from the gas stream irrigate and help carry particulates to the bottom of the unit.

Various innovations have been made to address specific application needs. The final particulate matter cleanup from wood fired boilers is often done with ESPs since the flyash has a low resistivity. Rapping for such systems is of paramount importance as resins and unburned material may be present on the collector surface, and any sparking could cause it to ignite. Sonic horns were installed and tested, replacing rappers for cleaning precipitator internals for wood fired applications [40]. Emissions of particulate matter with sonic horn rapping were shown to have decreased. An optional way of treating diesel soot is with an electrostatic agglomerator [41]. A corona-less pipe-type ESP is used to collect and agglomerate diesel soot particles which grow into larger particles and may be collected downstream with a simple inertial device.

A number of theoretical models have been developed recently to characterize ESP behaviour. The performance of existing ESPs can be enhanced with improved feed stream distribution through their internal volume. A CFD study was conducted to help design a flow distributor for ESPs used in the cement industry [42]. The design recommendations were used to bring a dry-process cement plant into regulatory compliance in Indiana, USA. On a more micro-scale, a CFD study was made on ionic wind, which is the secondary flow that develops under mass conservation requirements when ionized gas drifts towards the collecting plate. It was found that ionic wind effects are significant for superficial flow velocities under 0.6 m/s and a collection efficiency reduction of over 10% may occur when the superficial flow velocity falls below 0.2 m/s [43]. Conditioning the carrier gas often increases the feed stream humidity. The influence of humidity on the charge density and the electric field in a precipitator was modelled and solved with good results [44].

2.3. *Fabric filters*

Fabric filters remove dust from a gas stream by passing the stream through a porous fabric. Dust particles form a porous cake on the surface of the fabric. It is normally this cake that actually does the bulk of the filtration.

The manner in which the dust is removed from the fabric is a crucial factor in the performance of a fabric filter system, so that flux losses from excessive pressure drop with a thick cake are balanced against dust leakage occurring with too thin a cake.

Fabric filter systems are frequently called baghouses, since the fabric is usually mounted in cylindrical bags. The two most common baghouse designs are the reverse-air and the pulse-jet types. These names describe the affiliated fabric cleaning system.

There has been an increasing recent trend towards selecting fabric filters for new equipment installations and upgrades in existing plants. Improvements in fabric filter performance, simplicity of operation and low capital cost have been motivating factors. The most significant innovations have come in the area of fabric materials.

Since the late 1980s, baghouse installations have begun to appear featuring pulse-jet fabric filters (PJFFs). These systems are quickly replacing conventional reverse-gas-cleaned baghouses (RGB), as the most widely used fabric filter unit. PJFFs are characterized by their use of periodic short, powerful bursts of air to clean the bags, allowing the unit to be operated at two to three times the face velocities of the reverse-gas-cleaned systems. In general they exhibit improved pressure drop characteristics and can be retrofitted into ESP casings. See Fig. 5.

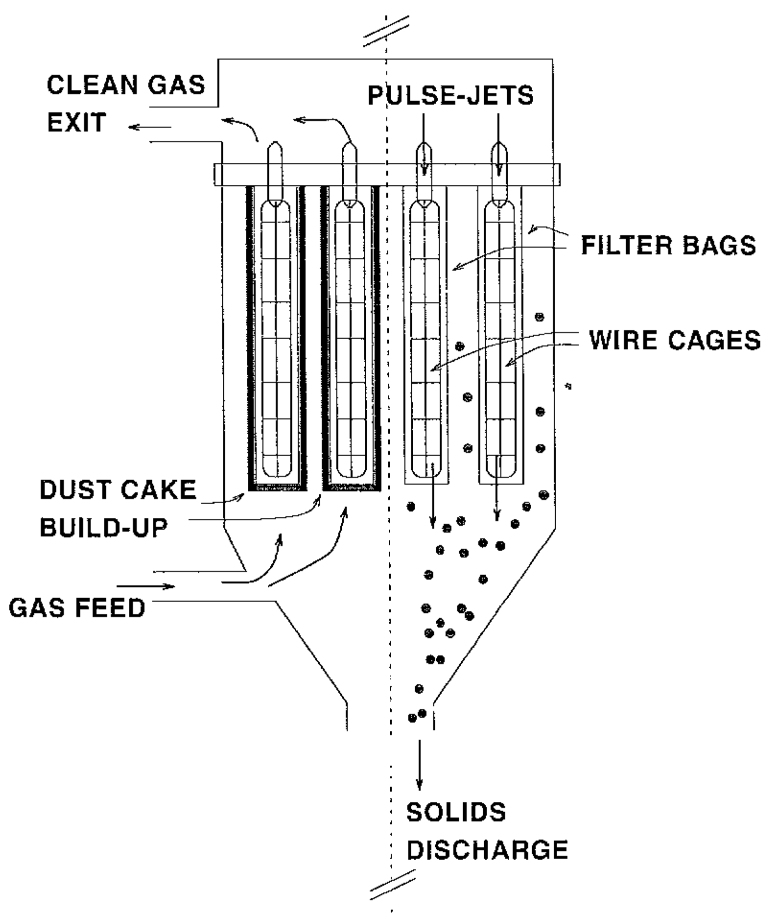

Figure 5. Schematic of a pulse-jet fabric filter baghouse. The filter bags on the left-hand side are shown in filtration mode and those on the right-hand side are shown in the pulse-jet cleaning mode.

A three-part series of papers was published to provide an overview of the performance and operating experiences with PJFFs for coal-fired boilers, a leading application [45–47]. Extensive data on various PJFF installations were provided. In general, these units operate below 0.03 lb/MBtu (0.054 mg/Kcal) which is the US EPA particulate matter emissions standard. Woven felts such as Dralon T®, Ryton and Nomex were recommended bag materials. Teflon bags have shown some difficulty with particulate matter collection, possibly owing to the large fibre diameters, despite their ability to operate in hotter and more corrosive atmospheres. Part 2 of the series reported on pilot tests for fossil fuel installations, including oil-fired boilers with uniformly good results. Higher frequency bag cleaning was required for high ash coals. Part 3 of the series provides an economic comparison with ESPs and RGBs. ESPs could only compete with PJFF systems with low-resistivity feeds. Compared to RGBs, the PJFF systems offer a 10% less levelized cost over a 30 year plant life according to this analysis.

There are some commercial PJFF systems available. The OPTIPULSE system from ABB is aimed at steelmaking applications [48]. The Hosokawa Micropul system was designed with inlet gas diffusers to provide uniform face pressures over the filter bag surface, giving an overall improvement in performance [49, 50]. Similarly, filter cage designs made from perforated metal sheet, rather than wire mesh, subject pulse-jet bags to less stress and prolong their lives [51].

Baghouses are often employed to collect particulate matter from some of the feed conditioning processes discussed in Section 3.3. Filter bags made from 3M Nextel 312 woven alumina/boria/silica ceramic fibre have been installed in the SNRB process and have been successfully tested at temperatures up to 590°C against the EPA standards [52, 53].

The fabric materials themselves are of course the subject of considerable research. The extra mechanical demands placed on pulse-jet systems make glass-based filter media prone to failure. As a consequence of this, there have been numerous synthetic felts developed for some of these applications, such as industrial boilers, combusting fluidized beds and incinerators [54]. Polytetrafluoroethylene (PTFE) or Gore-Tex® filter materials have been developed. Some early work shows that the favourable PTFE surface properties permit easy dust layer removal, and operation at temperatures up to 260°C. Fine particulate matter still poses a problem, with 50% escape at 0.86 μm [55]. Pulp and paper bark boilers present special problems as these gas streams can contain incandescent particles. Temperature resistance up to 600°C is provided with Biothermica stainless steel fabric filters. A fault-free 4-year test was conducted at an industrial site with this material [56, 57].

On a more fundamental level, there have been studies conducted on some of the detailed fabric properties. A parametric study was conducted on the effects of yarn processing and weaving variables on the filtration efficiency of woven glass fabrics. It was found that processing conditions which keep the glass filaments in the yarn bundle separated produced the best performance [58]. A number of commercially available conductive fabrics have been designed to reduce electrostatic charge in dust collectors where flammable dusts are present, such as in flour mills, wood working operations and polyvinyl chloride manufacturing [59].

An alternative to the filter bag is the filter 'box' or cartridge filter. These units are made of stiff corrugated filter materials, which can offer much higher filter surface area compared to baghouses of the same footprint. Many of the technical capabilities are similar to baghouses, but their design makes them inherently less cleanable. They are rated for particulate matter loadings of about 25% of that for baghouses [60].

Owens-Corning Fiberglas have been developing a vanadium/titanium catalyst coated woven glass fabric for simultaneous NO_x and particulate matter control. Over 90% NO_x removal has been obtained, but many operating parameters required to achieve this level economically have yet to be resolved [61, 62].

Fabric filter systems can be electrostatically enhanced. An early study showed that an electric field can alter the dust deposition pattern inside a bag, giving a lower pressure drop [63]. A number of analytical and experimental investigations of this phenomena are reviewed by Rao and Murthy [64]. A portable electrostatic cartridge-type filter has recently been developed, for applications such as cooking odour control and smoke treatment. Over 98% particulate matter capture has been achieved at diameters between 0.01 and 1.0 μm; however face velocities must be less than 0.1 m/s [65].

2.4. *Wet scrubbers*

In these units, a particle laden gas stream is subjected to a spray of liquid which contacts and captures the solid material. A variety of geometries and designs are available for implementing this technique. The mechanisms of impaction, interception and diffusion all play a role in particulate matter capture in wet scrubbers.

Condensation scrubbers can be considered to be a subclass of wet scrubbers. In condensation scrubbers, usually supersaturated water vapour is brought into contact with particulate matter and liquid condensation occurs on the surface of the solids. This can create a nucleation site for agglomeration with other wetted particles. The mass of the particles grows in this way and they can be more readily collected by inertial impaction or even gravity settling. The thermophoresis mechanism is also exploited in condensation scrubbers [9].

Wet scrubber technologies continue to enjoy favour for particulate matter removal, especially in coal-fired power generation applications where the flue gas also contains SO_2 and NO_x and can be removed simultaneously by the scrubbing liquid. Conventional units include venturi scrubbers, mechanically aided scrubbers, pump-aided scrubbers, wetted-filter type scrubbers and tray or sieve type scrubbers. An overview of recent work in this field is provided in an NTIS bibliographic database [66]. See Fig. 6.

