Recent developments in particulate control

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Abstract

Electrostatic precipitators (ESP) are the dominant type of particulate control in pulverised coal combustion (PCC) plant; fabric filters (FF) play a smaller role. Environmental pressures and subsequent tighter regulations have lowered emission limit values (ELV) for particulate matter from PCC plant, and they are now extending to specific toxic metals, such as mercury. Lower ELV are generally met by increasing the efficiency of the existing particulate control via numerous enhancements. However, the existing fleet is ageing, various restrictions on site limit what work can be done and PCC plant is progressively operating under non-design conditions. Despite this, further developments in technology have led to significant improvements in collection efficiency and regulations have been met. New hybrid ESP/FF systems aim to become more viable than the individual technology by utilising the advantages of both technologies. The purpose of this report is to review the technical and economic considerations of enhancements in particulate control for PCC plant over the last decade.

Acknowledgments

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Acronyms and abbreviations

A/C	air to cloth
AHPC	advanced hybrid particulate collector
CFD	computational fluid dynamics
COHPAC	compact hybrid particulate collector
EFIC	electrostatic-fabric integrated collector
GE	general electric
EHD	electro-hydrodynamic
ELV	emission limit value(s)
EPLI+	electrical low pressure impactor+
ePTFE	expanded polytetrafluoroethylene
EPRI	Electric Power Research Institute (USA)
ESFF	electrostatically enhanced fabric filter
ESP	electrostatic precipitator(s)
FF	fabric filter
FGC	flue gas conditioning
FGD	flue gas desulphurisation
IGBT	insulated-gate bipolar transistor
IPC	intelligent precipitators computer
LOI	loss on ignition
MBC	microprocessor based control
MEEP	moving electrode electrostatic precipitator
MHI	Mitsubishi Heavy Industries
MSC	multistage collector
NETL	National Energy Research Laboratory (USA)
NOx	nitrogen monoxide/nitric oxide and nitrogen dioxide
OEM	original equipment manufacturers
PAC	powder activated carbon
PAN	polyacrylnitrile
PCC	pulverised coal combustion
PE	pulse energisation
PI	polyimide
PJFF	pulse jet fabric filter
$PM_{2.5}$	particulate matter less than 2.5 µm
PM_{10}	particulate matter less than 10 µm
PPS	polyphenylenesulphide
PTFE	polytetrafluoroethylene
ROPE	rapid onset pulse energisation
SCA	specific collection area
SCR	selective catalytic reduction
SIR	switched integrated rectifier
SMPS	switched mode power supply
SNCR	selective non-catalytic reduction
T-R	transformer-rectifier
UBC	unburnt carbon
US DOE	United States Department of Energy
WHO	World Health Organisation

Contents

Acronyms and abbreviations . . . 2

Contents . . . 3

1 Introduction . . . 5

2 Background . . . 7
- 2.1 Emission limits values . . . 7
- 2.2 Market . . . 7
- 2.3 Fly ash properties . . . 8
- 2.4 Other flue gas cleaning equipment . . . 9
- 2.5 Biomass cofiring . . . 10

3 Electrostatic precipitator . . . 11
- 3.1 Fundamentals . . . 11
  - 3.1.1 Theory of operation . . . 11
  - 3.1.2 Configuration . . . 13
  - 3.1.3 Hot side ESP . . . 13
  - 3.1.4 Voltage-current curves . . . 14
- 3.2 Maintenance and upgrading . . . 14
  - 3.2.1 Discharge electrode . . . 14
  - 3.2.2 Plate electrode . . . 15
  - 3.2.3 Transformer-rectifier sets . . . 15
  - 3.2.4 Rappers . . . 15
  - 3.2.5 Rebuilding . . . 16
- 3.3 Flow distribution . . . 16
- 3.4 Power supply and control . . . 17
  - 3.4.1 Power supply . . . 18
  - 3.4.2 Control . . . 19
  - 3.4.3 Alstom . . . 19
  - 3.4.4 Siemens . . . 22
  - 3.4.5 NWL . . . 22
  - 3.4.6 Fujian LongKing . . . 22
  - 3.4.7 FLSmidth . . . 23
  - 3.4.8 IRS and EDF . . . 23
- 3.5 Modelling ESP operation . . . 24
  - 3.5.1 Models to aid control systems . . . 24
  - 3.5.2 Model for fault finding . . . 24
- 3.6 Electrical low pressure impactor + . . . 24
- 3.7 Flue gas conditioning . . . 25
- 3.8 Humidification . . . 26
- 3.9 Agglomeration . . . 26
- 3.10 Wet ESP . . . 27
  - 3.10.1 Plate electrodes . . . 28
  - 3.10.2 Croll-Reynolds Clean Air Technologies . . . 28
  - 3.10.3 Dynawave . . . 29
- 3.11 Colder side ESP . . . 29
- 3.12 Moving electrode ESP . . . 29
- 3.13 Electro-mechanical double-zone ESP . . . 30
- 3.14 Ion blast ESP . . . 30
- 3.15 Cross flow ESP . . . 31

4 Fabric filter . . . 32
4.1 Fundamentals . . . 32
4.1.1 Theory of operation . . . 32
4.1.2 Filters . . . 32
4.1.3 Cleaning . . . 34
4.1.4 Structure . . . 35
4.2 Filters . . . 35
4.2.1 PPS/ePTFE filters . . . 36
4.2.2 Multi-lobal fibre filters . . . 37
4.3 Microprocessor control . . . 37
4.4 Flow distribution . . . 37
4.5 Cohesivity . . . 38
4.6 Humidification . . . 39
4.7 Sorbent injection . . . 39
4.8 Replacing ESP with FF . . . 40

5 Hybrid systems . . . 41
5.1 Energy and Environmental Research Center (USA) . . . 41
5.2 Allied Environmental Technologies (USA) . . . 41
5.3 Electric Power Research Institute (USA) . . . 42
5.3.1 Compact hybrid particulate collector . . . 42
5.3.2 TOXECON . . . 43
5.3.3 PM screen . . . 44
5.4 General Electric (USA) . . . 44
5.5 Fujian LongKing (China) . . . 45

6 Conclusions . . . 46

7 References . . . 49

1 Introduction

Airborne particulate matter can cause adverse health effects on public health, predominantly on the respiratory and cardiovascular systems. Particulate matter less than 10 µm (PM_{10}) can be inhaled into the respiratory tract. Particulate matter less than 2.5 µm ($PM_{2.5}$) get into the alveoli and pass though the mucus membrane into the blood. For comparison, the average hair on a human head is 60 µm in diameter. Research has shown concern that $PM_{2.5}$ is more hazardous to health, as it contains more toxic metals than PM_{10}, and is more readily inhaled or absorbed by the food chain (Sloss, 2004). In order to prevent adverse health effects, the World Health Organisation (WHO) has guidelines for maximum mean annual ambient concentration of PM_{10} at 20 µg/m^3 and $PM_{2.5}$ at 10 µg/m^3 (WHO, 2006). The majority of advanced economies have enforced ambient air quality standards for particulate matter.

A contributor to concentrations of particulate matter to ambient air is emissions of fly ash from the stacks of pulverised coal combustion (PCC) plant. In order to lower concentrations of particulate matter in ambient air, fly ash emissions from PCC plant must be reduced. The USA, Japan and Western European countries were the first to introduce emission limit values (ELV) for particulate matter from PCC plant. Subsequently, this has led to the installation of particulate control.

Electrostatic precipitators (ESP) dominate the market for particulate control in a variety of combustion and industrial processes, including PCC plant, incineration plant, cement kilns, steel manufacture, oil refineries and paper industries. ESP negatively charge particulates with discharge electrode in order to collect them on a positively charged plate electrode. Fabric filters (FF) have been used for particulate control in smaller processes. However, FF are becoming more popular with large PCC plant because of higher collection efficiencies and effective use of sorbents to capture specific pollutants. FF capture fly ash by passing the flue gas through a filter which the particulates are too large to pass through – the same principle is found in a vacuum cleaner. New hybrid ESP/FF systems aim to become more viable than the individual technology by utilising the advantages of both technologies. Other technologies have been utilised for particulate control in PCC plant, with lesser success. Cyclones show inadequate collection efficiency at reasonable pressure drops and wet scrubbers are not practical as they require waste water treatment system, which require a high water and energy consumption. ESP and FF have proven to be the most suitable technology for particulate control. In most cases, collected fly ash is sold to the construction industry for use in various applications, such as concrete, cement and grout. However, collected fly ash must meet required quality parameters.

Due to concern about human health and air opacity, ELV for particulates have become more stringent with time, resulting in the enhancement of particulate control plant. This is especially the case for $PM_{2.5}$ as it is more hazardous to health and has low collection efficiency in existing conventional ESP.

Lower ELV are generally met by increasing the efficiency of the existing particulate control via numerous enhancements. However, this is made difficult by PCC plant operating outside the design conditions; this is due to two reasons. Firstly, fly ash properties are altered due to fuel variation (different coals or coal blends to design specifications and cofiring with biomass) and installation of emission reduction technologies in the boiler (such as low NOx burners) and post combustion (such as SCR). Secondly, PCC designed for base load operation have been run in cyclic operation. These two reasons adversely affect performance of older ESP. Other challenges are space restrictions on site for expansion of equipment and adequate working area. Despite this, increases in collection efficiency of ESP and FF have been achieved with additional benefits such as lower parasitic load, increased fly ash sales and longer equipment life.

This report reviews the technical and economic considerations of enhancing the performance of particulate control for PCC plant, focusing on 2008 onwards. This report is an update and expansion

of the following reports published by the IEA Clean Coal Centre:
- Zhu (2003) *Developments in particulate control*;
- Soud (1995) *Developments in particulate control for coal combustion*.

For further information on air pollution control technology, *see* the following reports published by the IEA Clean Coal Centre:
- Nalbandian (2006) *Economics of retrofit air pollution control technologies*;
- Nalbandian (2004) *Air pollution control technologies and their interactions*;
- Wu (2001) *Air pollution control costs for PCC plants*;
- Wu (2000) *Prevention of particulate emissions*;
- Soud and Mitchell (1997) *Particulate control handbook for coal-fired plants*.

Research and industrial establishments are looking into other forms of particulate control that integrate various electromechanical techniques for effective capture of particulate, and possibly other pollutants. Particulate control, besides ESP and FF, are assessed in the referenced IEA Clean Coal Centre reports – *ElectroCore* (Soud, 1995; Zhu, 2003); *CYBAGFILTER and the rotational particulate separator* (Zhu, 2003); *Nested fibre filter and the confined vortex scrubber* (Soud, 1995).

2 Background

2.1 Emission limits values

In the USA, emissions limit values (ELV) for particulate matter were introduced in 1971. For large PCC plant, the mass of particulates per unit heat input was limited and opacity percentages were restricted. Opacity is the portion of light which is scattered or absorbed as it passes through a flue gas stream and is measured with a transmissometer (Stultz and Kitto, 2005). In 2011, some states in the USA had limits of 20 mg/m^3 for total particulate matter and 10% for opacity levels. Across the USA the ambient air quality standard for $PM_{2.5}$ has been reduced, but it is up to each state how it will satisfy the new regulations, this may lead to specific regulations for $PM_{2.5}$ from PCC plant (Modern Power Systems, 2012; Li and others, 2011).

In Germany an ELV of 30 mg/m^3 is enforced (Li and others, 2011). The first day in 2012 saw China enforce a emission limit value of 20 mg/m^3 for PCC plant in certain urban areas and 30 mg/m^3 for the rest of China (Mao and Feng, 2012). In 2012 in the UK, existing PCC plant are limited to 50 mg/m^3 and new build have a limit of 30 mg/m^3. Emission standards are available on the IEA CCC website.

In some advanced economies, ELV are reduced to 1 mg/m^3 in some urban areas. Public opinion can also drive the emission limit value below legislative requirements (Popovici, 2012). In 2011, units 1 and 2 of Isogo PCC plant (Japan) had particulate emissions of 1 mg/m^3. Isogo is equipped with a state-of-the-art electric catalytic reduction, dry regenerable activated coke multi-pollutant system (ReACT) and a modern ESP (cold-side, dry, parallel plate). Depending on where a PCC plant is located, it may well be the case that flue gas leaving it will have fewer particulate than the ambient air.

2.2 Market

According to the McIlvaine Company, the 2012 global market for ESP equipment and repairs is greater than US$12 billion, and East Asia accounted for half of these sales. However the market for fabric filters equipment and repairs is just US$1 billion (Modern Power Systems, 2012).

In Germany, dry ESP designed for 'worldwide coal firing' are applied to all new PCC plant sized 600–1100 MW. ESP in Germany now accounts for 85% of the installed fleet of particulate control. In Italy, FF is favoured over ESP in large PCC plant. Some PCC plant in South Africa and Australia have switched to firing low sulphur and high ash coal, which dramatically reduces the collection efficiency of older ESP. In some cases the ESP has been replaced with a FF to restore collection efficiency. In the USA, despite the use of FF with sorbent injection, ESP makes up 80% of the installed fleet of particulate control (Li and others, 2011; Seyfert, 2011).

China has a large and increasing ESP research, development and manufacturing base. China make ESP for her own market and exports to other countries. Zhejiang Freida and Fujian Longking are the two leading brands producing ESP for 20–1000 MW units (Lin and Lui, 2008). A statistical research project by Li and others (2011) has shown that it is technically and economically viable to adapt 86.06% of the installed ESP fleet in China to meet the emission limit value of 30 mg/m^3 when burning 122 types of Chinese coal. The single most important enhancement would be adding another field. The economic analysis also shows that a six-field ESP is half the cost of a FF over a ten-year period in China.

In 2005, the USA had FF using the 'reverse air' cleaning method installed on approximately 28 GW of PCC plant, operating since 1973. However, since 1995 lower cost FF using the 'pulse jet' cleaning method are gaining the market share with an installed fleet of over 8 GW on over 35 units (Belba and others, 2006). For information on FF cleaning methods *see* Section 4.1.