Some recent developments in wet scrubbing equipment are in the area of rotary or centrifugal designs. One such system, based on a Confined Vortex Scrubber (CVS), for fine particulate removal from combustion flue gases has been developed and consists of a cylindrical vortex chamber with multiple tangential flue gas inlets [67]. Water is introduced into the chamber and is confined within the vortex chamber by the extremely high centrifugal forces generated by the gas flow. The confined water forms a layer through which the flue gas is forced to bubble, leading to collection

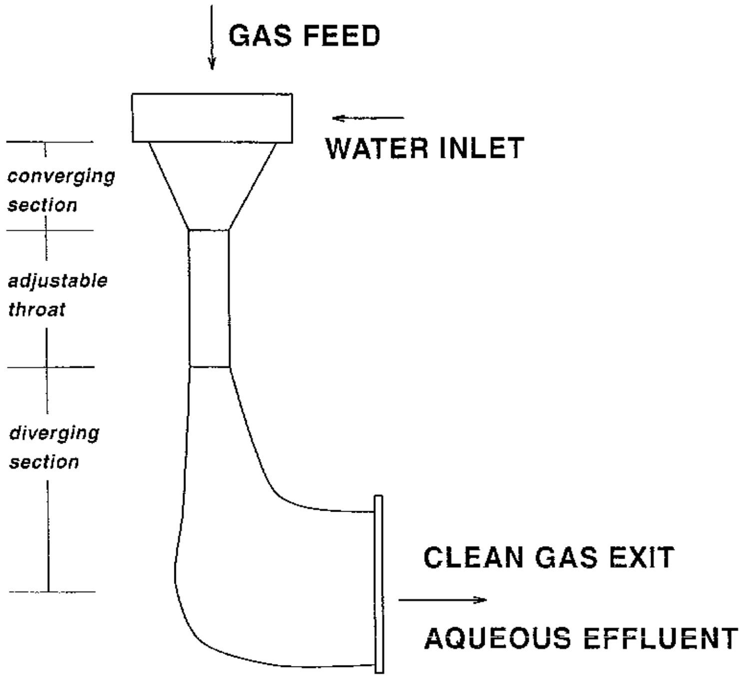

Figure 6. Components of a standard venturi scrubber. The outlet is often connected to a mist eliminator where the water and gas streams are separated.

efficiencies in excess of 99.5% for fine flyash of diameter 3 μm and 98% for 0.3 μm diameter particles. A commercial unit known as the Rotorfilter^{TM} makes use of scrubbing water in conjunction with a series of rotating airfoils, arranged so that the two streams carrying the liquid and solid phases contact each other at right angles. In this way, particulate capture occurs in recirculation regions created by the chevron shaped spokes [68]. These units are designed for small industry and can handle between 50 and 500 m^3 gas per minute. Upwards of 99% of particulates at 0.25 μm diameter can be recovered. A system designed for the power industries employs a jet bubble reactor and vessels made from fibreglass reinforced plastics to withstand the corrosive elements in the streams [69]. Downstream from an ESP, this scrubber was able to remove upwards of 90% of the escaping particulate matter while also achieving good SO_2 control.

New developments continue to occur with venturi scrubbers. A special integrated system has been designed with a two-fluid nozzle which can be controlled to enhance particle removal, aided by impingement plates in the vessel [70]. Another such system, aimed at acid gas control which scrubs particulates as well, is integrated with a steam stripper to remove and separate saleable SO_2 and VOCs [71]. A multi-staged system using a saturated vapour chamber to aid in the nucleation of water-wettable sub-micron particulate matter can achieve 99% removal at 0.15 μm, with high turbulence contributing to particle capture at the scrubber walls [72].

Some recent work has been carried out on the electrification of wet scrubbing systems. An ionizing wet scrubber has been developed to remove fine particulate matter down to 0.05 μm, while simultaneously removing acid gases [73]. Its main area of application is waste incineration. The unit combines the principles of wet scrubbing and electrostatic precipitation, charging and agglomerating particulate matter with subsequent collection by inertial impaction and image force attraction within an irrigated packed bed. A scrubber with oppositely charged rotating brushes downstream of an ionizing atomizer to remove particulate matter is presently in the development stage [74]. This design targets particulate matter below 5 μm diameter, and can operate at comparatively low liquid addition rates. Treatment of metal fume from a hazardous waste incinerator in an ionizing wet scrubber was investigated [75]. Collection efficiencies ranged from 22 to 71% and were generally higher for less volatile metals. A fundamental study has modelled a complex interdependence of the applied field, the particle charge and the direction of the field relative to particle motion for electrified wet scrubbers [76]. Additionally, a fundamental study examining the influence of surface electric properties of spray droplets and particulates, in conjunction with surfactant addition for dust suppression has been carried out [77]. The most important effect for enhanced particulate matter capture was an elevated droplet charge for cationic droplet solutions.

Some recent work has addressed sector-specific wet scrubbing needs. Mist eliminators used in flue gas desulfurization are expected to have some difficulty complying with anticipated 0.002 lb/MMBtu (14 mg/N m^3) emissions regulations [78]. It has been shown that horizontal flow configurations can upgrade the performance of systems, which may need to remove upwards of 99.5% of PM10 dust. A two-stage scrubber designed for the aluminum industry has been shown to remove over 99% of particulate matter as well as HCl and more than 90% of Cl_2 from aluminum reduction cast-house furnace offgas [79]. Irrigation with chemical cleansing agents allow scrubbed materials to be recycled into the reduction process.

Finally, a less recent, but rarely implemented technology is that of counterflow inertial impaction wet scrubbers [5]. An early study for the collection of alunite dust (an alumino-silicate) had two colliding axisymmetric dusty gas streams, sprayed with fluid at the impaction zone. Deceleration of the particles and turbulent mixing at the impaction zone bring about agglomeration of the particulates, whereby they drop out of the stream and can be removed [80].

2.4.1. Condensation scrubbers. Condensation scrubbers can be considered a subclass of wet scrubbers, although there are key differences in the mechanisms employed to remove particulate matter. In the case of condensation scrubbers, the particles travel in a vapour saturated gas stream, where vapour condenses on their surfaces and acts as an agglomerating agent. One such design, for the treatment of sub-0.25 μm particulate matter from municipal wastewater incinerators is documented [81]. Existing wet scrubbers can be retrofitted to operate in the condensation mode. A similar design for municipal waste incinerators makes use of flue gas moisture mixed with a cold gas stream resulting in flux force condensation scrubbing [9].

2.5. *Granular bed filters (GBFs)*

In an analogous fashion to wet scrubbers, a particle laden stream can be passed through a bed of solid material where the particulate matter is captured. The bed can be stationary, moving or fluidized. The collector material typically possesses some favourable surface properties to enhance capture of the particulate matter. Granular bed filters are often used when waste water problems posed by wet scrubbing systems are unacceptable, such as for fluorine control in some aluminum plants. Fluidized GBFs are currently under consideration for hot gas cleanup applications, especially as an alternative to ceramic candle filters which have had a troublesome debut. A recent study has found that the economic performance of GBFs compares favourably to candle filters for coal-fired power generation facilities [82, 83]. These units are mechanically simple and require less fine-tuning and maintenance. The moving collector bed has some by-product value and also eliminates the need for costly filter media cleaning. More than 97% of flyash can be removed by GBFs at a face velocity of 1.6 m/s (based on the standpipe cross-section), but they are known to have problems collecting particulate matter under 2 μm. At face velocities over 4 m/s, the collection efficiency drops to about 80% [84].

Moving GBFs have also been investigated combined with electrostatic enhancement. The basic unit developed by the Combustion Power Co. performed well for particulate matter over 2 μm. Various field strengths, both under AC and DC mode were tested. The AC enhancement at 75 Hz produced a slight optimum. DC operation also showed very promising initial results, but its implementation is considered to be less practical [85, 86]. At low face velocities (0.11 m/s), upwards of 98% of 0.5 μm flyash could be collected. The efficiency drops off to 50% at face velocities near 0.7 m/s.

A novel system has been developed with a fluidized GBF exiting across a metal filter screen [87]. A sketch of the unit is shown in Fig. 7. The screen surface can be cleaned by momentarily interrupting the gas flow. The pressure drop in this system is low, although material finer than about 1.5 μm is difficult to capture. This system allows relatively high face velocities, over 2.5 m/s.

There are a few instances where GBF systems provide a good particulate matter removal solution. Most traditional air pollution control devices are ineffective for collecting submicron metal fume, which often arises in waste incineration. One approach has been to test various sorbents in a fluidized bed filter [88]; another has been to use activate charcoal packed beds [89].

A number of fundamental studies have been conducted recently to further the understanding of granular bed filters. Fine material was found to be more readily collected at elevated temperatures [90]. Reynolds number effects were considered in another study [91].

Sometimes granular bed filters are referred to as dry scrubbers, but more often dry scrubber means a somewhat similar, but different type of unit. A number of systems exist where the stream dust may be removed, but then a sorbent is introduced for NO_x and/or SO_x removal. This creates a need for subsequent particulate matter removal from the gas stream. In view of this, the sorbent material can be chosen so that it is sufficiently large and uncohesive to be easily separated by low pressure drop baghouses. With an appropriate choice of sorbent, the sulfur and nitrogen containing product can be used to make a number of saleable by-products [92, 93]. An electron beam dry scrubber exists in which the electrons generate OH^- radicals which oxidize SO_2 and NO_x into sulfuric and nitric acid, precursors for making fertilizers [94].

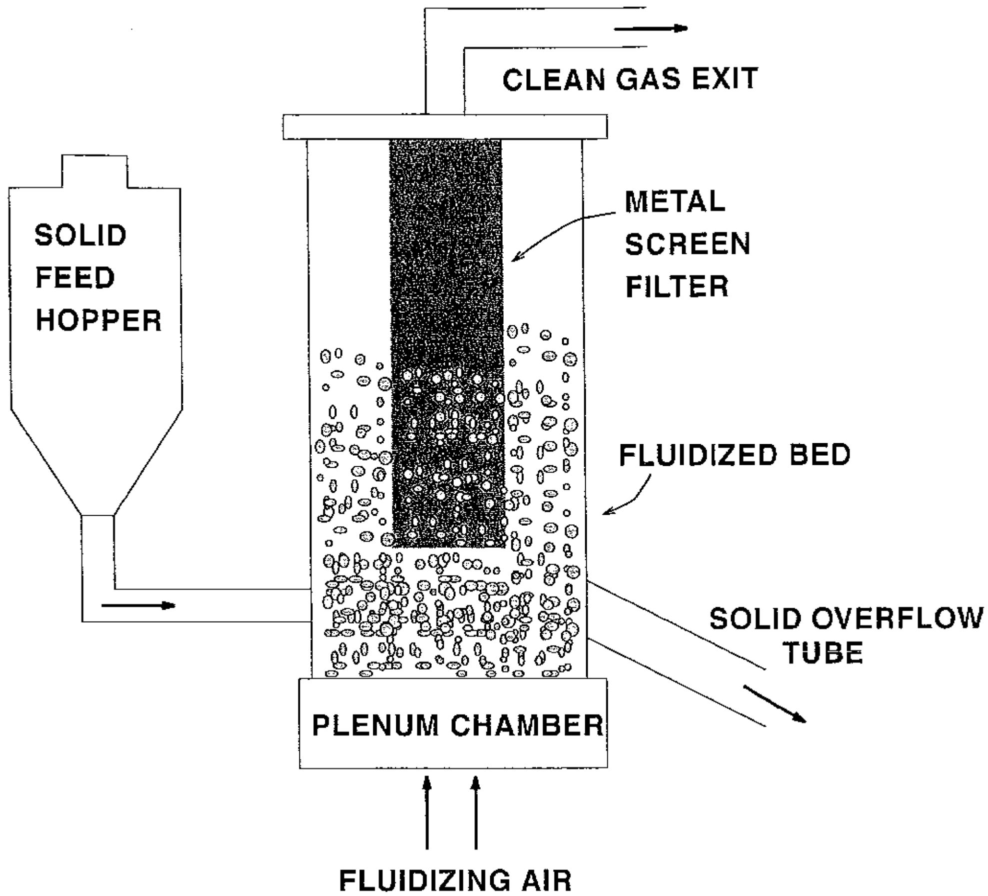

Figure 7. Fluidized granular bed filter fitted with metal screen to prevent filter material entrainment. Adapted from [87].

2.6. Ceramic filters

Ceramic filters are rigid barrier filters constructed with pore sizes designed to remove fine airborne solids. The physical properties of the ceramic material allow these units to be operated under high temperatures and in corrosive environments as well as being suitable for cleaning with corrosive agents. They are made in two standard formats: dead-end low density 'candle' filters and multi-channel cross-flow modules.