2.3 Fly ash properties

In PCC plant, 15–20% of the total particulate matter drops out at the bottom of the furnace, this is known as furnace bottom ash. The other 80–85% remains buoyant in the flue gas and is known as fly ash. On a dry mass basis, the majority of coals contain less than 15% particulate matter. However some coals, such as Indian, Australia, South Africa and Russia have ash content greater than 15%. Particulates are generally spherical but can be of various shapes, such as oblong and irregular. The surface can be smooth or rough. The mass distribution of fly ash particulates is conventionally described by a log-normal curve centred on a specific value and the number distribution is conventionally described using a bi-modal distribution (Stultz and Kitto, 2005; Arrondel and others, 2011). Figure 1 shows the various shapes and sizes of particulates in fly ash magnified 1000 times.

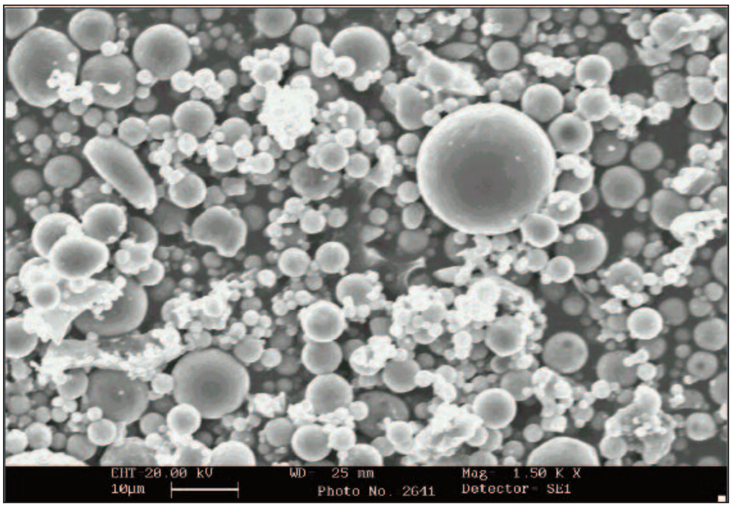

Figure 1 Typical fly ash photo (Barnes, 2010)

Fly ash particulates are predominantly comprised of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO) and to lesser extent trace elements, including toxic metals. Typical compositions produced by the main coal types are shown in Table 1, in percentage mass. Loss on ignition (LOI) is used as a measure of unburnt carbon (UBC).

The mass, shape and composition of particulates in fly ash depend on every factor upstream of the particulate control. These factors include coal type (possibly including biomass type), pulverisation method, combustion system (such as burners, boiler type and temperature) and operating conditions (base load or cycling). Altering one variable can lead to significant changes in fly ash properties (Barnes, 2010, 2012). Particulate cohesivity increases as the particulate become finer and as the surfaces become rougher. Particle cohesivity is also affected by the flue gas properties, components and temperature (Wu, 2001).

Table 1 Typical range of chemical composition for fly ash produced from different coal types, mass% (Barnes, 2010)

Component	Bituminous	Subbituminous	Lignite
SiO_2	20–60	40–60	15–45
Al_2O_3	5–35	20–30	10–25
Fe_2O_3	10–40	4–10	4–15
CaO	1–12	5–30	15–40
MgO	0–5	1–6	3–10
SO_3	0–4	0–2	0–10
Na_2O	0–4	0–2	0–6
K_2O	0–3	0–4	0–4
Loss on ignition (free carbon)	0–15	0–3	0–5

Fly ash is conductive and this property is utilised in ESP to capture particulates (*see* Section 3.1 for more information). Conductive particulates such as lithium oxide (Li_2O), sodium oxide (Na_2O) and iron oxide (Fe_2O_3) reduce resistivity. Sulphur trioxide (SO_3) is highly conductive and dramatically lowers fly ash resistivity, because it dissolves into water on particulates forming sulphites. Silica (SiO_2), alumina (Al_2O_3), magnesium oxide (MgO) and calcium oxide (CaO) tend to increase fly ash resistivity. Magnesium oxide and calcium oxide also neutralise sulphuric acid, which again increases resistivity. Increased levels of UBC increase resistivity. Typically coals which produce high resistivity come from Australia, Colombia, Russia and South Africa (low sodium oxide and iron oxide and high calcium oxide). Polish coal produces low resistivity fly ash due to a combination of high sodium oxide and iron oxide with low calcium oxide (Arrondel and others, 2011; Altman and others, 2008).

The concentration of trace elements in fly ash depends mostly on the mode of occurrence in the fuel, oxidising or reducing conditions, the presence of halogens (most importantly chlorine), the presence of compounds that can act as sorbents (such as calcium), temperature and pressure. These factors vary continuously, rendering it virtually impossible to predict concentrations of trace elements in fly ash. In a volatilisation-condensation process, the majority of trace elements will partially volatilise in the boiler and then condense out in the colder back end of the boiler on the fine particulates since these have a higher surface area to volume ratio. Therefore, capture of fine particulates is especially effective at removing volatile trace elements than capture of larger particulates.

Highly volatile elements such as mercury, selenium and arsenic remain mostly in the gas phase and are difficult to control. Mercury will remain in the flue gas in three main forms – particulate, oxidised and elemental. Particulate mercury [Hg(p)] is mercury condensed onto particulate; this is a small amount and is easily caught in the ESP, FF or a wet scrubber. Oxidised mercury (Hg^{2+}) is soluble in water and is easily captured in a wet scrubber and FF. Elemental mercury (Hg^0) passes through most flue gas cleaning systems. Approximately 40% of the total mercury is caught in flue gas cleaning systems that contain some form of particulate control and a wet scrubber, which translates to average emissions of within the range of 1–10 $\mu g/m^3$. For PCC plant with only particulate control as the flue gas cleaning have unabated mercury emissions of 2–27 $\mu g/m^3$. Due to emerging or tightening mercury emissions standards, commercial mercury specific control systems are available. Mercury control can be tied into particulate control, as discussed later (Sloss, 2002, 2007, 2012). In all particulate control plant, the collection efficiency of mercury is higher at lower temperatures due to the fact mercury condenses out. The colder the flue gas when the particulates are captured, a greater amount of mercury will be captured (Meij, 1997).

2.4 Other flue gas cleaning equipment

Burners

Production of unburnt carbon (UBC) in ash is a result of incomplete combustion – usually boiler combustion efficiency is extremely high and UBC is low. UBC is monitored as it is directly related to thermal efficiency and ash quality. However, the recent retrofit of low-NOx burners slightly lower combustion efficiency and therefore increase the proportion of UBC (Arrondel and others, 2011).

Selective catalytic reduction

Selective catalytic reduction (SCR) can be utilised in modern flue gas cleaning systems to reduce NOx levels. The process involves injecting a reducing agent (ammonia or urea) upstream of the SCR catalyst. In most cases, SCR is located in the high-dust arrangement, which is just after the economiser, ahead of the air heater and upstream of a cold-side ESP. Some sulphur dioxide is converted into sulphur trioxide over the SCR catalyst. The amount of sulphur trioxide produced is comparable to the amount produced by the boiler. SCR can potentially double sulphur trioxide levels.

Sulphur trioxide can react with ammonia to form either sub-micron ammonium sulphates, which are difficult to capture, or low melting point substances such as ammonium bisulphate ($(NH_4)HSO_4$), which increases particulate cohesiveness. High concentrations of sulphur trioxide in the stack increase stack opacity levels (Arrondel and others, 2011).

Wet flue gas desulphurisation

In the advanced economies, most utility-scale PCC plant have seen the addition of wet flue gas desulphurisation (FGD) in series after the ESP for acid gas scrubbing. Fortunately, wet FGD also scrubs out approximately 60% of particulates from the ESP outlet, of which mostly is $PM_{2.5}$. This is known as co-benefit reduction and will apply with the use of FF as well (Li and others, 2011).

A PCC plant in China has seen wet FGD reduce particulate emissions after a dry ESP from 23.4 to 6.2 mg/m^3, a decrease of 73.5%. This reduction includes 88.4% of heavy metals and 97% of the gaseous selenium, arsenic, lead and tin (Wang and others, 2010).

2.5 Biomass cofiring

The chemical and physical properties of fly ash particulates from biomass combustion are different from those of coal. Relative to coal, biomass combusts to create high amounts of aerosols, low levels of sulphur dioxide and sulphur trioxide and can create significantly higher amounts of trace metals. Stack emissions are site-specific, depending on the combustion system, type of biomass and the flue gas cleaning equipment. In general, cofiring biomass with coal leads to a reduction of fly ash loading, and emission regulations have been met to date (Fernando, 2012)

Anatol and others (2011) have investigated the effect of cofiring biomass in PCC plant equipped with ESP. Positive effects can include reduced emission of mineral particulate, reduced fly ash loading, and increased overall collection efficiency due to larger particulates and ease of agglomeration. Negative effects can include reduced collection efficiency due to high resistivity fly ash, increased carbon monoxide emissions (fire risk in flue gas ducts), increased $PM_{2.5}$, corrosion of electrodes and casing, due to increased chlorine and sulphur concentrations, and increased tar emissions can contaminate the insulators, changing the electrical properties.

3 Electrostatic precipitator

ESP operates on a complex amalgamation of mechanics, electrics, electronics, fluid-dynamics and chemistry. ESP theory, design and operation will be summarised in Section 3.1 to provide background information in order to understand the subsequent sections. Section 3.2 discusses basic ESP maintenance, Sections 3.3 to 3.6 expand on basic maintenance with detailed discussion on what upgrades can be implemented as part of the maintenance programme, the important upgrades being power supply for superior charging, microprocessor control for sophisticated operation and flow control devices to ensure uniform flow distribution. Sections 3.7 to 3.9 assess additional features to improve the existing ESP, especially when ESP collection efficiency decreases as a result of firing low rank coals; these additional features included flue gas conditioning, to create an optimum fly ash resistivity, and agglomeration, to increase particulate size. Sections 3.10 and 3.11 assess wet ESP and colder-side ESP respectively, which use conventional collection plates with slight variations in operation for improved performance. Finally, Sections 3.12 to 3.15 show alternate configurations of ESP technology, illustrating that the conceptual development of ESP technology continues, and in some cases has proved successful.

3.1 Fundamentals

Figure 2 ESP photo (FLSmidth, 2012a)

ESP has a high collection efficiency of at least 99%, low pressure drops (0.12 to 0.25 kPa), robustness, scaleability and ease of manufacture. When emission limit values (ELV) for particulate matter were introduced, ESP was either retrofitted to existing PCC plant or integrated into new build PCC plant. Increasingly stringent ELV have been met by enhancing the existing ESP performance. All the information in Section 3.1 has been referenced from Soud (1995), Zhu (2003) and Nalbandian (2004), unless otherwise stated. Figure 2 shows an ESP in a large-scale PCC plant application.

3.1.1 Theory of operation

ESP consist of wire discharge electrodes (the anode) and large collection plate electrodes (the cathode). A high voltage direct current (HVDC) power is applied to the electrodes. Particulates flow into the ESP and are negatively charged by the discharge electrodes into ions. Electrostatic attraction causes ions migrate to and stick to the plate electrodes. This phenomenon is commonly known as an electro-hydrodynamic (EHD) flow (also known as ionic wind or electrophoresis). The particulates therefore become part of an electrical circuit. The particulates are ionised in a circular region encompassing the discharge electrode, which is called the corona discharge.

To allow continuous operation, the accumulated particulates have to be removed. In dry ESP, the accumulated particulates are periodically knocked off the plate electrodes by rappers and fall into the hoppers – this process is called rapping. Discharge electrodes also need to be rapped, but much less frequently. In a variation called wet ESP, accumulated particulates are washed off with water.

An ESP is a constant efficiency device, which means that an increase in input fly ash loading beyond

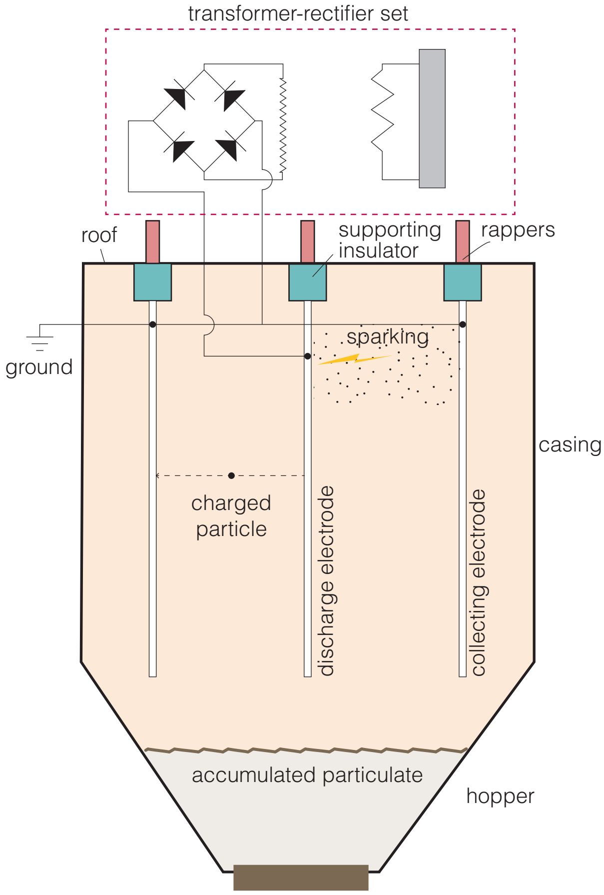

Figure 3 Dry ESP schematic (Majid and others, 2011; Grass and Zintl, 2008; Soud 1995)

the designed specifications will result in an increase in fly ash emissions (Popovici, 2012).

Particulates are predominantly charged by direct or diffusion charging, or to a lesser extent, a combination of both. The corona discharge ionises most (>99.9% mass) of the large particulates (>2 µm in diameter), which become negatively charged ions – this is called direct charging. These ions then migrate across the flue gas stream towards the collecting plate, passing on charge to smaller particulates – this is known as diffusion charging. Migrating fly ash also adhere to smaller particulates (<1 µm) due to particulate cohesivity. Particulates between 0.1 and 2 µm are not charged well, reaching a low point between 0.2 and 0.6 µm which happens to coincide with the transition between direct charging and diffusion charging. Brownian motion helps charge and migrate particulates less than 0.1 µm, this effect increases as the particulate size decreases (Arrondel and others, 2011).

The fly ash must be able to hold sufficient charge in order to migrate to, and collect on, the plate electrodes. The ability of a particulate to hold charge is determined by the its resistivity and size (Parker and others, 2009). Fly ash resistivity is determined by its composition and temperature *see* Section 2.3.

The ESP in cold-side operation is placed after the combustion air pre-heater but before the induced draught fan, and operates within 130–180°C, this is known as cold-side ESP (Stultz and Kitto, 2005). The majority of the installed ESP fleet is cold-side. There are approximately 2500 PCC plant worldwide – for the purpose of comparison, 95% of the fleet has a form of particulate control and approximately 80% of this is cold-side ESP. Therefore approximately 1800 PCC plant is equipped with cold-side ESP. Figure 3 shows a cross-sectional view of a conventional cold-side, dry, parallel plate ESP.

Dry cold-side ESP operates efficiently with a fly ash resistivity range between within $1 \times 10^7 – 2 \times 10^{10}$ ohm-cm. If the resistivity is lower than 1×10^7 ohm-cm then the fly ash cannot hold sufficient charge to be captured in the ESP. The fly ash is either not collected on the plate electrodes or are re-entrained into the flue gas. If the resistivity exceeds 2×10^{10} ohm-cm, then the increased drop in voltage through the fly ash decreases collection efficiency because of low migration velocity. The voltage drop can become large enough to cause a flow of electrons back to the discharge electrode, this is seen as a spark and is known as sparking (also known as spark over, flash over or arcing).

Sparking significantly reduces collection efficiency; this is because no charging takes place during a sparking event, which results in no collection and fly ash is re-entrained from the plate electrodes as there is no holding force. In theory, the ESP collection efficiency is proportional to the squared power of the corona discharge, but this is limited by sparking. However, a small amount of sparking per minute is desirable as this is the point at which maximum charging occurs, therefore maximum collection efficiency, without compromising power consumption. Too much sparking will increase power consumption per mass of particulate collected. Specifically, sparking occurs between the discharge electrode and the surface of the accumulated fly ash on the plate electrodes. Another term, called back corona, refers to sparking between the discharge electrode and the surface of the plate electrodes. This occurs partly as a result of resistivity drop across the flue gas but mostly as the resistivity of the ash layer reaches a critical level. It is important to note that sparking will also occur if the power from the discharge electrode gets too high.

Current suppression, or space charge, is the amount of charge present on fly ash in the area between the electrodes. High current suppression suppresses the corona discharge and can cause sparking. Current suppression increases with increasing particulate concentration and slower migration velocity. Thus high concentrations of fine particulates, which have a low migration velocity, will give a high current suppression. This is usually found in the first field.

Migration velocity is the average velocity at which the particulates travels towards the plate electrodes. The more charge a particulate can hold, the faster its migration velocity will be. Migration velocity is proportional to the voltage of the corona discharge squared (Parker and others, 2009). Residence time is the time period in which the flue gas remains in the ESP; for most PCC plant residence time is 19.5 to 20.5 seconds. Collection efficiency increases exponentially with residence time up to a point of diminishing returns (Arrondel and others, 2011). In order to capture particulate between 0.1 and 2 µm, impractically long residence times are required.

3.1.2 Configuration

Most parallel plate ESP have a number of independent fields in series. Each field has separate plate electrodes, discharge electrodes, hoppers, rappers and power supplies. The space between a pair of plate electrodes and a central discharge wire is called a chamber. The specific collection area (SCA) is simply the unit area of plate electrodes per unit volume of gas to be treated. An increase in SCA will result in an increase in collection efficiency.

Each field collects a certain percentage of the fly ash loading, allowing for optimal operating conditions for each field. The first field collects 75–95% of the fly ash, and in most cases collection is limited by current limitation as opposed to sparking (Chakrabarti, 2011). In PCC plant the optimum number of fields is three to five. More fields will increase collection efficiency up to a point of diminishing returns.

An ESP is enclosed in an air-tight carbon steel casing. The casing, ductwork and hoppers are insulated and heated to prevent condensation and subsequent damage by flue gas components such as sulphuric acid (H_2SO_4). Insulation and heaters also protect the metal from thermal shock. The casing sits on a frame, accommodating movement from thermal expansion. Electrodes are supported from the top of the casing and there are hoppers below to catch and temporarily store the fly ash. Fly ash is removed from the hopper with a drag chain or screw conveyor system.

3.1.3 Hot-side ESP

Hot-side ESP is located before the combustion air pre-heater and operates at 300–450°C. A 1990 study showed 150 hot-side ESP were built in the USA between 1935 and 1990. The temperature of hot-side ESP allowed for the optimum resistivity with the coals fired during that time in Japan and the USA. Hot side ESP initially performed well, but the performance deteriorated with time. A thin layer of high resistivity fly ash built up on the plate electrodes due to a loss of sodium ions from this layer of fly ash. The hot-side ESP eventually performs so badly that the plate electrodes had to be sand blasted clean, only to last another month or so. In 2008, almost all hot-side ESP in the USA had been rebuilt downstream of the air pre-heater and operated in cold-side ESP mode. A case study on a hot-to cold-side conversion at Council Bluffs Energy Centre PCC plant is covered in Soud (1995). The sodium depletion problem can be solved by the following methods; positive polarity energisation assessed in Zhu (2003) and sodium injection assessed in Wu (2000).

3.1.4 Voltage-current curves

Voltage-current (V-I) curves are a signature of ESP operation – the curve is drawn from having voltage on the x-axis and current on the y-axis. V-I curves are specific to the ESP geometry, fly ash properties and flue gas conditions such as temperature, pressure and humidity. For normal operation a reference V-I curve can be drawn up, however if there is a fault in the operation then there is a different V-I curve. Each fault has a distinct V-I curve, or fault V-I curve. The most likely faults are electrode fouling (resistivity increases so V-I curve shifts to right), broken electrodes (sparking point lowers), sparking (steep rise in current), electrode insulator problem or misaligned electrode (resistivity decreases so V-I curve shifts to left).

Analysis of the V-I curves coupled with knowledge of the reference and fault V-I curves allows faults to be identified and quantified quickly without visually inspecting the electrodes, saving time and money. The gradual change in V-I curves over time will be an indication of maintenance required. Optimal and fault V-I curves can be drawn-up using experimental procedures or modelling and simulation software (Arrondel and others, 2008).

3.2 Maintenance and upgrading

Many ESP used in existing PCC plant were installed up to 40 years ago. They were designed by original equipment manufacturers (OEM) to meet regulations that have since tightened significantly. Over time, ESP performance deteriorates with wear and tear. Proper ESP maintenance will maintain original design performance (providing the plant is still operating under design conditions) and will allow maximum lifetime. Maintaining an ESP gives a good opportunity to upgrade parts, rather than renovate or replace them – upgrading equipment can improve performance and may lower costs. Some parts may have to be upgraded as older parts are no longer available. On average, ESP built in the 1960-70s in the USA can be maintained and upgraded to provide 15% to 20% more collecting surface, without increasing the footprint of the unit. This figure is >30% in Europe (Nuendorfer, 2012a). The ESP OEM will provide routine maintenance schedules. Sections 3.2.1–3.2.5 will highlight the most significant aspects of ESP maintenance.

3.2.1 Discharge electrode

There are various types of discharge electrodes – varying in wire, support and insulation design. Broken, eroded or corroded discharge electrodes will need repairing or replacing with an upgraded design. The first popular discharge electrode was the weighted wire design. Older designs can now be replaced with the more robust rigid pipe design. The rigid pipe design also has spikes facing upstream and downstream of the flue gas in order to overcome current suppression problems and therefore maximise corona discharge. The spikes are tailored to minimise corona suppression depending on the particulate size distribution, composition and loading.

Farnoosh and others (2011) used a 3D numerical model to investigate particulate concentrations and velocities in order to assess precipitator performance. The study proved that spiked discharge electrodes have better collection efficiency for fine particulates than other ESP configurations.

3.2.2 Plate electrode

Plate electrodes are made from stainless steel sheets. Plate electrodes should not be excessively warped or fouled, as this would lead to non-uniform loading, resulting in collection and re-entrainment problems. Widening the spacing between the plate electrodes from the original 23–30 cm to 40.6–45.7 cm increases the collection efficiency and reduces operating and maintenance costs (Soud, 1995). Widening the plate spacing decreases the SCA, however the subsequent higher operating voltage increases the collection efficiency more than enough to compensate. Wider plate spacing also decreases maintenance costs through fewer electrodes and rappers. In any case, the spacing between the plate electrodes and ionising wires should be consistent.

Providing there is sufficient space in the ESP casing, the plate electrode width can be increased, which increases the SCA and therefore increase the collection efficiency. Increasing the height of the plate electrodes also increases collection efficiency. However, increasing the plate electrode height is only effective to an aspect ratio of 0.8 minimum. Aspect ratio is the ratio of the plate electrode width to height. An aspect ratio lower than 0.8 (high plate electrode) would have excessive re-entrainment.

3.2.3 Transformer-rectifier sets

Power to run the ESP is taken from the PCC plant itself in single or three phase alternating current (AC). Traditionally, three phase AC is transformed into a higher voltage (HV) and then rectified, using a silicon controlled rectifier (or thyristor), into a direct current (DC) in a transformer-rectifier (T-R) set. The resultant high voltage direct current (HVDC) is generally at 45 to 85 kV (depending on plate electrode spacing) and 50/60 Hz – this is known as line frequency power supply. Figure 3 on page 12 shows a typical T-R set on an ESP field, or bus-section. Conventional T-R sets have a high ripple voltage within 30–40% peak-to-peak. As sparking occurs at the peak voltage, average power input is limited. Sparking is detected by the HV controller, subsequently the T-R set reduces voltage and turns off the current until the high space charge has de-ionised, no charging happens during this de-ionisation time (0.01 to 0.1 s), the current and voltage are then re-applied. This reaction to sparking allows for continuous power adjustment with varying fly ash loading and resistivity. The parasitic load of the ESP can be in the MWe range, so there can be a significant energy saving potential (Stultz and Kitto, 2005; Grass and Zintl, 2008).

In older ESP, insufficient power provided to the electrodes by worn out power supplies (typically transformer-rectifier sets) will result in decreased collection efficiency. Replacement can restore original factory collection efficiency at low costs (Salib and others, 2005). However, conventional T-R sets have now been superseded by new power supplies called switch mode power supplies (SMPS). SMPS charge particulate more effectively, resulting in increased collection efficiency together with decreased parasitic load, amongst other advantages (*see* Section 3.4 for further detail).

3.2.4 Rappers

Rapping is carried out by rappers – there are various types of rappers. The most common type is tumbling hammer and magnetic impact, which can be electrode-specific. The force of rapping can be fine-tuned in order to sufficiently knock the collected fly ash into the hoppers but keeping the force low enough to minimise fly ash re-entrainment caused by rapping. The optimum frequency of rapping depends on the fly ash properties and loading.

Malfunctioning or broken rappers need repairing or replacing with new, possibly upgraded rappers. Additional rappers improve collection efficiency in two ways. Firstly, more rappers keep the plate electrodes cleaner. Secondly, more rappers allow for sequential rapping, which minimises particulate re-entrainment. Adding rappers has low cost and negligible unit outage requirement (Salib and others, 2005).

3.2.5 Rebuilding

The most dramatic option is to remove the ESP internals, replacing or upgrading everything apart from the existing casing and hoppers. Uniform flow distribution (*see* Section 3.3) can be ensured during the retrofit. These combined modifications will allow for a huge increase in collection efficiency and could entail a lower capital cost and shorter outage period than several smaller maintenance and upgrading procedures. The cost is site-specific, but it will entail a large capital cost and require at least a three-month outage period.

Bigger casing and hoppers would require relocating the duct work and possibly improving or extending foundations. This work would be considerably expensive and require a long outage period (Salib and others, 2005). A new build ESP entails a unique capital cost which is site- and date-specific. Each installation differs in design and construction materials, component and labour costs vary globally. Rebuilding an ESP provides a perfect opportunity to add another field to increase the collection efficiency. If rebuilding the ESP will not meet ELV then a fabric filter could be installed to do so, utilising the existing casing and hopper (*see* Chapter 4).

Boundary Dam PCC plant

In 2013, Boundary Dam PCC plant in Estevan (Canada) will rebuild an ESP on a 120 MWe lignite-fired unit. The rebuilding work includes removing all the internals of the existing ESP and replacing them with upgraded parts, utilising only the existing casing and hoppers. The original ESP built in 1995 was designed for greater than 99.5% collection efficiency. Since in operation, performance has deteriorated and a rebuild with upgraded parts should result in collection efficiency greater than 99.5%. However it is not possible to calculate collection efficiency as there are no particulate input and output monitors, and only the stack opacity is measured. The driver for the rebuilding is the provincial regulations, public concern, Environment Canada, the US Environmental Protection Agency, North Dakota Health and Environment and the Kyoto Protocol (Nalbandian, 2006; Wang, 2012).

Aiysis PCC plant

In 2006, Lanzhou Electric Power Equipment Manufacturer (China) rebuilt the ESP on unit 2 of Aiysis PCC plant in Jiaozuo (China). Major work included widening and heightening the existing plate electrodes, wider plate spacing, installed two additional fields (from three to five five fields), minimised air leakage (from >5% to <3%), upgraded rappers and discharge electrodes were installed all round, and flow control devices were added. After a year of operation particulate emissions reduced from 265 to 31.5 mg/m^3, an increase in collection efficiency from 96.89% to 99.81% (Yangand others, 2008).

3.3 Flow distribution

It is important to ensure that the flue gas is uniformly distributed in the ESP. If not, the non-uniform flow will overload certain areas, avoid the collection areas (below, above or beyond the plate electrodes) and cause re-entrainment from the plates and hoppers, resulting in low collection efficiency. Another disadvantage is excessive erosion. Flow control devices such as turning vanes, perforated plates, dampers, screens and baffles can be added to the ESP inlet and outlet ducts to ensure uniform flow distribution. Flow control devices can also be added to the edge of the plate electrode and at the hopper to prevent re-entrainment (Nuendorfer, 2012a).