In the rapidly evolving field of hot gas filtration, ceramic filter elements have proven to be suitable for efficient particulate removal, with the ability to perform in harsh environments. Ceramic membranes were first used in the 1940s for uranium enrichment, yet it took until the mid-1980s for particulate matter removal applications from gas streams to first appear. General overviews of this field are provided by Eggerstedt *et al.* [95] as well as by White *et al.* [96]. Recently, ceramic materials have also found their way into hot gas applications as structural filter components, replacing exotic alloys and simplifying design approaches. A number of different ceramic filtration devices are currently available, each with advantages and disadvantages. These devices include ceramic cross flow or ceramic membrane filters, ceramic fabric filter bags, and porous ceramic filter tubes or 'candles'. In addition, these designs are available in different ceramic materials, each having properties which may or may not be suitable for a given process application.

Despite the roughly 40% higher cost per unit filtration area compared to bag filters (1991), ceramic units are gaining popularity [97]. In addition to benefits previously mentioned, they can also handle heavy dust loadings and face velocities upwards of 3 cm/s, compared to about 1.5 cm/s for fabric systems. Provided that the system selected is cleanable, the unit life can be several times longer than with other materials.

High-efficiency particulate air (HEPA) filters have been in existence for over 50 years. They are typically made of glass microfibres and are used for very high efficiency removal of submicron particulate matter. HEPA filters are suitable for applications where a very high level of air purity is required or for the removal of hazardous particulate materials [98].

2.6.1. Candle filters. Figure 8 shows a schematic unit where ceramic candle filters are used to remove particulate matter from a gas stream [3]. Here, the filter medium is provided in the form of long, hollow tubes or 'candles', closed at one end and hung vertically from a support plate so that the gas passes from the outside inwards. A dust cake accumulates on the outside surface of the candle and is cleaned at regular intervals with a strong pulse or jet of gas sent from the inside out via the pulse nozzles.

There are two common types of filtration media used in ceramic candles. The first is a high-density sintered or bonded granular silicon carbide (SiC). The other type

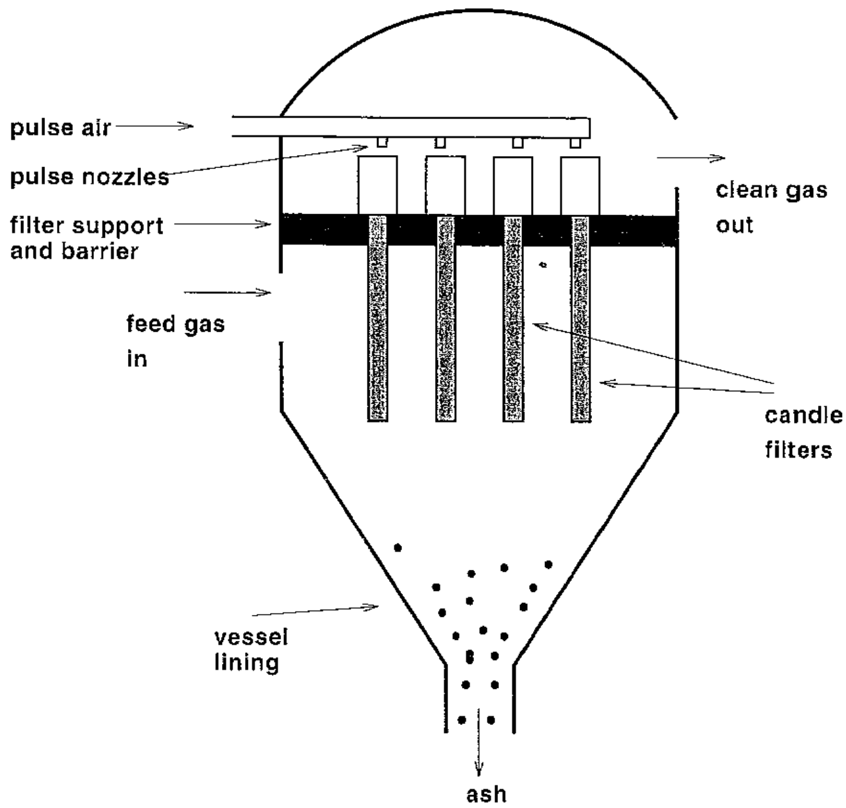

Figure 8. Simplified schematic of a ceramic candle filter unit with pulse air cleaning.

is primarily a low-density alumina (Al_2O_3) in the form of bonded fibres. The low-density units show less resistance to flow, are less prone to thermal shock and are less expensive [99].

The most attractive feature of ceramic candle filters is their ability to perform gas cleaning at high temperatures, presently near 1000°C. The demand for hot gas cleaning is strongest in coal-fired power plants using pressurized fluid bed combustion (PFBC) or integrated gasification combined cycle (IGCC) processes. Conventional bag filters have thermal tolerances which require that gas streams be cooled, typically by diluting the stream with atmospheric air. Direct hot filtration eliminates the need for extra process equipment, reduces the gas volume for treatment and allows waste heat to be recovered, giving a 2–3% increase in operating efficiency [100].

The Schumacher SiC candle filters were some of the first to undergo extensive testing in pilot facilities. In 1988 at Grimethorpe in the UK, a pilot hot gas particulate removal system using ceramic candle filters was built in a PFBC test facility [101]. Early tests were conducted with Schumalith SC40 model candles (mean pore size 100 μm), as well as the DiaSchumalith F40 candles which are made with an additional surface layer of alumina fibres. The DiaSchumalith F40 candles were found to be superior because they were able to work in a surface filtration mode at higher face velocities and required lower stresses for dust cake detachment. The F40 candles were used in most subsequent work at Grimethorpe where they gave promising dust removal results over 800 h tests conducted at 850°C and 10 bar pressure [102]. Further testing at Grimethorpe revealed that extended use with cold pulse cleaning caused the candles to lift and descend repeatedly resulting in fractures both in the candles and their sealing gaskets [103]. A similar pilot test was reported by Schumacher themselves, with over 4000 h at temperatures between 780 and 850°C. At temperatures above 700°C more than 99.999% of all particulate matter was removed, with the most penetration occurring in the 0.2–0.4 μm size range (*cf.* Fig. 1) [104].

Increasingly, demanding testing of the DiaSchumalith F40 has been reported more recently. Concerns over performance have focussed on candle integrity over repeated hot-cold cleaning cycles. The strength of the candle was found to decrease by 2.2% over a 4 month period at tests conducted at 850°C. A thermal shock (temperature change) of over 600°C was found to occur by numerical simulation of the cleaning pulse flow inside the candle [105]. By 1993, new tests had shown improved versions of the DiaSchumalith F40 candles, but still a recommendation for hot pulsing was made to minimize the severe materials duty [106]. Other tests have revealed that breakage of candle filters arose from the mechanical stresses associated with lifting and dropping. Specifically, the deterioration mechanisms were the oxidation of SiC to form cristobalite (SiO_2), microcracking and crystallization in the glass bond necks and glass/SiC interface and pitting of the glass bond by $CaSO_4$ [107]. Service lives of up to about one year could be expected from the SiC candle filters. The thermal shock resistance of the DiaSchumalith F40 filters was compared to other SiC candles made by Refracton as well as candles from Asahi Glass Co. made of cordierite [108, 109].

Schumacher SiC candle filters have been pilot tested for hot gas cleaning at a low-level-waste incinerator at a German nuclear facility, and were found to be promising when the feed stream particulate matter contains very little submicron material [110].

Fibrous, layered, low-density alumina-silica based candle filters made by Foseco (Foseco Cerafil 2000i) have been tested for PFBC hot gas cleaning [111]. These tests were conducted at temperatures up to 740°C and typically upwards of 99.9% of the particulate matter was removed. The nominal pore size for these units is less than 10 μm [3]. Although none of the filters in these tests failed, the testing period of 340 h was considered too short to comment on their durability.

Candle filters made of β-cordierite by the Asahi Glass Co. were tested on PFBC dusts [112]. Of note is that these candles filter from the inside out, using a positive pressure rather than suction. At comparable permeation rates, they were found to give a downstream dust level under 3 p.p.m.w., compared to less than 1 p.p.m.w. for the Schumacher SiC candles. The Asahi filters were tested for over 2000 h at temperatures up to 880°C. Likely due to their quite large physical size (length of 5.8 m) and being fastened to the vessel at both ends, the thermal shocks related to the pulse cleaning produced a much higher rate of filter mechanical failure compared with other candles. An update on the status of the Asahi candle filters was provided by Higashi and Maeno [113].

Testing has been conducted on surface treated SiC candles (Lay Cer 50/5) made by the Industrial Pump and Filter Manufacturing Co. (USA) [114]. They have a nominal pore size of 24 μm, were tested at 870°C and gave a filtration efficiency near 100%. This study focussed on the nature of the cake buildup on the filter surface and how different operating conditions related to the pressure–flux relationship.

Westinghouse has developed a new housing unit for candle filters and has tested the DiaSchumalith F40 candles [115]. They were expected to replace the SiC filters with alumina/mullite candles. A project sponsored by the US DOE is being conducted to develop practical hot gas filter designs that meet the operational requirements of PFBC [116].

The economics and process options to consider for implementing ceramic candle filter systems are discussed by Zievers *et al.* [117].

2.6.2. Cross-flow filters. Particulate filters can also be made from dense sintered ceramic constructed into box-like structures. Such designs include separate passageways for the feed and cleaned gas which are linked by the porous ceramic filter material. Figure 9 shows a schematic sketch of one corner of a generic block shaped ceramic cross-flow filter. As can be seen, this arrangement gives a very high filtration area to volume ratio compared to configurations used in other technologies. All the other benefits attributed to ceramic candle filters in the previous section apply to ceramic cross-flow filters [95]. Backflow pulsing is used to clean the particulate matter which cakes on the passage walls.

The emission of soot from diesel engines has posed a problem from a regulatory standpoint. To meet these standards, and since it is not practical to cool exhaust gases from a vehicle, various particulate traps making use of ceramic cross-flow filter technology (and other types of ceramic filters) have been being investigated since the early 1980s [118–120]. The proposed EPA air quality standards for 1994 have renewed interest in this topic [121].

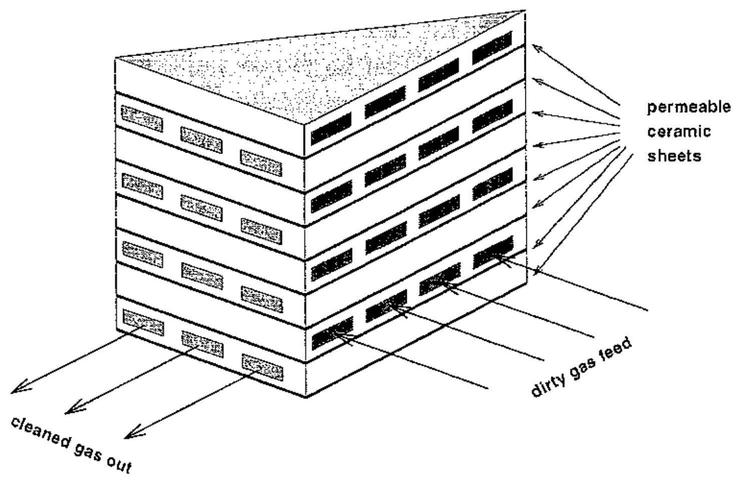

Figure 9. Simplified schematic of a ceramic cross-flow filter. Shown here is the top corner of a box-shaped unit.

The Asahi Glass Co. has developed a new particulate trap system [122, 123]. It features both a cross-flow type ceramic filter and reverse cleaning regeneration. The filter is made up of thin plate elements of modified cordierite. Each plate has a row of some two dozen open-end, oval-sectioned channels. A periodic reverse jet cleaning by compressed air injection removes the particulate from the filter wall and drops it into the vessel bottom. It is burned by an electric heater. The trap efficiency of this system ranges from 88 to 95%. The durability has been confirmed by both laboratory tests and field tests with public buses in Los Angeles, USA.

NGK Insulators Ltd also produce a cordierite diesel particulate trap [124]. Recent attention has focussed on cleaning requirements under specified combustion flow rates with minimal thermal shock. The NGK unit has been tested extensively on buses in Italy and performed well in principle [125]. It was recommended that the cross-flow filter unit be enabled with continuous filter loading control, to bring particulate matter collection efficiency to acceptable levels for practical operating conditions.

In North America, General Motors in cooperation with Corning have developed a cordierite wall-flow filter for light duty diesel engines [126]. The thermal durability was tested and designed to achieve a required 120 000 vehicle miles (192 000 km), without exceeding the 0.13 g/mile particulate emissions regulation. The use of Corning particulate traps on heavy diesel equipment in underground mines has been shown to improve air quality [127].

In related research on filter regeneration, it has been shown that it is possible to provide a more uniform energy input to a filter by incorporating microwave-susceptible materials in the filter body and then using RF (microwave) energy to initiate combustion [128]. This method gives improved control over the soot combustion and lower thermal stresses within the filter.

For generic air pollution control applications, preliminary commercial units have been made available by CeraMem (USA) [129]. The particulate matter removal ability is near 100% with nominal pore sizes from 0.5 to 0.004 μm, depending on the surface membrane coating used. A set of 36 modules each with external dimensions of 12 × 12 × 30 cm and over 3.4 m^2 filter area was able to clean satisfactorily the 0.28 m^3/s flue gas at 120°C from an EPRI baghouse facility over a period of 1100 h. Testing on hot gas streams from a magnetohydrodynamic (MHD) power generation combustor revealed some unit sealing problems along with unsatisfactory pressure drops and face velocities [130]. Ceramic cross-flow filters for MHD plants were, however, still considered to be a promising technology. A recent advance was the use of a catalytic vanadia coating for simultaneous NO and particulate matter removal from hot gas streams [131]. The US DOE is also investigating a catalytic mixed metal oxide coating on ceramic cross-flow filters for integrated SO_2, NO_x and particulate matter removal [132].

A cross-flow ceramic filter unit has been under development by Westinghouse and Coors Ceramics [133]. It underwent tests at 900°C for periods of 1000 h with various types of PFBC flyash. In general, particulate matter removal was quite high, but post test inspection revealed a number of material flaws. When the mean size of the airborne particulate matter fell below 5 μm, the flow resistance from the dust cake and the required cleaning pulse intensity increased markedly.

A new product by CeraNova and Specific Surface Corp. uses a novel powder processing method to tailor ceramic cross flow filter elements [134]. They employ a 'three-dimensional printing' process, whereby functional ceramic components are created directly from computer generated model structures which control a fabricating unit which 'prints' the monolith, layer by layer. The composition within each build-plane can be selectively controlled by varying the composition of powder and suspending fluid. An ink jet printing head is used to meter the materials. In this way the microstructure can be controlled by the relative influence of cohesive and capillary forces of the materials introduced to each layer. Functioning filters have yet to be made in this way, but sample monoliths have been prepared in the laboratory.

3. RECENT PROCESSING INNOVATIONS

In addition to improvements made on air pollution control equipment, there has been much recent attention given to addressing airborne particulate emission removal and/or reduction from an integrated perspective. Research and development on process modifications aimed at producing a higher quality gas emission are discussed below.

3.1. Hybrid systems

The need for simultaneous control of particulate matter and toxic gases, or even particulate matter of variable size and character often, results in the use of hybrid systems. These systems comprise either a single unit or a process in which various particulate matter collection methods are employed in series to obtain significantly reduced solids emissions.

For the purpose of this treatise a hybrid system will be considered to be a single physical unit which combines two or more particulate matter removal technologies.

A technology developed by EPRI in the US combines electrostatic precipitation with fabric filtration. This system is known as the Compact Hybrid Particulate Collector (COHPAC) [135]. The baghouse follows the ESP, either in series or actually inside the ESP housing. In a COHPAC system, the air leaving a power plant flows first through an ESP, then through a baghouse. The initial ESP treatment significantly reduces the concentration and often imparts some electric charge to the particles entering the baghouse. The charged particles are more liable to repel each other as well as the fabric filter material, so that the level of pore clogging is reduced and bag cleanability is increased. For these reasons, the face velocity in the COHPAC baghouse can be four to eight times higher than in conventional installations. In turn, the increased throughput allows a much smaller physical unit size [136]. A number of pilot and commercial scale tests of the COHPAC system have been made. The particulate matter emission requirements were met satisfactorily, but bag life concerns were raised, perhaps owing to the comparatively higher face velocities to which the bags are subjected [137].

A few miscellaneous hybrid-type technologies have been developed. A process and apparatus for treating particulate matter and acid gas in one unit has been patented [138, 139]. Here, the exhaust gas (i.e. from sintering plants or fuel-fired plants) is first de-dusted in a cyclone stage, then after carefully controlled moisture addition, passed to an ESP stage where the particulate matter collected is humidified but essentially dry, thus allowing it to be separated from the acid gas. A small industrial module has been developed which combines centrifugation and wet scrubbing for particulate matter removal, followed by passing the gas stream through activated carbon sponge bags for demisting [140]. The demisting step can include acid gas fixation and/or odour removal.

3.2. Feed sampling and process control

The electrical nature of ESPs makes them well suited for implementing on-line control systems, principally for power efficiency. Some of these control strategies have been noted in Section 2.2. On-line monitoring of emissions to the atmosphere for regulatory compliance is a different matter and some technologies for this purpose have recently been developed.

A prototype ESP device was developed containing a total-reflection X-ray fluorescence spectrometer (TXRF), intended to detect heavy elements and metals [141]. At flow rates under 1.3 l/min, essentially 100% of submicron particulate matter is collected and the concentration of HAPs in the stream may be accurately monitored. An on-line air sampling apparatus has been developed for measuring VOC concentrations in gas streams [142]. Two initial filtration stages remove particulate matter above 2.5 μm in diameter, at which point impaction separators make size classes below 2.5, 1.5, 0.8 and 0.32 μm. The captured particulate matter can then be analyzed for adsorbed VOCs. Some devices have been developed for on-line measurement of particulate concentrations in gas streams. A glass fibre filter has been incorporated into a gravimetric device for continuous sampling of particulates down to 0.01 μm in size. The glass fibres have superior optical characteristics which can be exploited for other analytical measurements and are available with this sampler [143]. Similarly a conceptual design has been patented featuring a series of impinging collectors which provide a gas stream particulate concentration and size distribution [144]. Practical operating ranges have not yet been established.

The BHA Group have a line of continuous particulate monitoring devices using a modulated LED light signal which responds only to moving particulates, so it remains unaffected by accumulation of dust or moisture [145]. The extent of signal modulation can be calibrated to dust concentration in the gas stream. A primary intended use is in baghouse installations as a monitor for filter bag leaks or failures. Another potentially useful device for baghouse installations is the Hansentek^{TM} spark detector and extinguisher [146]. Sparks of diameters down to 0.4 μm can be detected by infrared sensors and an appropriate extinguisher can be triggered to eliminate them. Such a system would allow the introduction of fabric filters to control particulate emissions from wood-fired pulp and paper boilers. Fabric filters have been slow to gain widespread use in this sector due to the risk of fire from airborne micro-embers.

Process control systems have found a more limited application in particulate control installations. The Harwell Laboratory in England has been developing an expert system for the control of fabric filters [147]. The state of the art in this area is somewhat rudimentary because the primary operating variable, the pressure drop at steady state, is not readily predictable. Using on-line pressure drop measurements, the flow, compressor pressure and pulse periods can be adjusted in real time, and early results have shown up to 20% savings in power consumption.

3.3. Feed stream conditioning

Often the performance of air filtration units can be enhanced if the particulate matter in the feed stream entering these units is given some preliminary treatment. Feed stream 'conditioning' may consist of such treatments as injecting additives to the stream, irradiating it or subjecting it to acoustic shock. The objectives typically are to modify the surface properties to improve the particulate matter collection efficiency or to agglomerate the particulate matter to larger, more readily removable entities.

A well known conditioning approach is the injection of SO_3 into the exhaust streams from low-sulfur coal burning power plants, which is known as flue-gas conditioning (FGC). The presence of the SO_3 reduces the resistivity of the flyash in these streams for easier capture by ESPs. A review of recent advances in this area is provided by Krigmont and Coe [148]. Some innovations include hot-side injection, co-injection of ammonia (dual-conditioning), and dual-conditioning in front of fabric filters where the resulting filter cake drag can be significantly reduced. A patented process was designed where NH_3 and SO_3 are injected at a ratio of 2:1, in concentrations of 1 to 100 p.p.m. [149]. Fabric filter pressure drops for cleaning flyash from Pittsburgh #8 and Monticello coal samples were found to be typically two to three times lower, and the particulate matter capture was also improved. This result was followed up by tests in Australia which showed opposite results, where a highly cohesive filter cake was reported [150]. The disparity in the results was attributed to differences in the coal and fabric materials.

Tests have been conducted with a number of different sulfur and ammonia containing conditioning compounds for ESP feeds. Regarding cost effectiveness, ammonium sulfate [$(NH_4)_2SO_4$] in low dosages was found to perform best for low sulfur coal flyash [151].

A related technology is known as sorbent injection. In this case, solid sorbent particulates such as silicates, calcium salts, limes, etc. are injected into a gas stream to adsorb SO_x from the gas. A recent review presents six such commercial processes [152]. A follow up article on high-temperature sorbent injection reports that the electrical resistivity of the particulate matter is increased substantially and the performance of the electrostatic precipitator is degraded accordingly. The resistivity may be brought back to an acceptable level by the use of flue gas humidification or conditioning with SO_3. Certain mixtures of ash and highly reactive sorbent do not appear to respond to SO_3 conditioning. Various catalytic additives were viewed as a potential means to make high-temperature sorbent injection a more viable process [153]. Sorbent injection puts increased loads on particulate matter collection equipment and also modifies the particulate properties, especially with humidified sorbent injection. Recent research has focussed on designing sorbent systems which possibly benefit, or at least do not hinder the performance of the particulate matter removal equipment. The ADVACATE process developed by the US EPA uses a specially prepared calcium silicate sorbent which appears to be quite cohesive and enters the system in an agglomerated state which aids the overall particulate matter control by not introducing additional submicron material [154]. Babcock & Wilcox have developed a sorbent process designed to work in front of baghouses [155]. It is known as the SO_x-NO_x-Rox Box™ system (SNRB) and is an advanced air pollution control process that significantly reduces sulfur oxide (SO_x), nitrogen oxide (NO_x) and particulate emissions from coal-fired boilers [156]. The process uses a high-temperature catalytic baghouse for integrating SO_x reduction by injecting an alkali sorbent (such as hydrated lime or sodium bicarbonate), NO_x removal through ammonia injection and selective catalytic reduction, and particulate collection.