The size, type and positioning of flow control devices used have historically been determined using physical models and/or in situ trial and improvement field tests, both of which are expensive and time consuming. Field tests can require plant outage time. However, the last decade has seen computational fluid dynamics (CFD) revolutionise the way in which fluid flows are analysed. CFD uses numerical methods and algorithms to solve and analyse problems that involve fluid flows – computers are used to perform the calculations. CFD analysis can be used to quickly identify the most effective use of flow control devices in ESP/FF of any shape or size.

CFD analysis involves making a 3D computer model of the ESP/FF (such as walls, ceiling hoppers, ducts, plate electrodes, filter bags), putting in the boundary conditions (such as fluid entry and exit, fluid velocity, temperature, pressure, heat conductivity and stiffness of materials) and then running simulations of fluid flow through the subject. The simulation visually shows and quantifies the flow velocity, heat and pressure. Flow control devices can then be added or modified to determine their most effective use with minimum cost. Assumptions are made in CFD analysis – more detail in the model and boundary conditions will result in more accurate simulations. CFD analysis is quicker, more effective and less expensive than traditional physical models or trial and improvement field tests. Another advantage is that CFD can consider higher particulate loads that would not be practical in traditional methods.

Many companies provide services for CFD analysis. FLSmidth (Denmark) have a CFD analysis service for uniform flow distribution (Nielsen and others, 2011). For ESP with re-entrainment problems, Skewed Gas Flow technology developed by Stothert Engineering (Canada) can be implemented to ensure uniform fly ash loading accounting for re-entrainment, for more information *see* Zhu (2003).

CFD analysis of single phase fluid flow due to flue gas momentum in an ESP is simple and effective; however there are more complex and accurate ways of doing this. The models have to take into account other factors, such as the fact that there are solids and gases in the fluid, and that there is an ionic wind created by EHD forces which results in additional turbulence. Due to a complex interaction of mechanisms such as fluid dynamics, electrostatics and fly ash properties, fluid flow in ESP is not completely understood, but models and boundary conditions are improving. Enviroserv (Germany) offer a state-of-the-art CFD analysis service. Boundary conditions, including an accurate computer generated model, particulate size distribution and EHD flow are used to make a CFD simulation. ANSYS CFX°11 software is used to simulate the two-phase flow of gas and solid particulates (based on Euler-Lagrange equations). Assumptions made in this model are that the material properties are constants, the gas flow is steady and incompressible and the ESP is isothermal. This model aims to link the fields of electrostatics (corona power and charge distribution), fluid dynamics (mean flow and turbulence) and particulate dynamics (charging, migration velocity and ionic wind) to form a complete method for modelling fluid flow in an ESP. As the particulates flow to the plate electrodes is simulated, collection efficiency can be estimated (Feldkamp and others, 2008).

Iskenderun PCC plant

To improve ESP performance at Iskenderun PCC plant (Turkey), SteagEnergy Services have implemented CFD analysis to ensure uniform flow distribution. This has led to the modification and addition of flow control devices which has resulted in a 15% drop in average ESP outlet emissions from 65 mg/m^3 to 55 mg/m^3 (Atmaca and others, 2012).

3.4 Power supply and control

The advent of miniature and affordable electronics have revolutionised ESP technology in three main areas. Firstly, low cost and capable computers are solving the theories behind ESP operation. Secondly, power supplies that use modern transistors can more effectively energise, or charge, particulates. Finally, ESP control systems can be run by sophisticated and intelligent microprocessors. The most common modification to an old ESP is to upgrade the old on/off T-R sets to modern power supplies with integrated microprocessor based control (MBC). Results have shown power consumption reduce by a third whilst increasing collection efficiency. The work involves replacing the old ESP power supply box which is located on top of the ESP casing. A few hours outage are required and the work has a precise cost. Power supplies, microprocessors and software are continuously improving with mass application in electronics, such as mobile phones, subsequently the ESP industry is benefiting.

In the USA, Alstom and NWL lead the market with hundreds of commercial units; Applied Plasma Physics, Genvolt and VEI are also major players. Fujian LongKing and Zhejiang Feida dominate the market in China. Manufacturers are now selling third and fourth generation power supplies with integrated MBC, which have seen significantly improved performance with each generation.

Sections 3.4.1 to 3.4.8 will assess the latest significant improvements in power supplies and MBC (Karlsson and others, 2011; Parker and others, 2009; Grass and Zintl, 2008; Pokryvailo and others, 2008; Salib and others, 2005). Previous IEA Clean Coal Centre reports have assessed ESP power supplies and MBC:

Power supplies:
- Switched mode power supply (SMPS):
  - FLS, Kraftelektronik AB and FLS Miljø (Zhu, 2003);
  - Switched integrated rectifier (SIR), Alstom (Zhu, 2003);
  - Hard switching, Applied Plasma Physics AS (Zhu, 2003);
  - Rapid onset pulse energisation (ROPE), Southern Company Services (Zhu, 2003);
  - Intermittent energisation by Southern Research Institute and EPRI (Soud, 1995);
  - Alternating polarity power supply (Soud, 1995);
  - Direct-coupled pulse energisation system by MHI (Soud, 1995);
- High voltage filter: Juice can precipitator power maximiser, BHA Group (Zhu, 2003);
- Pre-charging: Temperature-controlled electrode pre-charger, EPRI (Soud, 1995).

MBC:
- EPIC II ESP by Alstom (Zhu, 2003);
- PIACS Expert system by FLS Miljø a/s (Zhu, 2003);
- ESPert by EPRI (Zhu, 2003);
- Energy Management Control System by FLS Miljø (Soud, 1995);
- The Merlin II by Belco Technologies Corporation (Soud, 1995);
- Thyristor Power Supply (Soud, 1995).

3.4.1 Power supply

A switched mode power supply (SMPS) is an advancement of a T-R set using electronics, most notably the insulated-gate bipolar transistor (IGBT). SMPS have been available for ESP since 1999 and are capable of dramatically improved performance over T-R sets. SMPS have a high power factor at 93% (less power lost in conversion), a low ripple voltage within 1–3% peak-to-peak and operate at frequencies up to 50 kHz – they are known as high frequency power supplies. Operation at high frequencies allow the transformer, and consequently all other components, to be smaller. A common example of SMPS is the power supply unit of a desktop computer; it converts single phase, 240 V, 50 to 60 Hz alternating current (AC) from the plug into <12 V, <50 kHz direct current (DC) for use in computer circuit boards. SMPS presents many advantages over a traditional T-R set. Average power levels are higher due to low ripple voltage and optimum power levels maintained in each field. The processing time for dealing with sparking is much quicker – this increases average power input. When sparking is detected, the current is turned off instantly, particulate de-ionisation time is short (due to low space charge density), the current is re-applied instantly and the voltage recovers quickly.

Depending on the nature of the fly ash, SMPS can be operated in three different ways in order to maximise charging – these are direct, intermittent and pulse energisation. Direct energisation supplies constant power. Intermittent energisation provides power intermittently. Pulse energisation superimposes a high voltage pulse for a few microseconds onto a direct current.

3.4.2 Control

Microprocessor based controls (MBC) integrate all ESP control, process measurements and use software to operate the electrode power supply, rappers and hopper heaters automatically in order to maximise collection efficiency for minimal power consumption.

During a rapping event, re-entrained fly ash causes a peak emissions. The need for rapping is therefore a major disadvantage for ESP. However, sophisticated rapping techniques controlled by microprocessors can minimise the problem.

The power supply voltage and current depend on the energisation type which depends on the fly ash properties. The frequency of sparking dictates the power across the electrodes and sparking is detected from changes in the V-I curve.

The MBC can detect when the plate electrodes need to be rapped (resistivity rises), this lowers power use and emission peaks by eliminating unnecessary rapping. MBC can operate rappers in different fields sequentially allowing downstream fields to collect re-entrained fly ash from upstream fields, thus decreasing these peaks. The force behind a rapping event can also be optimised depending on the rapper type. Power levels can be increased or decreased during rapping to ensure clean plate electrodes, but this depends on particulate loading, cohesivity and resistivity (Karlsson and others, 2011). Rapping optimisation is site-specific and in all cases will take time to reach optimum performance. Operation of the rapping has benefited substantially from MBC.

All operating information can be seen in the control room (via networking), performance data are logged and analysed in order to further optimise operation. MBC work most effectively with SMPS. Installing MBC has a known cost and requires limited unit outage. In 2005, installing MBC alone increased ESP collection efficiency in the range 5–20%.

3.4.3 Alstom

EPIC III

EPIC III is a third generation of MBC from Alstom. Consisting of a single-board computer housed in a sturdy steel casing, EPIC III can be retrofitted to SMPS or comes pre-installed on Alstom's SMPS, which is called switch mode rectifier (SIR). EPIC III comes with three standard process control algorithms EPOQ, OpOpt, and PCR.

Electrostatic precipitator optimisation of charges (EPOQ, where Q is charge) is an algorithm that continuously analyses and automatically sets the voltage and current in each field so that sparking is not a problem and collection efficiency is at maximum. If flue gas conditions change then a corresponding change is seen in the voltage and current by EPOQ, which subsequently optimises each field. This process is instantaneous so optimal operating conditions are maintained consistently. OpOpt uses an opacity signal to optimise energy use.

Power control rapping (PCR) is a complex method of rapping optimisation. PCR reduces the holding force on the plate electrode during rapping by reducing charging so that a low force rapping can be used to get cleaner plate electrodes. Rapping frequency and duration is continuously optimised for minimum rapping events, minimum sparking and maximum collection – this is done using a network of gates (Boolean algebra). Although PCR creates emission peaks compared to traditional rapping, the increase is negligible compared to the increased collection efficiency of cleaner plates and less frequent rapping. Also, rapper and electrode lifetime are increased through less mechanical wear. PCR operates most effectively when used with SIR as the increased corona power creates higher fly ash layer holding force and consequently less re-entrainment when rapping. One PCR software package can be linked up to four rappers per field. Power consumption is reduced through lower charging and rapper use. If PCR fails, EPIC III can be programmed for a set start time, duration and frequency.

Alstom found that by decreasing the rapping frequency in the last field of an ESP only, collection efficiency increased by 50%. Turning the corona discharge off, at every other rapping event, increases collection efficiency by 37.5–38% (Karlsson and others, 2011).

The hopper heaters can be wired into EPIC III so that the temperature can be monitored and controlled; an alarm comes on when current to the heaters fail. The V-I curve function enables fast and accurate data collection of operational data. These data sets can be transferred to a spread sheet for further numerical and graphical analysis by the operator. EPIC III is programmed to operate at six different operating modes, favouring better performance in certain aspects of ESP operation, such as minimal power use or maximum collection. With increased operating data, EPIC III will optimise control for the specific site conditions. EPIC III has an internet connection and its own web server to enable monitoring and control to be done via any web browser. This allows Alstom to record progress easily and to provide help if needed (Deye and Layman, 2008).

Switched integrated rectifier (SIR)

For ESP power supply, Alstom have developed the switched integrated rectifier (SIR). SIR uses SMPS technology and can operate in direct or pulsed energisation at high frequencies of 20–50 kHz, which reduce the ripple voltage down to negligible values, meaning that the power supply is kept closer to an optimum high voltage direct current (HVDC) than conventional T-R sets. This provides two to three times more corona discharge power, causing more charging and therefore increased collection efficiency, especially for the finer particulates. Severe sparking is avoided in SIR as the power is limited just below the sparking point. The graph on the left of Figure 4 shows the ripple voltage difference between SIR and conventional T-R, this shows that higher voltages are maintained. The graph on the right of Figure 4 shows that SIR can give higher currents before sparking than conventional T-R sets. As with all SMPS, SIR has a high power factor.

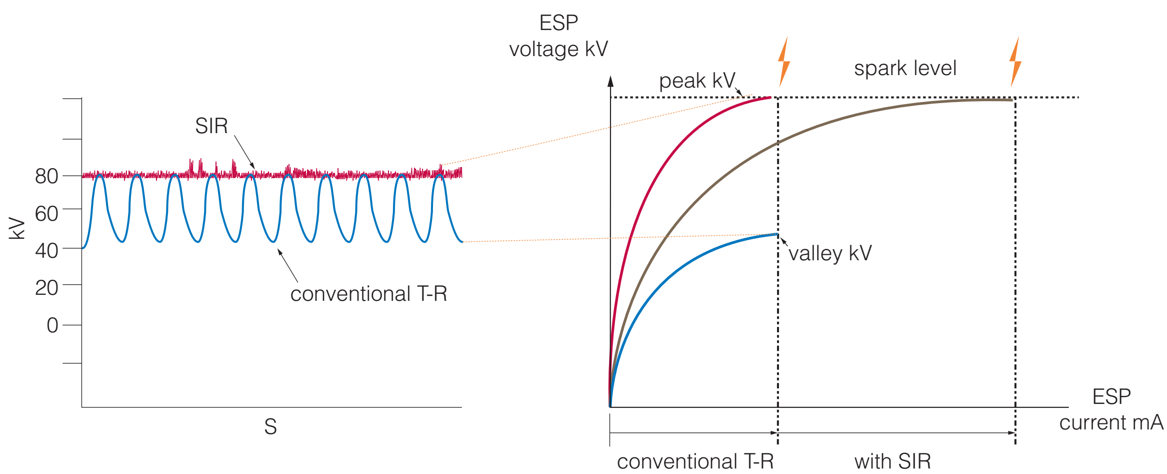

Figure 4 Ripple difference between SIR and conventional T-R (Ranstad and other, 2011)

The high frequency transformer in SIR weighs only 200–230 kg, which is 10–15 times less than a line frequency transformer. All SIR components are integrated and built into one box, *see* Figure 5. Components include a SMPS, controller (usually with EPIC III pre-installed), liquid cooling system

Figure 5 Switched integrated rectifier photo (Deye and Layman, 2008)

and motor groups for the rappers and hopper heaters (so that they can be integrated into EPIC III). This lightweight box is installed outside the ESP and therefore little ESP outage is required for installation. When combined, SIR and EPIC III can reduce fly ash emissions by 40–70% (Deye and Layman, 2008; Pokryvailo and others, 2008; Chakrabarti, 2011).

Johnsonville PCC plant (USA)

In 2005 Johnsonville PCC plant (USA) averaged 1.04 GWe, opacity levels were approximately 16% and ESP power consumption was 100 kW. In order to meet ELV, coal blends had to have the following characteristics: minimum sulphur content (1.3% and 1.5% in units 1 to 6 and 7 to 10 respectively), low ash content and an excellent heating value (creates a low fly ash loading). Therefore, as coal quality was fixed, fuel flexibility was limited which prevented the selection of cheaper coals. The only other option to lower fly ash emissions was to derate the boiler, which was economically unviable, so the ESP had to be upgraded. In 2006, the project was to replace the conventional T-R power supplies (some contaminated with polychlorinated biphenyl) with SIR and whilst doing so, integrate EPIC III in the control room.

Unit 4 of Johnsonville PCC plant has an ESP with four fields; all T-R sets were replaced with SIR. Without operating under EPIC III, 13% opacity levels were found when firing a 0.82% sulphur coal, however ESP power consumption rose to 297 kW. Running SIR under partial EPIC III and firing a 0.67% sulphur coal resulted in 14.8% stack opacity with a power consumption of 119 kW. Running SIR under fully operational EPIC III and firing a 0.52% sulphur coal resulted in 13.5% stack opacity with a power consumption of 124 kW. No specific performance correlations can be determined, as opacity levels were taken from a single stack which serves all ten units – there were different coal blends and reductions in stack opacity could partly be put down to lower concentrations of sulphur trioxide. Ideally the concentration of particulates at the inlet and outlet of the ESP should be monitored for proper comparison. However, as seen with unit 4, SIR combined with EPIC III has allowed the coal sulphur content to drop by 60%, whilst decreasing opacity by 2% and increasing power consumption by 24 kW, which is a beneficial result. The payback period of SIR and EPIC III was short and more cost effective power is now being generated (Deye and Layman, 2008).

In 2011 the installed SIR fleet was >2000 units strong. SIR is usually only applied in the first field, as this is where the majority of fly ash collection occurs. From 2004 to 2011, Alstom have focused their efforts on optimising the design and operation of high frequency power supplies for collection efficiency and availability, especially at the higher power levels. Tests have shown a mean time between failures exceeding 200 years – this indicates 100% availability (Ranstad and Linner, 2011).

3.4.4 Siemens

SIPREC ODS

Siemens have MBC software for ESP called SIPREC ODS (formerly WINPIC), which analyses the changing conditions with an integrated diagnostics tool and continuously optimises ESP operation. Use of SIPREC ODS software with different ESP has seen reduction in power consumption by 30–60% whilst meeting ELV (Grass and Zintl, 2008; Kloeckner and Grass, 2011). SIPREC ODS uses information from all controls to optimise energisation and rapping, to enable effective internal diagnostics and safety functions. SIPREC ODS can recall operating modes and is equipped with a graphical colour user interface for the operator an optical data interface for networking. Networking allows SIPREC ODS to be controlled through any internet browser and information is continuously and instantly sent to Siemens remote service, allowing fast and cost-effective customer support.

Siemens SMPS

Siemens have worked with SMPS since the 1980s and have found that SMPS are most effective in the first field due to high current suppression caused by a high loading of fine particulates. Installation of Siemens SMPS and SIPREC ODS will reduce outlet fly ash emissions by approximately 50% (Kloeckner and Grass, 2011).

3.4.5 NWL

PowerPlus by NWL is an SMPS that can operate in three modes – direct, intermittent or pulse. Intermittent energisation can be operated with 1 to 10 milliseconds on and 1 to 99 milliseconds off, which allows for high efficiency collection of highly resistive fly ash. PowerPlus integrates the transformer, rectifier, air cooling system and controls into a single package. For best performance it is advised that PowerPlus be equipped with MBC designed by NWL, which includes a precipitator control and management system (PCAMS) and graphic rapper controller (GRC). Application of PowerPlus on a PCC plant in Poland saw emissions drop from 170 to 18 mg/m^3 at the ESP outlet. Lansing Smith PCC plant (USA) found a 70% reduction in opacity levels and a reduction in power consumption when using PowerPlus. In summary, the advantages of PowerPlus over traditional T-R sets include improved power factor, increased charging rates, more effective energisation of high resistivity particulates, and they are small, light and therefore have straight forward installation. In 2012, 1200 PowerPlus units were in service globally (NWL, 2012; Herder and Strydom, 2012; Herder and others, 2008).

3.4.6 Fujian LongKing

High frequency power supply

Fujian LongKing (China) have developed a SMPS, known as high frequency power supply. The high frequency power supply rectifies and transforms the three phase AC to HVDC, which is then converted into a high frequency DC waveform. Advantages include suppressed sparking, energy saving, a power factor greater than 90% and capability to deal with variations in fly ash properties and loading. It is small and lightweight, which enables the unit to be located directly above the ESP. High frequency power units are pre-installed with intelligent precipitators computer (IPC). In 2008, 100 sets of installed high frequency supplies in China were critically acclaimed (Fujian LongKing, 2012; Lin and Lui, 2008).

IPC

Depending on the fly ash properties, IPC software will optimise the power and rapping for maximum collection efficiency and minimum power use. Data on the coal type have to be manually put into IPC software.

Panshan PCC plant

Panshan 500 MWe PCC plant (China) is equipped with three double-storey, two-chamber, six-field ESP. ESP internals include C type plate electrodes with barbed electrodes, spacing of 350 cm and an effective height of 9 m. Power was supplied through T-R sets. The power was tested and rated at 40–49 kV and 150–300 mA. ESP collection efficiency was 99.61% with an emission of 52 mg/m^3 and power consumption of 780 kW. The power supply of the first three fields was upgraded to high frequency power supply (GGYAJ series) capable of supplying 1.2 A at 66 kV. The rapping controls were also upgraded to allow for advanced rapping sequences. A new performance test was carried out and showed that ESP collection efficiency increased to 99.77% with an outlet emission of 24 mg/m^3 and a much lower power consumption of 440 kW. This is a power reduction of 43.4% this figure will be reduced further if the last two fields of the ESP are converted. For outlet emissions of 52 mg/m^3, the high frequency power supply reduces power consumption by 56.4% (*see* Figure 6) (Li and Zheng, 2011).

Figure 6 High frequency supply photo (Fujian LongKing, 2012)

Waigaoqiao PCC plant

A high frequency power supply was installed on unit 3 at Waigaoqiao PCC plant (China). The results were positive. ESP outlet emissions reduced from 25 to 12 mg/m^3 (52% reduction) and ESP power consumption reduced from 871 to 266 kW (69.5% reduction). In 2011, an extra 1147 tonnes of fly ash was collected with a cumulative power reduction of 9.07 GWh (Mao and Feng, 2012).

3.4.7 FLSmidth

FLSmidth has developed its latest version of pulse power supply – the Coromax Mk IV. The Coromax pulse energisation consists of narrow HV pulses in the range of tenths of microseconds, superimposed on a base voltage. The Coromax Mk IV has improved shortened pulse width and higher voltage differential, which result in better charging and therefore increased collection efficiency. The Coromax Mk IV can be integrated into MBC, enabling optimal operation, such as quick spark detection and avoidance. The technology is made up of commercially available parts and therefore is easily maintained.

Nordjyllandsværket PCC plant

A prototype Coromax Mk IV was tested in unit 3 of Nordjyllandsværket PCC plant (Denmark). When firing coal blends producing a medium resistivity fly ash and a loading at the ESP inlet of 18.5 g/m^3, the Coromax Mk IV reduced outlet concentrations to 35 mg/m^3, which corresponds in a 99.81% collection efficiency. By May 2011, twenty units had been sold (Reyes and Elholm, 2011). Pulse energisation is the most effective way to operate SMPS with high resistivity fly ash (Grass and Zintl, 2008).

3.4.8 IRS and EDF

ORCHIDEE is a good example of V-I curve simulation software developed by IRS (Italy) and EDF (France). It works offline and only with direct current power supplied (not intermittent or pulsed). Through analysis of the V-I curves produced from the input data, faults can be predicted and avoided or identified and solved. If required, ORCHIDEE can work out optimum injection rates for flue gas conditioning (Arrondel and others, 2008).

3.5 Modelling ESP operation

Modelling ESP operation can be used to determine fly ash resistivity, sparking onset voltage, collection efficiency and other ESP operating conditions. These models can be integrated into the MBC and used continuously to optimise the ESP power supply and rapping. Modelling ESP operation is complex – there are many variables, processes, interactions and other phenomena. ESP geometry, flow distribution, gravity and other environmental conditions have to be included for accurate modelling. This section briefly explains some of the latest models developed for fixed parallel plate, dry ESP.

3.5.1 Models to aid control systems

Andrabi and others (2011) of the Indian Institute of Technology (Delhi, India) have developed a model than can calculate fly ash resistivity based on its chemical composition. The model gives better fit to the actual resistivity than the Bickelhaupt and other models in temperatures lower than 160°C.

Majid and others (2011) of the Technical University in Dortmund have found a new way to measure the fly ash resistivity using a laboratory set-up, which can directly detect the onset of back corona during the experiment and reduce the power immediately.

Stackelberg and Lengert (2011) of Rico-Werk Eiserlo and Emmrich (Germany) have developed an enhanced electrical model which measures fly ash resistivity, discharge and the capacitance. This model is based on ESP geometry, power supply, power cable and electrical characteristics of the particulates (includes the resistance values and permittivity). The model also includes the flashover ignition time of the particulates.

Czajkowski (2011) of the Silesian University of Technology (Poland) have developed a model called the ODEUS method to optimise corona discharge voltage using sparking onset voltage, corona discharge control loops, fly ash resistivity and flow distribution. The next stage in research is to develop software for a self-learning control system.

Kiss and others (2011) conclude that, in order to accurately model ESP operation over the long term, it is essential to account for the electrical properties of the fly ash collected on the plate electrode and model the effect of rapping.

In the future, it may be possible to combine models of fluid flow, fly ash resistivity and cohesivity, EHD force, the amount of accumulated fly ash, migration velocity, turbulence and re-entrainment and others into one single model. This single model could then be used in the design of state-of-the-art ESP.

3.5.2 Model for fault finding

The US EPA has developed the ESPVI 4.0, this is a program which models an ESP and can be used as an analytical tool to diagnose problems or suggest upgrades. This software has been applied to PCC plant in Russia and newly independent states (ex-Soviet states). Improvements recommended by the model include modification of operational conditions, improved maintenance practices, improved flow distribution and application of the up-to-date ESP components (Zykov and others 2004).

3.6 Electrical low pressure impactor +

ESP operation is optimised using measurements of fly ash resistivity (using a resistivity probe), power supplied and ESP outlet emissions (measured at the ESP outlet or stack) or opacity (measured in the stack). However, there are two problems with using ESP outlet emissions or opacity to optimise operation. Firstly, the results are not real-time. Secondly, the results can be affected by processes after the ESP.

If a particulate is sufficiently charged then it will be captured by the ESP (unless there are re-entrainment problems). Charging efficiency is directly related to collection efficiency and therefore measurement of charging efficiency could be effectively used to optimise ESP performance. The electrical low pressure impactor + (EPLI+), developed by Dekati (Finland), measures real-time (10 Hz) size distribution, concentration and level of charge on particulates in the size range from 0.006 to 10 µm.

The EPLI+ was tested on a PCC plant in Finland. Measurements were taken before and after the ESP. The flue gas is sampled by an FPS-4000 before passing to the EPLI+. The FPS-4000 (also made by Dekati) conditions the flue gas temperature and humidity, and the concentrations are altered for more accurate measurements. Results showed low baseline concentrations of $PM_{2.5}$ at 0.5 mg/m^3 and peaks occurred during rapping. In this case, the measurement of charging efficiency, as opposed to collection efficiency or stack opacity, allowed for direct optimisation of the ESP operation, reducing both emissions and operating costs (Lamminen and others, 2011).

FLSmidth have used the EPLI and say that it is a robust instrument, results are available instantly (no weighting procedure), and it provides important information on the size distribution of particulates, which would be difficult to get with a gravimetric impactor (Poulsen and Löfstöm, 2008).

3.7 Flue gas conditioning

Most older ESP are designed to capture fly ash with a medium resistivity. When the resistivity of the fly ash becomes too high, collection efficiency decreases. A common example of this is when PCC plant switches from firing medium or high sulphur coal to low sulphur coal, or increases the proportion in the blend. This decreased concentrations of highly conductive sulphur trioxide. To exacerbate this problem, low sulphur coals are generally of lower quality. Low sulphur coals contain higher amounts of ash, thus increasing the fly ash loading. Low sulphur coals also have a lower heating value, the PCC plant will increase the firing rate in order to meet the rated plant electricity output, which again increases fly ash loading. This increase in fly ash loading can possibly go beyond the design parameters of the ESP.

However, fly ash resistivity can be decreased by adding chemicals into the flue gas in a process known as flue gas conditioning (FGC). FGC chemicals include sulphur trioxide (SO_3), ammonia (NH_3) and proprietary chemicals. There are numerous designs for the injection equipment. Using sulphur trioxide as a FGC chemical is a popular solution. However, increasing sulphur trioxide in the flue gas increases stack opacity, fouling and corrosion. Therefore, different FGC chemicals can be favourable. Installing an FGC system entails a moderate capital cost and an additional operating cost. A short outage is required for the installation of the injection equipment (Zhu, 2003; Salib and others, 2005).

Previous IEA Clean Coal Centre reports have covered the majority of FGC processes up to 2003. Here is a list of the chemical used followed by process name, manufacturer and report in which it was covered:

Sulphur trioxide (includes elemental sulphur injection):

- EPRICON, EPRI (Soud, 1995; Wu, 2000; Zhu, 2003);
- WET, WET Native and WET In-duct, Wilhelm Environmental Technologies Inc (Wu, 2000; Zhu, 2003);
- Chemithon SO_3, Chemithon Corporation (Wu, 2000; Zhu, 2003; Fernando, 2003);
- Wahlco Processes, Wahlco Inc (Wu, 2000; Zhu, 2003).