The Westinghouse ILEC (Integrated Low Emissions Cleanup) system represents a different approach to feed conditioning. The use of ceramic filters is envisioned for particulate control at temperatures above 900°C in direct coal-fired turbine applications. Some adhesive flyash particles will be emitted that could form a difficult-to-remove filter cake. The ILEC process injects sorbent particles to either remove the adhesive particles before they reach the ceramic barrier filters, or modify the adhesive nature of the filter cake so that it is more easily removable [157].

From a more fundamental perspective, a recent review is available on how the performance of fabric filters and electrostatic precipitators used to collect ash from the combustion of coal depends on bulk properties of the ash, such as cohesivity or electrical resistivity [158]. A number of recent findings have been cited; the surface of flyash was found to be extremely complex in terms of chemical species; sorbent materials can be added to enhance surface charge properties for streams treated by ESPs; NH_3 added alone or with SO_3 changes the cohesivity of ash, reducing rapping emissions from ESPs; small sized sorbent particulates have been found to act as steric inhibitors to reduce cohesivity of coal ash cleaned by fabric filters; a humidified stream in fabric filters will exhibit a lower pressure drop due to the higher porosity in the dust cake, which forms more compact ash agglomerates. A US DOE experimental program is now underway to follow up on characterizing the mechanisms at work in flue gas conditioning [159].

Acoustic agglomeration has been recently employed to enlarge the size of submicron material so that they can be removed more readily by ESP. At present, some laboratory testing has shown improved results on model systems [160, 161]. Some theoretical analyses suggest that orthokinetic, hydrodynamic and turbulent mechanisms contribute to an increase of particle–particle collisions for systems subjected to acoustical vibration [162, 163]. A numerical simulation was run to model bimodal (flyash with sorbent) acoustic agglomeration, with some comparison to experimental data provided. The net effect of the contributing collision mechanisms was estimated by curve-fitting; no modelling of the adhesion process between particles was provided [164]. The US DOE is aiming to develop acoustic agglomeration methods that would allow the use of conventional cyclones to achieve very high particulate collection efficiency and eliminate the need for barrier filters, which have been problematic in view of durability and economics for proposed direct coal-fired turbines [165]. A patent has been procured [166] and initial testing is underway [167].

Yet another novel technology to be investigated is known as the electron beam precharger [168], also envisioned for coal flyash removal. An electron beam is employed to ionize gas molecules in a precharger region, producing a bipolar plasma of ions and electrons in a continuous state of formation and recombination. When subjected to a strong electric field, the plasma is separated into two monopolar fractions. Only the negative fraction is used and is drawn across the duct to charge the dust to very high levels, which facilitates its removal by ESP. The electron beam precharger was found to improve the particulate collection efficiency of a conventional ESP. Testing has also been conducted to compare pulse charging instead of direct current charging, which can be done at higher strength where it should create a more stable environment for free electrons to precharge particles.

3.4. Process modifications to reduce emissions

As part of an overall strategy to comply with environmental standards, a preferred longer term solution is simply to modify the process which emits the particulates to lower emission levels. Thus, reduced load is placed on the particulate removal equipment. Without augmentation of existing equipment, lower emission levels of particulate matter can be attained.

For example, in the steelmaking industry, it has been demonstrated that by reducing the quantity of lime added to the furnace early in the oxygen blowing cycle, the resulting slag becomes more viscous and foamy, reducing particulate emissions by up to 59% [180].

The chrome electroplating process produces a toxic hexavalent chromium emission. Changes in four process conditions were implemented with the objective of reducing emissions from the process [181]. These included the freeboard height of the electroplating bath, elimination of compressed air for bath agitation, the use of floating balls on the tank surface and an anti-mist bath additive. In four different test facilities using their existing common particulate matter control equipment, reductions in chromium emissions of 85–95% were observed, all meeting the quantitative industry objective of 0.006 mg/A h.

Unfortunately at this time, there are not many examples of such processes in the literature, but use of emission reduction strategies is expected to increase in the future.

3.5. Sector-specific airborne particulate matter control considerations

A subject receiving considerable attention recently is the treatment of emissions from incineration sites. Medical, municipal and industrial wastes being incinerated have been subject to increasingly tight regulations due to the potentially toxic content of the emissions. The wet ESP system (also described in Section 2.2) has been found to be an effective means for reducing particulate and toxic emissions from sewage sludge incinerators under the proposed Part 503 US EPA (February 1989) regulations [169]. Part 503 would limit arsenic, beryllium, cadmium, chromium, lead, mercury and nickel contents of particulate emissions to maximum concentrations of 6.3, 42.3, 1.8, 233.9, 125.1, 135.5 and 72.6 mg/kg, respectively. The US EPA has projected that more than 50% of the existing sewage sludge incinerators will be out of compliance with these proposed regulations. Pilot testing with a post-scrubber feed consisting of particulate matter which was 50% below 0.6 μm, was able to increase the overall particulate matter removal efficiency from 98.3 to 99.88%. Equipment options and cost considerations are discussed for clean air act compliance for waste incinerators [170]. A study of the the nature and composition of incinerator generated particulate matter as related to fuel type was done by Hackfort and Borchardt [171].

A short review is available which discusses particulate matter treatment in the mineral processing industries [172]. Four main sources of pollution are considered: mining and site treatment, smelting, recycling and large scale combustion processes. Attention is given to process modifications which reduce particulate matter emissions or produce gas streams more amenable to particulate matter removal. A paper devoted to recent developments in iron ore sintering discusses environmental aspects including particulate control [173]. Pertinent ESP and scrubbing systems are noted as well as some processes by British Steel and Lurgi which have been updated to produce lower particulate matter emission levels. The US DOE conducted a study providing an overview of particulate matter control technologies for hot gas steams from coal-fired installations [174]. The major particulate control device issues addressed included the integration of the particulate control devices into coal utilization systems, on-line cleaning techniques, chemical and thermal degradation of components, fatigue or structural failures, blinding, collection efficiency as a function of particle size, and scale-up of particulate control systems to commercial size.

Particulate control is also an issue in the pulp and paper sector. Powers *et al.* conducted a survey of applicable technologies for magnesium or ammonium sulfite recovery furnaces in pulp mills [175]. Wet systems are recommended in this case as simultaneous SO_2 removal is also desired. Normally, pulp mills have a waste water treatment system, so transfer of airborne contaminants to an aqueous stream does not pose an additional environmental concern. Successful systems tested on a pilot scale were wet ESPs from Fluid-Ionics and Beltran, and Monsanto's Dynawave Scrubber. A similar approach is taken in the particleboard industry. Fine particulate cleaning has been successful with wet ESPs for treating the gas stream from a sander dust fired drum dryer [176].

With tightening environmental regulations, recovery of heavy metal emissions is becoming a more crucial issue. Of the 189 HAPs regulated under the new Clean Air Act, 11 are heavy metals and most are captured as PM10. The viability of various existing and emerging technology for particulate heavy metal capture is discussed by Nudo [177]. A general overview on the scrubbing of inorganic toxics is given by McInnes *et al.* [178]. Wet scrubbing or absorption are the most common particulate matter removal methods for nonmetallic inorganics, while ESPs and baghouses are the primary effective means of controlling metals. A special venturi scrubber operated at a larger pressure drop when compared to standard venturi scrubbers, was designed to remove heavy metals from waste incinerator gas streams down to US EPA guideline levels [179]. The increased operating costs of this system may hinder its widespread acceptance.

4. SUMMARY

In general, many of the conventional process units used for airborne particulate control are considered to employ effective mature technology. The choice of specific units and the way they are inserted into an engineering design depend on the source of the airborne particulates and the final emission requirements. A survey of recent relevant scientific and engineering literature on this subject has revealed that most of the research and development in this area is incremental, and is often undertaken to achieve site specific objectives to reach compliance with tightening emissions regulations, i.e. air pollution control units are typically installed as add-ons and some research may be done to fine tune the unit to function properly for each specific gas stream in question. Most reports of new technologies describe enhanced versions of conventional units, which are sometimes improved by combining capture mechanisms that are normally exploited in isolation (i.e. electrification of fabric filters).

The US Clean Air Act Amendments of 1990 did not specifically update regulations for all particulate emissions, but there is growing expectation that stricter legislation is forthcoming in this area [182]. As stated previously, particulate emission compliance at present does not pose a serious technological challenge. However, particulate emissions are often concentrated in the 0.1–2.0 μm diameter range, since existing process units are collectively least efficient in removing solids of this size from gas streams. Further, the list of 189 Hazardous Air Pollutants targeted for control in the US Clean Air Act Amendments contains many heavy metals and heavy organics which exist as submicron particulate matter [183]. Health related studies recommend cleaning of sub-2.5 μm particulates, since material in this size class is respirable and contributes to human illness.

The US EPA has an Air and Energy Engineering Research Laboratory which also monitors trends and developments in air pollution control. They cite development occurring in the process design area where variations of combinations and sequences of particulate control units can produce some desired benefit [1]. The concept of process design and integration is increasingly important for new installations where, for example, novel heat-resistant filter materials may be used for particulate removal at elevated temperatures so that the heat energy may be more efficiently retained.

Coupled with process design are methods to reduce the at-source emission of particulates so that their post-processing requirements are minimized. For regulations which allow emissions as mass per unit of energy generated (i.e. fossil fuel based power stations), upgrading of the fuel source prior to combustion may become increasingly necessary. Scrubbers and agglomerating systems where particulates and gaseous toxics are simultaneously removed are also under consideration.

One area where new advances are being made in airborne particulate control technologies is that of filter materials. Many of the fabrics used in baghouses are now available with higher thermal and chemical resistance, longer service life and finer particle diameter control. Cross-flow, pulsed-jet, ceramic tubular and rigid candle-type filters are also employed and show promising results. Many of these filter types offer the advantage of being readily and easily cleaned. Ceramic cross-flow particulate traps have been shown to perform at levels meeting 1994 EPA standards.

For the problematic submicron particles, much attention has been devoted to agglomeration of these particles to form larger conventionally treatable units. Modifications to wet scrubbing have been made with a pre-treatment step where the gas stream was subjected to a condensing steam injector which induced particle agglomeration [81]. Similar pre-treatments are being studied for streams sent to ESPs [184].

Other new directions in particulate control relate to the sources generating the pollution. Municipal waste incineration is a relatively recent process and poses difficulty owing to the variability in the feedstock. Special catalytic scrubbers and process design combinations have been studied for particulates from waste incineration.

From the present scientific and technical perspective, the following trends can be identified as emerging in the development of advanced fine particle control technologies.

(1) Process modelling, simulation and control for improved performance.

(2) As a result of, or closely related to (1), are opportunities to integrate several technologies through process models which identify synergy between the techniques.

(3) Size enlargement techniques which move sub-3 μm particles into the larger more treatable range.

(4) Filtration modules and materials applicable to high temperature situations and/or which are cleanable and anti-fouling.