Ammonia:
- Ammonia, Wilhelm Environmental Technologies Inc (Zhu, 2003);
- U2A, Emission Control and Chemical Technologies (Zhu, 2003).

Dual sulphur trioxide and ammonia:
- Wilhelm Environmental Technologies Inc (Zhu, 2003);
- Chemithon Dual (Wu, 2000; Zhu, 2003; Fernando, 2003).

Proprietary Chemicals:
- Combustrol FACT, Calgon Corporation/Wheelbrator Air Pollution Control (Wu, 2000; Zhu, 2003);
- Ada Environmental Solutions (Soud, 1995; Wu, 2000; Zhu, 2003).

Fujian Longking (China)
In 2010, Fujian Longking (China) installed a sulphur trioxide FGC system at Guangdong Pinghai PCC plant (China). The installation necessitated a low capital cost and short outage period, primarily because the system was not restricted by space on site. The system is reliable, has low operating and maintenance costs, and the sulphur trioxide injection rate is fully automatic. As intended it can meet ELV of less than 45 mg/m^3 with collection efficiencies peaking at 99.65%, when burning coals that produce highly resistive fly ash (Lui and others, 2011).

Chemithon (USA)
Chemithon sulphur trioxide, ammonia and dual FGC systems are described in detail in Zhu (2003) and Wu (2000). In 2008, Chemithon FGC technologies were installed in 170 PCC plants globally. For perspective, there were 600 operating sulphur trioxide FGC systems globally at that time. Chemithon systems have proven to be a cost-effective and reliable way of reducing fly ash resistivity (Trivedi and Phadke, 2008).

3.8 Humidification

Humidification, also known as water conditioning, is a technique that sprays water into the flue gas upstream of the ESP. The water evaporates in the hot flue gas, increasing the humidity, and as water is conductive the fly ash resistivity is lowered. Humidification also reduces the flue gas volume, which increases the SCA and lowers the fly ash resistivity yet again. Increasing the SCA allows for higher voltages across the ESP. Higher voltages and lower resistivity result in increased collection efficiency. Additionally, the fly ash is more saleable as no hazardous chemicals are added. There are two problems with humidification. The first is producing water droplets small enough to allow for complete vaporisation and mixing. The second problem is the cost of clean water. Humidification is not wet ESP, as the plate electrodes are not washed with water sprays. Zhu (2003) covers a humidification system developed by ADA Technologies and EnviroCare International.

Big Stone PCC plant
Big Stone PCC plant (South Dakota, USA) had an ESP installed in 1975. In 1995, Big Stone switched from firing lignite to firing subbituminous coal. Subsequently, the fly ash resistivity increased and so did emissions of particulates, beyond the stack opacity limit of 20%. A humidification system was installed to lower the resistivity of the ash and increase collection efficiency. However this did not lower the resistivity of the ash and performance problems persisted (Lugar and others, 2012).

3.9 Agglomeration

For conventional ESP, the collection efficiency for $PM_{2.5}$ is low. This problem can be solved by retrofitting an agglomerator. Using various chemical and physical techniques, an agglomerator binds fine particulates into larger particulates, which have high collection efficiency in conventional ESP. The following agglomeration technologies are assessed by Zhu (2003):

- Fine particulate agglomerator developed by Environmental Elements Corporation (Michigan, USA): a full-scale test conducted at the Presque Isle PCC plant which resulted in 41% increase in migration velocity;
- High concentration agglomeration also developed by Environmental Elements Corporation: this technology soon evolved into multi-pollutant control with sorbent injection after a pilot test in Mercer PCC plant (USA);
- Multifrequency Acoustic Agglomerator developed in the Institution de Acústica (Spain): pilot tests on a fluidised bed combustor reduced outlet emissions by 37%.

Indigo technologies

The Indigo Agglomerator, developed by Indigo Technologies (Australia), is installed at the inlet duct of the ESP. The device agglomerates the particulates firstly with a physical process in order to promote collisions, and secondly by charging the particulates positively and negatively, creating bi-polar attractions.

In March 2003, a commercial Indigo Agglomerator was installed at the Watson PCC plant (MI, USA) and achieved a reduction in $PM_{2.5}$ of 80%. Tarong PCC plant (Australia) found increased capture of fine particulates, this included an increase in the capture of arsenic from 16% to 21% and total mercury from to 65% to 79% (Truce and Wilkinson, 2008).

In December 2007, an Indigo Agglomerator was installed at a PCC plant in China. Trials burning Chinese and Indonesian coals showed a 30–40% drop in stack emissions. In 2008 there were eight commercial installations of the Indigo Agglomerator, in various applications across Australia, the USA and China (Wilkins and others, 2008).

3.10 Wet ESP

The difference with wet ESP as opposed to dry ESP is that accumulated particulates are constantly washed from the electrodes with water spray nozzles. Wet ESP has three significant advantages. Firstly, there is no rapping, thus eliminating the emission peaks created during rapping. Secondly, higher corona power can be used to increase charging. Finally, the high humidity lowers the temperature of the flue gas; this increases SCA and lowers fly ash resistivity. Wet ESP has high collection efficiencies for PM_{10}, $PM_{2.5}$, sulphuric acid and other soluble acid aerosols.

However, wet ESP has high water consumption and generates wastewater which requires remediation in complex treatment systems. Flue gas exiting the wet ESP will be cooler than that from cold-side dry ESP, which could prove problematic for gas clean-up systems downstream of the ESP and require the addition of a heat exchanger. In some applications the sulphur trioxide mist can be at pH 0.5 – this is extremely corrosive and will require the wet ESP materials to be fabricated from corrosion resistant alloys, which are expensive. Wet ESP can be integrated with various scrubbing techniques such as wet FGD for multi-pollutant control (Stultz and Kitto, 2005). Spraying water onto the plate electrodes creates mists, these mists can create a short circuit for the corona discharge to the plate electrodes, and this adversely affects collection efficiency. A water delivery system that drips water onto the plate electrode can overcome the problem of short circuits, whilst reducing parasitic load associated with high pressure water.

Wet ESP is mainly used in chemical and mineral processes to capture fine particulates and acid aerosols. Recent applications include wood chip driers (which also have a lower fire risk than dry ESP), glass ovens and incineration plants. Wet ESP can be cooled in order to condense any water vapour out of the flue, leading to a plume-free flue gas leaving the stack, which is beneficial where there is public opposition against plumes. Historically, wet ESP has not been used on large PCC plant due to unfavourable economics. However, wet ESP could have favourable economics on smaller scales, such as on smaller PCC plant or as an additional measure to other particulate control on larger PCC plant (Seyfert, 2011).

3.10.1 Plate electrodes

Plate electrodes are traditionally made from heavy carbon steel, stainless steel and, less commonly, lead. These materials tend to corrode and creep over time, especially in low pH environments created by condensed acid aerosols. To avoid this problem, metal plate electrodes can be made from corrosion resistant alloys, such as stainless steels. However, the cost of these alloys has limited their application in wet ESP. As the water film in wet ESP acts as the cathode, non-conductive materials can be used to make the plate electrodes. Non-conductive materials include plastic (such as polyvinyl chloride and polypropylene) and, more recently, membranes made from plastic fibres. Plastics do not corrode, are light and thin and therefore have lower transportation and maintenance costs. However, areas of the plastic or membrane plate electrode that are not covered in a water film, or dry spots, can either have holes burned in them by sparking or have an accumulated layer of fly ash. It is important that a constant water film is maintained, but this is not an easy task as water tends to bead due to water surface tension and channel because the plate electrode is not perfectly flat. Fortunately, membrane plate electrodes can distribute the water film evenly based on vertical and horizontal gravity assisted capillary flow through the weave, eliminating the problem of dry spots. Also, the plastic membrane can be kept flat with a small amount of tension (Shah and Caine, 2010). Membrane ESP was studied extensively in Ohio University. For further detail on wet and dry version *see* Zhu (2003).

3.10.2 Croll-Reynolds Clean Air Technologies

In 2003-04, a pilot wet ESP was installed and operated by Croll-Reynolds Clean Air Technologies at the Bruce Mansfield PCC plant in Pennsylvania (USA). The wet ESP was installed downstream of a wet FGD and there was no other form of particulate control. Two types of wet ESP were installed, both tubular and up flow design with two fields operating at 52°C, one with metal plate electrodes and one with membrane plate electrodes. Table 2 summarises the results.

Significant reductions are shown in fly ash, sulphur trioxide, particulate mercury and oxidised mercury, but little effect on elemental mercury, especially for the membrane plate electrodes. However, years of operational experience are needed to prove membrane technology in terms lifetime and performance.

Table 2 Wet ESP test results at Bruce Mansfield PCC plant (Shah and Caine, 2010)

Field	Metal collecting electrodes		Membrane collecting electrodes	
	1	2	1	2
SCA	35	19	35	18-21
Opacity %	<2	<5	<2	<5
Particulate removal efficiency %	93	70	96	80
SO_3 efficiency %	88	65	93	71
Hg^{2+} efficiency %	76	50	82	61
Hg^{2+} average efficiency %	72			
Hg(p) average efficiency %	78			
Hg^0 average efficiency %	10			

Operating the wet ESP in 'condensing mode' provides significant benefits. Operating below 100°C increases the amount of liquid water on the particulates, this lowers resistivity, in most cases to an optimum level. Additional water raises the pH of the acid solutions formed (less acidic) and eliminates the need for make-up water (lowering the amount of chlorides added through make-up water). These two factors lower the water corrosiveness which allows lower cost materials to be used. Flue gas leaving a condensing wet ESP will be cool and clean, making it ideal for a typical carbon dioxide absorbing vessel (Shah and Caine, 2010).

3.10.3 Dynawave

The Dynawave membrane wet ESP combines limestone slurry scrubbing and membrane ESP into one unit with high removal efficiencies for sulphur trioxide, sulphur dioxide, oxidised mercury and fly ash. The technology has low capital and maintenance costs, high reliability and can operate in condensing mode. The first commercial installation was in March 2005, with felted polypropylene membrane. Typical removal efficiencies are 99.5–99.8% for sulphur trioxide, 83% for sulphur dioxide and 99.5% for fly ash. Installation of this Dynawave membrane wet ESP on <350 MWe coal-fired boilers is expected to be cost effective for multi-pollutant control (Caine and Meyer, 2010).

3.11 Colder side ESP

Colder side ESP (or CESP) operates in the temperature range 90–100ºC. The colder flue gas temperature decreases the fly ash resistivity in two ways. Firstly, it increases the SCA because the gas is more dense. Secondly, the lower temperatures increase water condensation onto the particulates, increasing the surface conductivity, as opposed to volume conductivity. Colder flue gas can extend the life of the ESP by reducing the thermal stress and prevent structural degradation. However, the lower temperatures form ammonium sulphate/bisulphate and sulphuric acid, causing fouling and corrosion respectively (Zhu, 2003).

After pilot tests in various locations, Liddell PCC plant (Australia) installed colder-side ESP in the 1970s. Despite successful operation the technology was not followed up. In the mid-1980s, Alstom installed colder-side ESP at Ensted PCC plant (Denmark). The flue gas was cooled by air pre-heater adjustments and results were positive with no corrosion issues. In the 1990s, Alstom installed a full-scale colder-side ESP on Tosho Nanyo PCC plant. The flue gas is cooled upstream of the ESP and used to reheat the flue gas after the wet FGD. Results were positive, the lowest emissions were 6.7 mg/m^3 and there was a 50% reduction in power use, or 90% reduction in power use when just meeting the ELV. Since the 1990s Mitsubishi Heavy Industries (Japan) have installed colder-side ESP, with a similar set-up to that of Tosho Nanyo, on over 10 GW of Japanese PCC plant. Notable plants include Haranomachi, Tachibanawan, Tomatoh and Maizuru (Back, 2008).

3.12 Moving electrode ESP

Hitachi Plant Technologies (Japan) have developed a moving electrode electrostatic precipitator (MEEP) to counteract the effects of high fly ash resistivity (Soud, 1995). In fixed plate ESP, high resistivity fly ash sticks to the plate electrodes and is difficult to remove with conventional rappers. High impact rapping is required which entails problems with fly ash re-entrainment. As there is a layer of highly resistive fly ash on the plate electrodes coupled with the highly resistive fly ash in the flue gas, the corona discharge power is limited. MEEP is equipped with multiple plate electrodes attached on a chain that slowly rotates on two sprockets. Close to the hopper there is a rotary metal brush which brushes accumulated fly ash from the plate electrodes. Re-entrainment is minimised and corona discharge power can be increased, and collection efficiency is therefore high. Figure 7 shows a schematic of MEEP.

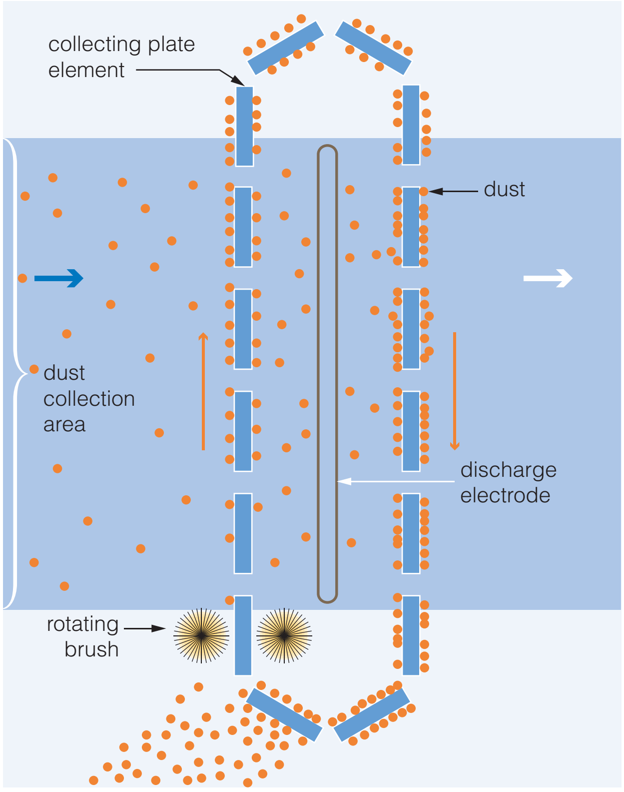

Figure 7 MEEP schematic (Hitachi, 2012)

However, moving parts such as the chain and sprocket, will wear with increased fly ash loading. Presently MEEP is installed downstream of one or two fields of fixed plate ESP, where there is a fly ash loading of 1 g/m^3 or less, to prolong MEEP lifetime. Hitachi are modifying MEEP in order to withstand higher fly ash loading. In a test rig with highly resistive fly ash, MEEP required half the space of conventional fixed plate ESP, thus halving the site footprint (Ando and others, 2011). Hitachi claims that MEEP requires a third to two-thirds less electricity and less space than conventional ESP (Hitachi, 2012). In 2011 there were 30 installed MEEP in PCC plant in Japan, ranging from 75 MWe to 1000 MWe application, achieving efficiencies up to 99.4% (Hitachi, 2012).