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REFERENCES

1. Environment Canada. Technology advancement program for advanced fine particle removal. Environmental Protection Service report no. TS-34 (1995), 82.
2. B. B. Crocker, D. A. Novak and W. A. Scholle. Air pollution control methods. In: *Kirk-Othmer: Encyclopedia of Chemical Technology*, 3rd edn, Vol. 1. Wiley, New York (1984), pp. 649–716.
3. K. V. Thambimuthu. *Gas Cleaning for Advanced Coal-based Power Generation*. IEA Coal Research, London (1993).
4. W. Strauss. *Industrial Gas Cleaning*, 2nd edn. Pergamon Press, Oxford (1975).
5. A. Tamir. *Impinging-Stream Reactors. Fundamentals and Applications*. Elsevier, Amsterdam (1994).
6. A. J. Buonicore and W. T. Davis (Eds). *Air Pollution Engineering Manual*. Van Nostrand Reinhold, New York (1992).
7. P. N. Cheremisinoff (Ed.). *Air Pollution Design and Control for Industry*. Marcel Dekker, New York (1993).
8. J. E. Brockmann, C. L .J. Adkins and F. Gelbard. Alternate particle removal technologies for the Airborne Activity Confinement System at the Savannah River Site. US DOE report WSRC-RP-91-0928 (1991), 108.
9. K. Schifftner. Flux Force Condensation Scrubbers for utilization on municipal solid waste incinerators. In: *Joint ASME/IEEE Power Generation Conf.* Dallas, TX (1989) (ASME paper 89-JPGC/EC-5).
10. P. A. Lawless, A. S. Viner, D. S. Ensor and L. E. Sparks. Computations on the performance of particle filters and electronic air cleaners. In: *5th Int. Conf. Indoor Air Quality and Climate*, Vol. 3. Toronto, Canada (1990), pp. 187–192.
11. J. van Heerden and P. Sullivan. The application of CFD for evaluation of dust suppression and auxiliary ventilating systems used with continuous miners. In: *Proc. 6th US Mine Ventilation Symp.* Salt Lake City, UT (1993), pp. 293–297.
12. A. Samanta, R. Bhaskar and R. Gong. Studies on the use of scrubbers in continuous miner faces. In: *Proc. 6th US Mine Ventilation Symp.* Salt Lake City, UT (1993), pp. 51–56.
13. P. Schmidt. Unconventional cyclone separators. *Int. Chem. Eng.* **33**, 8–17 (1993).
14. P. Schmidt and T. Richter. Dust strands in cyclone separators at low dust concentration. *Part. Sci. Technol.* **11**, 107–113 (1993).
15. J. Plucinski, L. Gradon and J. Nowicki. Collection of aerosol particles in a cyclone with an external electric field. *J. Aerosol Sci.* **20**, 695–700 (1989).
16. C. E. Romero, D. W. Shaw and J. S. Ontko. Particle collection efficiency of a cyclonic combustor. In: *AIAA/ASME National Fluid Dynamics Congr.* Los Angeles, CA (1992) (report DOE/METC/C-92/7020).
17. J. Barrett. Spinning tube cleans up emissions. *Eureka* **13**, 26–27 (1993).
18. C. Wadenpohl and F. Löffler. An electro-mechanical two-stage system for the separation of diesel soot particles. In: *Air Pollution Control: Papers from the 9th World Clean Air Congr.* Montreal, Canada (1992) (paper IU-18F-02).
19. National Technical Information Service, United States. Electrostatic precipitators (Latest citations from the NTIS Bibliographic Database), Feb. 1994, 250 citations, document PB94-866779/XAD.
20. EPRI-Int. Soc. Electrostatic precipitation. *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*. Washington, DC (1993).
21. G. R. Offen and R. F. Altman. Issues and trends in electrostatic precipitation technology for US utilities. *J. Air Waste Manage. Ass.* **41**, 222–227 (1991).
22. H. J. Del Gatto. Don't let ESP become Achilles' heel of compliance strategy. *Power* **138**, 81–84 (1994).
23. R. P. Gaikwad, D. G. Sloat, R. Altman and R. L. Chang. Economic evaluation of electrostatic precipitator retrofit options. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
24. R. L. Andrews, C. A. Altin and R. Salib. ESPs in the 21st century: extinction or evolution. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).

25. R. A. Mastropietro and R. LeBeau. Rebuild and enlargement of existing weighted-wire ESPs as a result of coal switching. In: *5th Int. Conf. and Exhibition for the Power Generating Industries—POWER-GEN '92*. Orlando, FL (1992), pp. 48–65.
26. T. Tanaka, H. Fujishima and Y. Tsuchiya. Development of advanced dust collecting system for coal-fired power plant. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
27. H. Yabuta. Recent dust collection technology for utility-use boilers. *Hitachi Rev.* **39**, 355–362 (1990).
28. G. Dinelli, V. Bogani and M. Rea. Enhanced precipitation efficiency of electrostatic precipitators by means of impulse energization. *IEEE Trans. Ind. Appl.* **27**, 323–330 (1991).
29. N. Tachibana and Y. Matsumoto. Intermittent energization on electrostatic precipitators. *J. Electrostatics* **25**, 55–73 (1990).
30. T. Watanabe, F. Tochikubo, Y. Koizumi, J. Tsuchida, J. Hautanen and E. I. Kauppinen. Submicron particle agglomeration by an electrostatic agglomeration. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
31. H. R. Falaki. Experimental study of flow diversion during the rapping of collector plates inside an electrostatic precipitator. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
32. L. Lind and E. M. Bojsen. Experience with baffle-free collecting plates in an electrostatic precipitator. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
33. V. S. Lee. US EPA-developed air-pollution control technology. In: *1st N. American Conf. on Emerging Clean Air Technologies and Business Opportunities*. Toronto, Canada (1994).
34. V. Reyes and P. Lausen. Utilization of expert computer systems for control and operation of electrostatic precipitators. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
35. Anon. Use advanced controls to maximize ESP efficiency. *Power* **135**, 56–57 (1991).
36. C. Eyraud. Gas cleaning by wet electrostatic precipitation: new prospects. *Filtr. Sep.* **30**, 637–639 (1993).
37. H. Fujishima and Y. Tsuchiya. Application of wet type electrostatic precipitator for utilities' coal-fired boiler. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*. Washington, DC (1993).
38. A. C. Sheth, J. K. Holt, J. R. Douglas and B. R. Thompson. Role of the wet electrostatic precipitator in the coal-fired magnetohydrodynamics system. In: *Symp. on Engineering Aspects of Magnetohydrodynamics* (*SEAM 30 Proc.*). Baltimore, MD (1992), pp. 9.1–9.11.
39. M. Valenti. Emission control: retrofitting process plants for the 1990s. *Mech. Eng.* **114**, 68–74 (1992).
40. E. H. Weaver. Innovative design features for electrostatic precipitators installed on biomass fired boilers. In: *Proc. 1994 Industrial Power Conf.* San Francisco, CA (1994), pp. 73–85.
41. D. B. Kittelson, J. Reinertsen and J. Michalski. Further studies of electrostatic collection and agglomeration of diesel particles. In: *Global Developments in Diesel Particulate Control*. Warrendale, PA, Society of Automotive Engineers, Publ. P-240 (SAE tech. paper 910329) (1991), pp. 145–163.
42. R. Ettema. Electrostatic precipitator performance improvement through numerical simulation. *World Cement* **25**, 63–66 (1994).
43. W.-J. Liang and T. H. Lin. The characteristics of ionic wind and its effect on electrostatic precipitators. *J. Aerosol Sci.* **20**, 330–344 (1994).
44. M. Abdel-Salam. Influence of humidity on charge density and electric field in electrostatic precipitators. *J. Phys. D. Appl. Phys.* **25**, 1318–1322 (1992).
45. V. H. Belba, W. T. Grubb and R. L. Chang. The potential of pulse-jet baghouses for utility boilers. Part 1: A worldwide survey of users. *J. Air Waste Manage. Ass.* **42**, 209–213 (1992).
46. C. J. Bustard, J. M. Cushing and R. L. Chang. The potential of pulse-jet baghouses for utility boilers. Part 2: Performance of pulse-jet fabric filter pilot plants. *J. Air Waste Manage. Ass.* **42**, 1240–1249 (1992).

47. D. G. Sloat, R. P. Gaikwad and R. L. Chang. The potential of pulse-jet baghouses for utility boilers. Part 3: Comparative economics of pulse-jet baghouse, precipitators and reverse-gas baghouses. *Air Waste* **43**, 120–128 (1993).
48. B. Svensson. Advanced fabric filters for effective emission control in the steelmaking industry. *ABB Rev.* **10**, 23–26 (1990).
49. Anon. Advanced filtration technology to satisfy tomorrow's legislation. *Filtr. Sep.* **30**, 37–38 (1993).
50. W. Brame. Fabric filter apparatus, Australian Pat. AU-B-35992/89 (1989).
51. T. G. Ebner, C. J. Bustard, F. J. Sagan and R. L. Chang. Design and development of a novel filter cage for improved cleaning and extended bag life. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
52. T. Gennrich. Filter bags help meet particulate control standards. *Power Eng.* **97**, 37–39 (1993).
53. G. A. Kudlac, G. A. Farthing, T. Szymanski and R. Corbett. SNRB catalytic baghouse laboratory pilot testing. *Environ. Prog.* **11**, 33–38 (1992).
54. W. T. McKenna. Filter media selection for fabric filters. Industrial boilers, CFBs, and incinerators. In: *Proc. 1990 Ind. Power Conf.*, PWR Vol. 9. St Louis, MO (1990), pp. 9–13.
55. G. A. Brinckman. Microporous Gore-Tex® membrane filter media can help control submicron particulate matter, heavy metal, and dioxan/furan emissions. In: *Air and Waste Management Ass. 85th Ann. Meeting and Exhibition.* Kansas City, MO (1992) (paper 92-111.05).
56. F. Noël, M. Dufour and G. Gosselin. Development of a dust collector for bark boiler exhaust gases. In: *1st N. American Conf. on Emerging Clean Air Technologies and Business Opportunities.* Toronto, Canada (1994).
57. G. Gosselin. Process for removing dust from high temperature gas streams. US Pat. 5112368 (1992).
58. R. Barnes. A parametric study of the effects of textile processing variables on the filtration efficiency of a woven glass fabric. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
59. L. Bergmann. Conductive fabrics in dust collectors. *Staub. Reinhaltung der Luft* **53**, 307–309 (1993).
60. T. Grafe and G. Kelley. Baghouse and cartridge dust collectors: a comparison. *Am. Cer. Soc. Bull.* **72**, 69–73 (1993).
61. G. F. Weber, S. R. Ness and D. L. Laudal. Simultaneous NO_x and particulate control using a catalyst-coated fabric filter. In: *Int. Power Generation Conf.* San Diego, CA (1991) (ASME paper 91-JPGC-FACT-2).
62. G. F. Weber, S. R. Ness and G. L. Schelkoph. Catalytic fabric filtration for simultaneous NO_x and particulate control. Quarterly technical progress report, Oct. 1–Dec. 31, 1993. Report DOE/PC/90361-T13 (1994).
63. A. S. Viner, G. P. Greiner and L. S. Hovis. Advanced electrostatic stimulation of fabric filtration: performance and economics. *JAPCA* **38**, 1573–1582 (1988).
64. S. Rao and D. V. S. Murthy. Electro statically enhanced fabric filtration. *CEW Chem. Eng. World* **24**, 21–24 (1989).
65. Y. Yamamoto. Filter for particulate materials in gaseous fluids. US Pat. 5368635 (1994).
66. National Technical Information Service, United States. Gas scrubbers (Latest citations from the NTIS Database), July 1993, 111 citations, document PB93-881811/XAD.
67. P. J. Loftus, D. B. Stickler and R. C. Diehl. Confined vortex scrubber for fine particulate removal from the flue gases. *Environ. Prog.* **11**, 27–32 (1992).
68. K. A. Jonsson. Gas cleaning methods and apparatus. US Pat. 5076818 (1991).
69. D. P. Burford and I. G. Pearl. Initial results from the CT-121 innovative clean coal technology demonstration project at Georgia power's plant Yates. In: *Proc. Joint ASME/IEEE Power Generation Conf.* Kansas City, KS (1993) (ASME paper 93-JPGC-EC-12).
70. J. J. Schwab. Venturi scrubber and process. US Pat. 5279646 (1994).
71. K. D. Nguyen and D. R. Spink. Scrubber products for acid rain and air toxics control. In: *1st N. American Conf. and Exhibition: Emerging Clean Air Technologies and Business Opportunities.* Toronto, Canada (1994).
72. C-C. Chen, H-K. Shu and Y-K. Yang. Nucleation-assisted process for the removal of fine aerosol particles. *Ind. Eng. Chem. Res.* **32**, 1509–1519 (1993).