3.13 Electro-mechanical double-zone ESP

Fujian LongKing (China) have developed the electro-mechanical double-zone ESP. This technology separates the charging zone from the collecting zone, both zones have a separate power source, which allows a HVDC of 80 kV without sparking. This technology has high collection efficiencies for PM_{10} and $PM_{2.5}$ with high and low resistivity fly ash.

Installation on 300 MWe units at Xiamen PCC plant has increased collection efficiency from 99.025% to 99.69%, and in another installation at Henan PCC plant from an average of 98.62% in two ESP to 99.96% (34.6 g/m^3 inlet to 13.8 mg/m^3 outlet) and 99.92% (35.2 g/m^3 inlet to 28.1 mg/m^3 outlet). On a larger 2 x 660 MWe Fujian XX PCC plant, the electro-mechanical double-zone ESP was placed in the second field of a five field ESP. The retrofit increased collection efficiency from 99.62% to 99.81% (<50 mg/m^3 outlet concentration). In total there are 74 electro-mechanical double-zone ESP units in China, eight in 660 MWe applications, forty-two in 300 MWe and twenty-four in 300 MWe (Zhang, 2011).

3.14 Ion blast ESP

GEA Bischoff (USA) has developed the Ion Blast ESP (*see* Figure 8). This technology utilises ionic wind to increase collection efficiency. Ionic wind is the wind produced from the flow of flue gas towards the plate electrodes due to the macroscopic migration of particulates. Capture of $PM_{2.5}$ should also be increased due to capture in the ionic wind. Two design features are required to create a high speed ionic wind. The distance between electrodes is increased two to three fold, compared to parallel plate ESP, which allows the particulates to pick up speed before hitting the plate electrode. To increase the charge on the particulate, the corona discharge voltage is increased to 150 kV, compared to conventional modern ESP which is within 55–85 kV. GEA Bischoff arranged the Ion Blast ESP as a vertical cellular one field ESP with a self-supporting honeycomb structure in order to increase ionic wind. Wet ion blast ESP requires less water than conventional parallel plate wet ESP as the SCA is smaller. In 2011, there were over 100 wet and dry ion blast ESP installations on biomass combustion plants or chemical processes (Seppälä and Skroch, 2011).

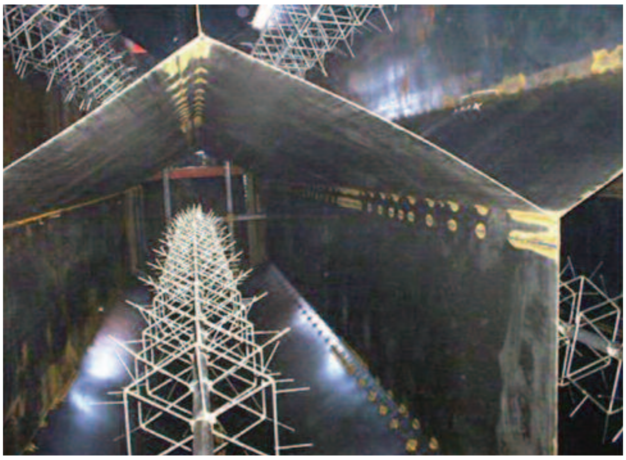

Figure 8 Ion Blast ESP schematic (Seppälä and Skroch, 2011)

3.15 Cross flow ESP

Originally developed by ERDEC (Japan), Alstom are assessing cross flow ESP technology. Cross flow ESP can be seen as conventional parallel plate ESP, where the plates are cut into sections and rotated 90°. Particulates alternatively pass discharge and plate electrodes flowing in the same direction as the electrical field lines. The discharge electrodes resemble the teeth of a saw, with the teeth pointing in the direction of the gas flow. Both electrodes need to be rapped. Figure 9 shows a computer model of a cross flow ESP, the green arrows show flue gas direction (Back and Francis, 2006).

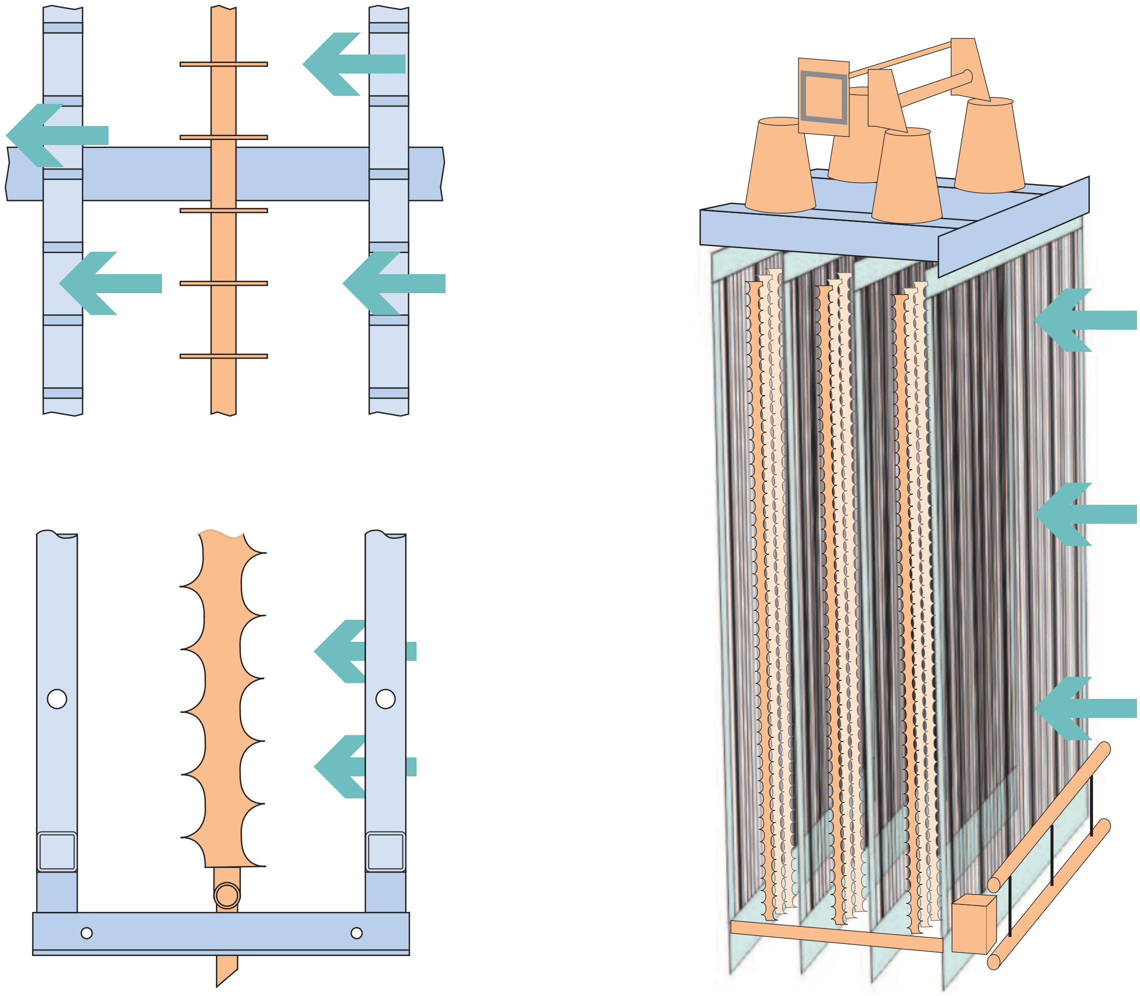

Figure 9 Cross flow ESP schematic (Back and Francis, 2006)

4 Fabric filter

Fabric filters (FF) operate on relatively simple processes compared to ESP. FF theory, design and operation will be summarised in Section 4.1 to provide background information in order to understand the subsequent FF enhancements. Section 4.2 will assesses the main filters used in PCC plant application. Section 4.3 and 4.4 assess microprocessor control for sophisticated operation and flow control devices to ensure uniform flow distribution. Section 4.5 mentions the use of flue gas conditioning and agglomeration for creating an optimum fly ash cohesivity. Section 4.6 demonstrates that humidification can be integrated in FF to flue gas temperature control with other advantages. Section 4.7 touches on multi-pollutant control which can be achieved through using FF coupled with sorbent injection upstream. Finally, Section 4.8 shows how an old ESP can be used to potentially halve the capital expense of retrofitting an new FF to an existing PCC plant.

4.1 Fundamentals

Figure 10 FF photo (FLSmidth, 2012a)

As shown in Chapter 3 there are many techniques to improve the performance of ESP. However, a FF can ensure >99% collection efficiencies of the fine particulates and >99.95% overall collection efficiency. All the information in Section 4.1 is referenced from Soud (1995) and Zhu (2003), unless otherwise referenced. Figure 10 shows a typical FF installation at a PCC plant.

4.1.1 Theory of operation

Figure 11 shows a schematic of a typical pulse jet fabric filter (PJFF). Particulates are collected by passing the flue gas through a filter that has smaller pores than most of the individual particulate. A common example of this is a vacuum cleaner. The flue gas is forced through the filter bags and the fly ash is caught either by the bag itself or by the accumulated fly ash, called filter cake, in a process known as impingement. FF collection efficiency is not directly related to fly ash resistivity and can therefore maintain a high degree of capture with highly resistive fly ash. The actual filter will depend on the level of fly ash removal required and the operating environment with regards to chemical degradation, thermal deterioration and mechanical wear. The shape of the filter is cylindrical, up to 11 metres long and usually 30 cm in diameter. Air-to-cloth (A/C) ratio is simply the ratio of the face velocity to the surface area of fabric required – it is a measure of the filtration rate. A higher A/C ratio means that less cloth has to be used in a fixed flow rate. Sizing a FF system depends on the A/C ratio and pressure drop. As with cold-side ESP, FF are located downstream of the combustion air pre-heater and operate in the temperature range 120–180°C, where most of the water remains in vapour form. FF are constant emission devices that can maintain high collection efficiencies with reasonable increases in flow rate or fly ash loading (Popovici, 2012). FF are also known as bag houses.

4.1.2 Filters

In PCC plant, the most common type of fabric used is felt; there are some woven fabrics. Felt is comprised of a base fibre (scrim) to which a fibre web (batt) is bonded by means of a needling

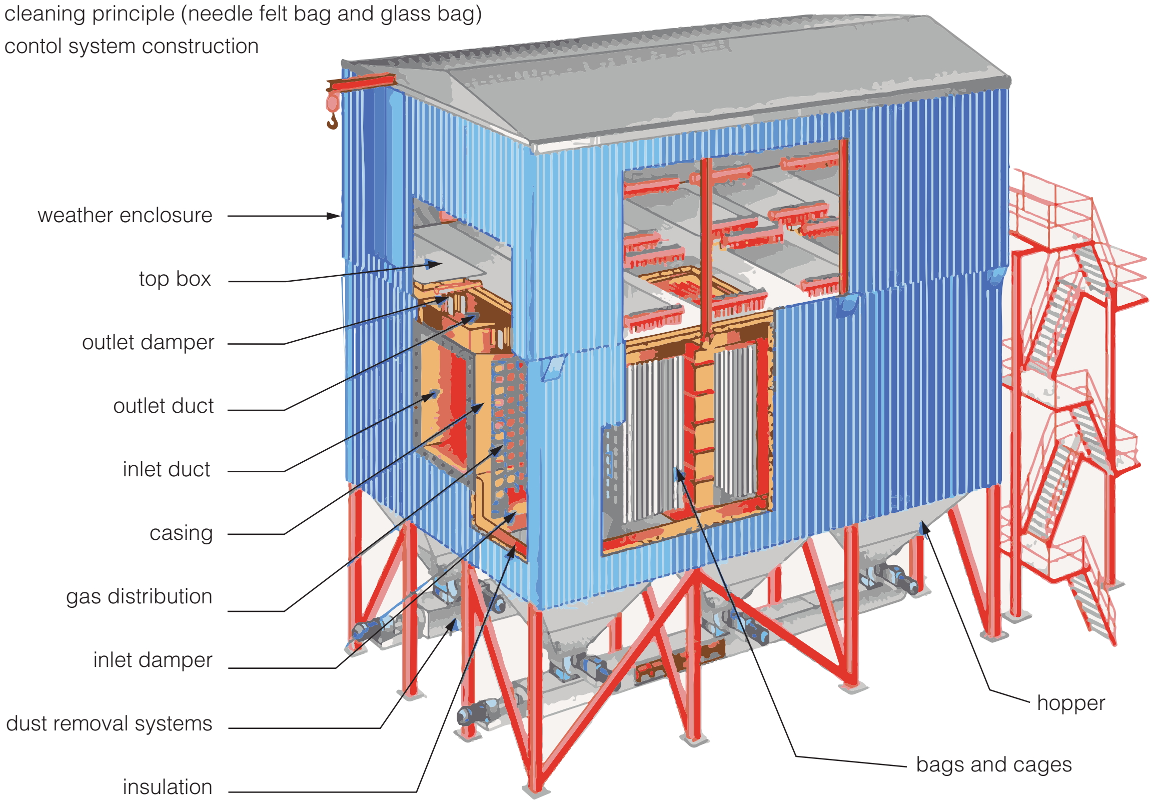

Figure 11 PJFF schematic (FLSmidth, 2012b)

process – either on one or both sides of the scrim. The scrim has large holes from needle punching and the batt has small pores from the resulting fibre web. Modern fibres used are synthetic.