73. S. V. Sheppard. Fine particle removal for hazwaste incinerators with the ionizing wet scrubber. In: *86th Ann. Meeting Air and Waste Management Association.* Denver, CO (1993) (paper 93-TP51.01).
74. T. F. Burger, D. M. Collins, S. M. Collins and M. R. Burger. Circulating air scrubber. Canadian Pat. 1316122 (1993).
75. L. R. Waterland, D. J. Fournier, Jr., J. W. Lee and G. J. Carroll. Trace metal fate in a rotary kiln incinerator with an ionizing wet scrubber. *Waste Manage.* **11**, 103–109 (1991).
76. S. Sumiyoshitani. Effects of an applied electric field on collection efficiency by a charged droplet for dust particles in charged dropled scrubbers. *Aerosol Sci. Tech.* **20**, 71–82 (1994).
77. H. Polat, Q. Hu, M. Polat and S. Chander. The effect of droplet and particle charge on dust suppression by wetting agents. In: *Proc. 6th US Mine Ventilation Symp.* Salt Lake City, UT (1993), pp. 535–541.
78. E. B. Hanf and W. Ellison. FGD mist eliminators for 0.002 LB/MMBTU solid particulate emission. In: *Proc. Joint ASME/IEEE Power Generation Conf.* Kansas City, KS (1993) (ASME paper 93-JPGC-EC-9).
79. Anon. Two-stage scrubber system removes HCl, Cl_2. *Chem. Eng. Prog.* **10**, 23 (1994).
80. A. I. Lainer, T. D. Israfilov, I. T. Elperin and V. L. Meltser. Study of counterflow trapping of alunite dust. *Sov. J. Non-Ferrous Metals* **48**, 43–45 (1975).
81. J. Sun, B. Y. H. Liu, P. H. McMurry and S. Greenwood. Method to increase control efficiencies of wet scrubbers for submicron particles and particulate metals. *J. Air Waste Manage. Ass.* **44**, 184–185 (1994).
82. K. W. Wilson, J. C. Haas and M. B. Eshelman. Applications of moving granular-bed filters to advanced systems. In: *Coal-fired Power Systems '93: Advances in IGCC and PFBC Review Meeting.* Morgantown, WV (1993) (report DOE/MC/27423-93/C0215).
83. K. W. Wilson, J. C. Haas and M. B. Eshelman. Granular-bed and ceramic candle filters in commercial plants: a comparison. Report DOE/MC/27423-3513 (1993).
84. W. Yang, R. Newby, T. Lippert and D. Keairns. MGBF concept looks good for hot gas cleanup. *Modern Power Sys.* **12**, 21–24 (1992).
85. C. A. P. Zevenhoven, B. Scarlett and J. Andries. The filtration of PFBC combustion gas in a granular bed filter. *Filtr. Sep.* **29**, 239–244 (1992).
86. C. A. P. Zevenhoven, K. R. G. Hein and B. Scarlett. Moving granular bed filtration with electrostatic enhancement for high-temperature gas clean-up. *Filtr. Sep.* **30**, 550–553 (1993).
87. J. S. Mei, P. C. Yue and J. S. Harlow. Fluidized-bed filtration for particulate clean-up. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion.* San Diego, CA (1993), pp. 1351–1358.
88. T. C. Ho, L. Tan, C. Chen and J. R. Hopper. Metal emissions control through heterogeneous deposition during fluidized bed incineration. *J. Hazard. Mater.* **24**, 292–293 (1990).
89. B. Neukirchen. Reduction of heavy metal and dioxan emission by means of an activated carbon filter on the hazardous waste incineration facility at RZR Herten. In: *Air Pollution Control: Papers from the 9th World Clean Air Congr.* Montreal, Canada (1992) (paper IU-18E-04).
90. W. Peukert and F. Löffler. Influence of temperature on particle separation in granular bed filters. *Powder Technol.* **68**, 263–270 (1991).
91. Y. Otani, C. Kanaoka and H. Emi. Experimental study of aerosol filtration by the granular bed over a wide range of Reynolds numbers. *Aerosol Sci. Technol.* **10**, 463–474 (1989).
92. Sorbent Technologies Corp. Supported-sorbent injection. In: *1st N. American Conf. and Exhibition: Emerging Clean Air Technologies and Business Opportunities.* Toronto, Canada (1994).
93. J. G. Toher, P. Feldman and K. S. Kumar. Circulating dry scrubbers—present and future capabilities. In: *1st N. American Conf. and Exhibition: Emerging Clean Air Technologies and Business Opportunities.* Toronto, Canada (1994).
94. H. R. Paur, W. Schikarski, W. Baumann, C. H. Leichsenring, W. Linder and H. Mätzing. State of the art in electron beam dry scrubbing of flue gas. In: *Air Pollution Control: Papers from the 9th World Clean Air Congr.* Montreal, Canada (1992) (paper IU-18A-03).
95. P. M. Eggerstedt, J. F. Zievers and E. C. Zievers. Choose the right ceramic for filtering hot gases. *Chem. Eng. Prog.* **89**, 62–68 (1993).

96. L. R. White, T. L. Tompkins, K. C. Hsieh and D. D. Johnson. Ceramic filters for hot gas cleanup. *J. Eng. Gas Turb. Power* **115**, 665–669 (1993).
97. C. Butcher. Hot news in ceramic filters. *Chem. Eng.* (*London*) **505**, 27–29 (1991).
98. T. W. Smith. New developments in high-efficiency particulate air filtration. *Am. Cer. Soc. Bull.* **72**, 79–84 (1993).
99. J. Seville. Handling hot gas. *Process Eng.* **74**, 51–54 (1993).
100. G. Ondrey and S. Moore. Gas cleaning comes out of the bag. *Chem. Eng.* **101**, 28–31 (1994).
101. W. Cheung, J. P. K. Seville, R. Clift, C. J. Bower and A. N. Twigg. Filtration and cleaning characteristics of ceramic media. In: *4th Int. Fluidized Combustion Conf.* London (1988), pp. II/9/1–II/9/14.
102. J. Stringer and A. J. Leitch. Ceramic candle filter performance at the Grimethorpe (UK) pressurized fluidized bed combustor. In: *Int. Gas Turbine and Aeroengine Congr. and Exposition.* Orlando, FL (1991) (ASME paper 91-GT-381).
103. J. Stringer and A. J. Leitch. Ceramic candle filter performance at the Grimethorpe (UK) pressurized fluidized bed combustor. *J. Eng. Gas Turbines Power Trans. ASME* **114**, 371–379 (1992).
104. M. Durst, M. Müller, M. R. Schnell and A. R. Wagner. Performance of rigid ceramic filter elements in an 8,000 hour durability test at high temperatures. In: *Proc. 1991 Int. Conf. on Fluidized Bed Combustion*, Vol. 3. Montreal, Canada (1991), pp. 1081–1086.
105. S. Laux, B. Giernoth, H. Bulak and U. Renz. Hot gas filtration with ceramic filter elements. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 1241–1251.
106. R. Clark, P. Holbrow, J. E. Oakley, K. Burnard and J. Stringer. Some recent experiences with the EPRI hot gas rigid ceramic filter at Grimethorpe PFBC establishment. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 1251–1258.
107. C. E. Selmer and W. T. Bakker. Evaluation of silicon carbide candle filters. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 1259–1264.
108. T. Eriksson, J. Isaksson, P. Stålberg, E. Kurkela and V. Helanti. Durability of ceramic filters in hot gas filtration. *Bioresource Technol.* **46**, 103–112 (1993).
109. K. R. Valentino, N. R. Brown, J. J. Brown, Jr. and W. T. Bakker. Durability testing of ceramic candle filters in PFBS environments. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 1375–1383.
110. H. Leibold, F. Dirks and V. Rüdinger. Particulate emissions from a LLW incinerator and off-gas cleaning with a new type of ceramic candle filter. *Waste Manage.* **9**, 87–94 (1989).
111. J. Jalovaara, I. Hippinen and A. Johkola. Particle removal in PFBC using a fibrous ceramic candle filter. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 713–718.
112. R. A. Brown and A. J. Leitch. Filtration of PFBC dusts using a rigid ceramic tube type filter. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 1229–1239.
113. K. Higashi and H. Maeno. The latest status of the development of the advanced ceramic tube filter. *Reports Res. Asahi Glass Co., Ltd.* **42**, 81–95 (1992).
114. J. P. K. Seville, R. Legros, C. M. H. Brereton, C. J. Lim and J. R. Grace. Performance of rigid ceramic filters for CFBC gas cleaning. In: *Proc. 1991 Int. Conf. on Fluidized Bed Combustion*, Vol. 1. Montreal, Canada (1991), pp. 279–286.
115. M. J. Mudd and J. D. Hoffman. Operating data from the TIDD hot gas clean up program. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 719–727.
116. T. E. Lippert, G. J. Bruck, R. A. Newby and E. E. Smeltzer. Specific filter designs for PFBC. In: *Coal-fired Power Systems '93: Advanced in IGCC and PFBC Review Meeting*. Morgantown, WV (1993) (report DOE/MC/21023-93/C0212).
117. J. F. Zievers, P. Eggerstedt, E. C. Zievers and D. Nicolai. What affects the cost of hot gas filter stations? *J. Eng. Gas Turbines Power, Trans. ASME* **115**, 652–657 (1993).
118. C. M. Urban, L. C. Landman and R. D. Wagner. Diesel car particulate control methods. In: *Diesel Particulate Emissions Control*. Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 830084) (1983), pp. 87–96.
119. P. R. Miller, J. Scholl, S. Bagley, D. Leddy and J. H. Johnson. The effects of a porous ceramic particulate trap on the physical, chemical and biological character of diesel particulate emissions.

In: *Diesel Particulate Emissions Control.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 830457) (1983), pp. 159–185.

120. J. J. Tutko, S. S. Lestz, J. W. Brockmeyer and J. E. Dore. Feasibility of ceramic foam as a diesel particulate trap. In: *Diesel Particulate Traps.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 840073) (1984), pp. 15–24.
121. C. Bertoli, F. E. Corcione, N. Del Giacomo, G. Police and M. Migliaccio. Performance evaluation of particulate traps for passenger car diesel engines. In: *Advances in Engine Emission Control Technology. Presented at the 12th Ann. Energy-Sources Technology Conf. and Exhibition.* Houston, TX (1989), pp. 27–35.
122. K. Takesa, T. Uchiyama and S. Enamito. Development of particulate trap system with cross flow ceramic filter and reverse cleaning regeneration. *SAE Trans.* **100**, 428–439 (1991) (SAE tech. paper 910326).
123. K. Takesa, T. Uchiyama and S. Enamito. Development of Asahi particulate trap system. *Reports Res. Asahi Glass Co., Ltd* **41**, 197–214 (1991).
124. J. Kitagawa, T. Hijikata and S. Satoru. Electric heating regeneration of large wall-flow type DPF. In: *Global Developments in Diesel Particulate Control.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 910136) (1991), pp. 63–71.
125. A. Balzotti, G. M. Cornetti, F. Pidello, M. Signe and V. Scorsone. Italian city buses with particulates traps. In: *Advances in Diesel Particulate Control.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 900114) (1990), pp. 79–86.
126. S. T. Gulati, D. W. Lambert, M. B. Hoffman and A. Tuteja. Thermal durability of a ceramic wall-flow diesel filter for light duty vehicles. In: *Diesel Particulate Control, Trap, and Filtration Systems.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 920143) (1992), pp. 69–79.
127. M. G. Grenier and S. G. Hardcastle. Safety and health in the Canadian mine environment. An overview of ventilation, dust, radiation and diesel emission research. *CIM Bull.* **83**, 41–46 (1990).
128. F. B. Walton, P. J. Hayward and D. J. Wren. Controlled energy deposition in diesel particulate filters during regeneration by means of microwave irradiation. In: *Advances in Diesel Particulate Control.* Warrendale, PA, Society of Automotive Engineers (SAE tech. paper 900327) (1990), pp. 131–140.
129. R. F. Abrams and R. L. Goldsmith. Field testing of ceramic membrane gas filters. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
130. C. J. Bustard, S. M. Sjostrom, R. H. Slye and J. Foote. Application of novel filtration technologies to the MHD process. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
131. R. L. Goldsmith and B. A. Bishop. Catalytic filtration device and method. US Pat. 5221484 (1993).
132. K. Benedek and M. Flytzani-Stephanopoulos. Cross-flow, filter-sorbent catalyst for particulate, SO_2 and NO_x control. Seventh quarterly technical progress report. Report DOE/PC/89805-T8, 1992.
133. R. A. Newby, T. E. Lippert, E. E. Smeltzer, A. Robertson and D. Bonk. Cross flow filter performance with second-generation PFBC carbonizer fuel gas. In: *Proc. 1993 Int. Conf. on Fluidized Bed Combustion*, Vol. 2. San Diego, CA (1993), pp. 703–712.
134. M. Parish and A. B. Jeffrey. Ceramic filter elements with tailored macro- and microstructures. *Filtr. Sep.* **32**, 31–35 (1995).
135. R. Chang. Compact Hybrid Particulate Collector (COHPAC). US Pat. 5158580 (1992).
136. L. Lamarre. COHPing with particulates. *EPRI J.* **18**, 18–23 (1993).
137. A. K. Hindocha, B. Brown and R. Chang. Commercial demonstration of COHPAC. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
138. K. Steinbacher, H. Schmidt and W. Leussler. Process and apparatus for purifying dust and pollutant-containing exhaust gases. Australian Pat. AU 643794 (1993).
139. K. Steinbacher, H. Schmidt and W. Leussler. Verfahren and Vorrichtung zun Reinigung staub- und schadstoffhaltiger Abgase. European Pat. EP 461695 (1991).
140. H. Schen. Pollution emission control system. US Pat. 5171446 (1992).
141. J. Dixkens, H. Fissan and T. Dose. New particle sampling technique for direct analysis using total-reflection X-ray fluorescence spectrometry. *Spectrochim. Acta* **48B**, 231–238 (1993).

142. R. M. Burton. Method and apparatus for sampling air contaminants. PCT Int. Pat. WO 9306910 (1993).
143. Anon. High volume particle sampling and analysis. *Atmospheric Monitoring & Abatement News*, July, 7 (1994).
144. D. E. Pike. Apparatus for the quantification of dust collectibility. US Pat. 5119684 (1992).
145. Anon. Choosing the correct particulate monitor for your facility. BHA Group Inc., company literature, June 14 (1994).
146. S. Rowsell. Spark detection help to prevent fires in dust collection systems. *Cdn. Firefighter*, July, 19 (1995).
147. K. Morris. Expert system control of fabric filters. *Filtr. Sep.* **28**, 275–280 (1991).
148. H. V. Krigmont and E. L. Coe, Jr. Flue-gas conditioning: key advances in recent years. *Power* **136**, 30–36 (1992).
149. D. L. Laudal and S. J. Miller. Controlling particulate emissions from coal combustion plant stacks—ammonia and sulphur trioxide gases are injected upstream of baghouse. US Pat. 5034030 (1991).
150. W. Humphries, R. Beck and A. Lowe. Effect of ammonia injection on fabric filter pressure drop. *J. Air Waste Manage. Ass.* **41**, 1523–1527 (1991).
151. L. A. Rikhter, S. L. Chernov, A. A. Averin and S. V. Cherepov. Improving the efficiency of removal of high-resistance ash in electrostatic precipitators by chemical conditioning of flue gases. *Thermal Eng.* **38**, 137–140 (1991).
152. R. S. Dahlin, T. R. Snyder and P. V. Bush. Effects of sorbent injection on particulate properties. Part I. Low-temperature sorbent injection. *J. Air Waste Manage. Ass.* **42**, 1592–1602 (1992).
153. R. S. Dahlin, T. R. Snyder and P. V. Bush. Effects of sorbent injection on particulate properties. Part II. High-temperature sorbent injection. *J. Air Waste Manage. Ass.* **43**, 91–96 (1993).
154. C. B. Sedman, R. E. Valentine and N. Plaks. Evaluation of pilot ESP performance with elevated loadings from sorbent injection processes. In: *9th Symp. on Particulate Control*. Williamsburg, VA (1991) (report EPA/600/D-91/244).
155. J. B. Doyle, E. A. Pirsh and W. Downs. Integrated injection and bag filter house system for SO_x–NO_x particulate control with reagent/catalyst regeneration. Canadian Pat. 1273474 (1990).
156. G. A. Kudlac, G. A. Farthing, T. Szymanski and R. Corbett. SNRB catalytic baghouse laboratory pilot testing. *Environ. Prog.* **11**, 33–38 (1992).
157. R. A. Newby, M. A. Alvin, D. M. Bachovchin, W. C. Yang, E. E. Smeltzer and T. E. Lippert. Integrated Low Emissions Cleanup system for direct coal fueled turbines (moving bed, fluid bed contactor/ceramic filter). Twenty-fifth quarterly report, Oct.–Dec. 1993. Report DOE/MC/24257-3705 (1993).
158. P. V. Bush and T. R. Snyder. Implications of particulate properties on electrostatic precipitator and fabric filter performance. *Powder Technol.* **72**, 207–213 (1992).
159. T. R. Snyder. Fundamental mechanisms in flue gas conditioning. Quarterly report, Oct.–Dec. 1993. Report DOE/PC/90365-T13 (1994).
160. J. Magill, P. Caperan, J. Somers, K. Richter, S. Fourcaudot, P. Barraux, P. Lajarge, J. A. Gallego-Juarez, E. Riera-Franco De Sarabia, G. Rodriguez-Corral and N. Seyfert. Characteristics of an electro-acoustic precipitator (EAP). *J. Aerosol Sci.* **23**, S803–S806 (1992).
161. A. Renoux. Action des ondes acoustiques sur les aerosols. In: *Air Pollution Control: Papers from the 9th World Clean Air Congr.* Montreal, Canada (1992) (paper IU-18F-05).
162. L. Song, G. H. Koopman and T. L. Hoffmann. An improved theoretical model of acoustic agglomeration. *J. Vib. Acoustics, Trans. ASME* **116**, 208–214 (1994).
163. M. A. Al-Nimr and V. S. Arpaci. Acoustical properties of interacting and agglomerated particles. *J. Sound Vib.* **165**, 19–30 (1993).
164. T. L. Hoffmann, W. Chen, G. H. Koopman, A. W. Scaroni and L. Song. Experimental and numerical analysis of bimodal acoustic agglomeration. *J. Vib. Acoustics, Trans. ASME* **115**, 232–240 (1993).
165. M. N. Mansour, R. R. Chandran, J. N. Duqum, A. W. Scaroni, G. H. Koopman and J. L. Loth. Particle collection enhancement by acoustics. In: *Coal-fired Power Systems '93: Advances in IGCC and PFBC Review Meeting*. Morgantown, WV (1993) (report DOE/MC/26288-93/C0223).

166. M. N. Mansour. Pulse combusted acoustic agglomeration apparatus and process. US Pat. 5197399 (1993).
167. US DOE. Sonic Enhanced Ash Agglomeration and Sulfur Capture. Quarterly technical progress report, Sept. 1993–Jan. 1994. Report DOE/MC/26288-3688 (1993).
168. W. C. Finney and W. N. Shelton. Pulsed electron beam precharger. Final report, Sept. 1989–May 1992 (progress report). Report DOE/PC/89768-T14 (1992).
169. L. H. Hentz, F. B. Johnson and A. Baturay. Air emission studies of sewage-sludge incinerators at the western branch waste-water treatment-plant. *Water Environ. Res.* **64**, 111–119 (1992).
170. V. J. Petti and P. Maurin. 'Clean air act compliance' trash-to-energy facilities-retrofitting for acid gas control. In: *Proc. Joint ASME/IEEE Power Generation Conf.* Kansas City, KS (1993) (ASME paper 93-JPGC-FACT-5).
171. H. Hackfort and J. Borchardt. Influencing and controlling ultrafine particulate emissions from a CFB-waste incinerator. *J. Aerosol Sci.* **23**, S729–S732 (1992).
172. A. Arrowsmith and N. Ashton. Air pollution control from the mineral processing industries. *Minerals Eng.* **4**, 1071–1080 (1991).
173. P. R. Dawson. Recent developments in iron-ore sintering. Part 4: The sintering process. *Ironmaking & Steelmaking* **20**, 150–159 (1993).
174. US DOE. Hot gas cleanup test facility for gasification and pressurized combustion. Quarterly technical progress report, Oct.–Dec. 1992. Report DOE/MC/25140-3555 (1992).
175. W. E. Powers, M. W. Short, J. A. Evensen and B. A. Dennison. Retrofit options for controlling particulate-emissions from a magnesium sulfite recovery furnace. *Tappi J.* **75**, 113–120 (1992).
176. D. Adair, J. L. Stafford and G. A. Raemhild. Innovative dryer and emission control systems at a particleboard installation. In: *Proc. Washington State University Int. Particle-board/Composite Materials Series Symp.* Pullman, WA (1990), pp. 209–225.
177. L. Nudo. Capturing heavy metals. *Pollut. Eng.* **25**, 80–82 (1993).
178. R. McInnes, K. Jameson and D. Austin. Scrubbing toxic inorganics: particulates are controlled with baghouses or electrostatic precipitators, while nonmetallics are scrubbed. *Chem. Eng.* **97** (9), 116–121 (1990).
179. R. J. Cowley, B. P. Gallagher and B. M., Jr. Nee. Development and execution of a metals pretest program for a hazardous waste incinerator. *Hazard. Waste Hazard. Mater.* **11** (1), 31–51 (1994).
180. E. Cocchiarella, M. S. Greenfield and S. Chubbs. The effect of foamy slag on basic oxygen steelmaking process emissions. *CIM Bull.* **86** (974), 56–61 (1993).
181. C. A. Popejoy and F. R. Weintraub. A systems approach to controlling chrome electroplating emissions. In: *Air Pollution Control: Papers from the 9th World Clean Air Congr.* Montreal, Canada (1992) (paper IU-18E-10).
182. R. W. McIlvaine. Forecast and markets for particulate control systems. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).
183. P. L. Feldman and K. S. Kumar. The challenge of high-efficiency control of fine particles. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 2. Washington, DC (1993).
184. M. D. Durham, D. B. Holstein, R. G. Rhudy, R. F. Altman, T. A. Burnett, L. Lepovitz and G. Blythe. Performance of ESPs with small SCAs in spray dryer retrofit applications. In: *10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation*, Vol. 1. Washington, DC (1993).