When a new fabric filter is used, particulates get caught in the interstices of the batt forming a primary layer of filter cake. Further particulates are then caught on the primary layer, developing a secondary layer of filter cake through a process called impingement. This filtering process is known as depth filtration. During the development of a primary and secondary layers, a large proportion of fine particulates will pass through the fabric filter. This is seen as a peak in emissions occurring after a cleaning cycle.

As the secondary layer filter cake builds up so does the pressure drop across the filter. This pressure drop eventually reaches a critical pressure, where any further rise would result in excessive induced draft fan power consumption, potentially leading to combustion suppression through lack of air flow and ultimately bag breakage. Consequently, when this critical pressure is reached the secondary layer is knocked off into the hoppers with a cleaning cycle.

It is important that the secondary filter cake remains on the filter bags for as long as practically possible for three reasons. Firstly, the filter cake has higher filtration efficiency than the fabric alone. Essentially the fabric is simply a support structure for the filter cake. Secondly, in applications where there is sorbent injection upstream of the FF for multi-pollutant control (*see* Section 4.6), it is essential for the filter cake to remain on the filter bag for as long as possible. This is to allow the sorbents in the filter cake to be exposed to the flue gas for complete reaction and therefore capture of pollutants. Finally, cleaning the bags uses power generated by the plant and decreases bag life due to mechanical deterioration.

When using new filter bags, the start-up procedure of the PCC plant is critical to the bag lifetime. As the new bags have not built up a primary layer, high fly ash loading can damage and blind the bags. Appropriate start-up procedures slowly load the bags so that a primary layer can build up and the bags are only cleaned when they need to be. The cleaning process should not clean the primary layer, otherwise emission levels will increase intermittently (bleed-through).

Monitoring the pressure drops across the bags and cleaning at the critical pressure point is essential for long bag life, high collection efficiency of particulates and other pollutants through sorbent injection, plant load requirements and minimised power consumption and maintenance of FF. Filter cake management is the most important single factor for optimum FF operation.

Fabric blinding takes place when the primary layer is overloaded with moisture, fine or cohesive particulates, which have few pores, resulting in a large pressure drop. An example of overloading with fine particulates is when an FF is used as a polishing filter downstream of an ESP, as there are mostly fine particulates left after the ESP (discussed in Chapter 5). The cohesiveness of particulates increases with certain chemical species; one common example is ammonium bisulphate that develops when there is ammonia slip from upstream SCR systems. Activated carbon sorbents can increase cohesivity and chemical slip from other scrubbers can alter cohesivity. Excessive moisture is found when there are water leaks upstream of the FF.

Filter bag lifetime is dependent on the following factors – chemical degradation, thermal deterioration and mechanical wear. Chemical degradation of the fabric and filter cages occurs when the temperature of the flue gas drops below the acid dew point, for example during start-up and shut-down procedures. Thermal deterioration occurs when the flue gas temperature exceeds the filter temperature limit. The flue gas temperature at the FF inlet duct can be regulated through the addition of ambient air. Mechanical wear is due to abrasion and fatigue, and the main causes are excessive cleaning and re-entrainment. Mechanical wear can be reduced with minimum cleaning cycles and installing filter cages. Another important point is that the filter bags are not too long, in order to avoid high pressure cleaning pulses, which increase mechanical wear.

Fibre selection is critical for effective filtering. The choice of fibre or fibres which make up the felt depends on process conditions such as chemical environment, temperature, fly ash properties and ELV. Fabrics must be proven in terms of filtration efficiency and bag life in real-world conditions as opposed to laboratory conditions. Tests undertaken in a laboratory simply do not reflect the varying temperature, fly ash loading, moisture levels and flue gas chemistry seen in PCC plant. Another important factor is the effect of the FF on downstream flue gas cleaning systems (Popovici, 2011; Nuendorfer, 2012b; Stark, 2012). Figure 12 shows depth filtration filters in a PJFF.

Surface filters have pores smaller than the particulates to be collected and therefore do not need to build up a primary or secondary layer for filtration. This eliminates the peaks in emissions seen in depth filtration after a cleaning cycle. There is also no abrasive action in the filter which increases filter life (Zhu, 2003). However, surface filters are yet to be commercialised, as bag breakages and pinhole leaks could prove a problem (Modern Power Systems, 2012).

Figure 12 PJFF internal photo (Cushing and others, 2008)

4.1.3 Cleaning

When a certain amount of filter cake has built up it has to be removed, otherwise air pressure will build up and break the filters. There are three methods to remove the filter cake – reverse air, shake/deflate and pulse jet. Reverse air and shake/deflate methods can only be carried out offline, and therefore are only suitable for non-continuous operation, such as in chemical process application. However, the pulse jet cleaning method allows the plant to be online whilst cleaning, which is required for continuous PCC plant application. Figure 11 on page 33 shows a pulse jet fabric filter (PJFF) schematic, where dirty flue gas enters at the bottom and clean gas exits at the top. The pulse jet cleaning method will pulse individual bags with compressed air, which dislodges the filter cake the filter and falls into the hoppers below. The bags are only cleaned when necessary. This allows a higher filtration rate to be used, resulting in a smaller size footprint. Generally, the higher the bag cleaning rate, the lower the bag life.

In PCC plant, reverse air was the main method of cleaning in the 1970-80s, however pulse jet cleaning has dominated the market since the 1990s. PJFF vary in operating pressure and volume, depending on the application. PJFF typically operates at 0.9–1.2 m/min (3–4 ft/min) and an A/C ratio of 3.5:1 (Stark, 2012; Stultz and Kitto, 2005).

The pressure drop across FF are much greater than that across ESP. There has to be sufficient force behind the flue gas in order for it to pass through the FF. To compensate for this large pressure drop, the induced fan is usually larger and has higher power consumption compared to applications where ESP is used. Pressure drops are related to the fly ash and filter properties, cleaning frequency and flow rate.

4.1.4 Structure

The casing and fly ash removal system of a FF is similar to an ESP. However, the internal supports for the bags and the inlet and outlet ducts are different, and there are air compressors for the pulse jet cleaning. FLSmidth (2012b) fabricate the casing from 5 mm mild steel, stiffened internally and externally by rolled steel sections and tubes. The hoppers are the same as found in ESP installations. Hoppers must be emptied when full to avoid re-entrainment and possible hopper fires. A steel wire cage is used to support the filter bags to ensure that they do not touch or collapse. These cages are designed to minimise abrasion and flexing – there are different designs for different bags (FLSmidth, 2012b).

4.2 Filters

Zhu (2003) has considered the following filter types:

- Expanded micro-porous PTFE membrane, spun bonded polyester (low pressure drop), duo-density felt, fibreglass (high temperature operation), CleanStac ceramic, ceramic membrane, activated carbon fibre and catalytic fabric filtration.

Soud and Mitchell (1997) have considered the following filter types:

- Cotton, Polypropylene (Propex), Acrylics (Dratex), Philip Fibres – Ryton, Glass, Lenzing – P-84 (high temp, expensive), SCAPA – Nylon (Neotex) and Polyester (Terytex), Dupont – Aramid (Nomex), Teflon and Tefair.

Soud (1995) has considered the following filter types:

- Ceramic (CeraMem), Nextelis a continuous aluminium borosilicate ceramic fibre (3M).

Table 3 summarises the fabric types used for filters in PCC plant applications.

Various felt surface treatments can be applied to the fabric (scrim or batt) for different performance enhancements, for example to increase filter cake release or to help create a porous filter cake to maintain low pressure drops with low cleaning frequencies. Table 4 summarises the treatments and coatings for filters in PCC plant applications:

Table 3 Fabric types (Stark, 2012; Popovici, 2011; Johnson and McMenus, 2011)

Name	Maximum operating temperature	Remarks	Relative cost
Acrylic felt (PAN or polyacrylnitrile)	130°C	Lowest maximum operating temperature	£
PPS felt (Polyphenylenesulphide)	190°C	Degrades at higher temperatures with >12% oxygen. Resist chemical and thermal attack. Effective when laminated with ePTFE	££
Aramid felt	204°C	Not as capable as PPS in chemically active flue gas	£££
Woven fibreglass	260°C	Fragile, require tight tolerances. Suitable with reverse-air cleaning systems	£
P84 felt by Evonik Fibres (polyimide, PI, multi-lobal, tri-lobal)	260°C	Dimensional stability over 204°C but requires oversizing of filter to maintain proper bag to cage fit. Small pore size of 0.5–1 µm (traditional needle felt scrim have a pore size of 15–20 µm)	£££
Pleated elements	Dependant on scrim fabric	A/C <3.5:1. Applicable only when additional cloth area is needed to lower A/C ratio and eliminate inlet abrasion	£££££

Table 4 Fabric treatments and coatings (Stark, 2012)

Treatment name	Maximum operating temperature	Remarks
PTFE coating (not membrane)	260°C	Improve filter cake release, sacrifices ability to maintain consistent airflow leading to increased cleaning frequency or high pressure loss
Expanded PTFE (ePTFE) membrane	260°C	Laminated to collection surface, average pore size of this scrim is 0.5 to 1 µm, low pressure drop with long filter bag lifetime
Singeing	–	Removes some fabric surface area, improves filter cake release
Teflon	–	Resistance against acid attack. High pressure drop and potential blinding with cohesive particulate
Glazing and silicone	–	Improve cake release
Calcium hydroxide	–	Common
Calcium carbonate	–	Common

4.2.1 PPS/ePTFE filters

Hawthorn 5 PCC plant had a PJFF installed with needle felt filter bags with a scrim of PPS and a dipped Teflon coating. Bag life was designed to be 42 months, but after month 30 the pressure drop rose to 2.49 kPa (10 inches of water) even with rapid pulse cleaning at 689.48 kPa (100 pounds per square inch) and the boiler had to be derated to cope. Laboratory tests found that a layer of sticky filter cake had built up that was not coming off with cleaning. This sticky layer was probably due to ammonia slip from the upstream SCR system forming ammonium bisulphate. All 13,520 filter bags were replaced with needle felt filter bags with a scrim of PPS laminated with expanded polytetrafluoroethylene (ePTFE). These new filter bags have proved to have a lifetime of 62 months whilst meeting regulations, at slow pulse cleaning at 517.11 kPa (75 pound per square inch), average pressure drop across the bags was 1.62 kPa (6.5 inches of water). No boiler derates were required and operational costs were decreased due to lower power use, increased power generation and longer bag life (Johnson and McMenus, 2011).

GE experienced similar results when replacing old filter bags in PJFF applications with PPS/ePTFE filters. Results from five case studies showed that average pressure drop reduced from 2.23 kPa (9 inches of water) to 1.69 kPa (6.8 inches of water), opacity levels decreased from 5% to just over 2%, bag life increased and cleaning pressure and frequency tended to be lower (Stark, 2012).

4.2.2 Multi-lobal fibre filters

Using results from a test rig and a PCC plant, Popovici (2011) shows that using a multi-lobal fibre (P84) in the batt achieves high capture efficiencies with low pulse rates and the capacity to handle high fly ash loading. Figure 13 shows a schematic and photo of the PPS scrim with a P84 batt, with an established primary filter cake layer (Popovici, 2011).

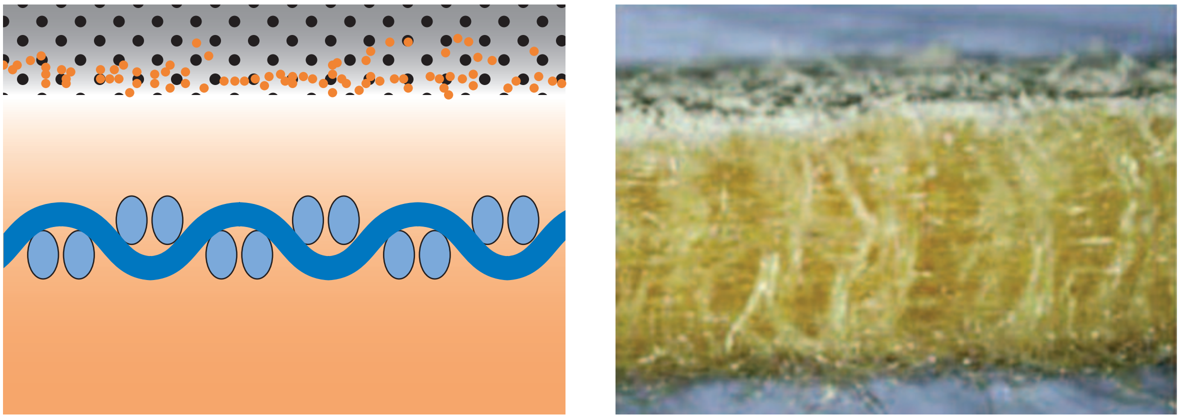

Figure 13 Needle felt filter schematic (Popovici, 2011)

4.3 Microprocessor control

A microprocessor based control (MBC) can optimise the operation FF controls for the highest collection efficiency and lowest operating and maintenance costs. The main parameter to control is the cleaning schedule. There are pressure sensors installed across the filter bags; when this pressure reaches a critical point, the bags are cleaned. Typically, the bags are cleaned in rows. Sequential cleaning has to be avoided as it simply leads to re-entrainment to adjacent cleaned bags – a random order minimises re-entrainment. The MBC system can also detect bag failures (Nuendorfer, 2012b).

4.4 Flow distribution

The flue gas flow rate is measured as face velocity. The flow has to be laminar and uniform; this minimises re-entrainment and overloading, resulting in minimal bag abrasion and high collection efficiency. Face velocity has to be low enough to allow for efficient collection but fast enough for practical operation. These factors combined result in long filter bag life and high collection efficiency.

CFD analysis can be applied to any type of FF in order to identify the most effective use of flow control devices to ensure uniform flow distribution. Section 3.3 explains this in detail. Figure 14

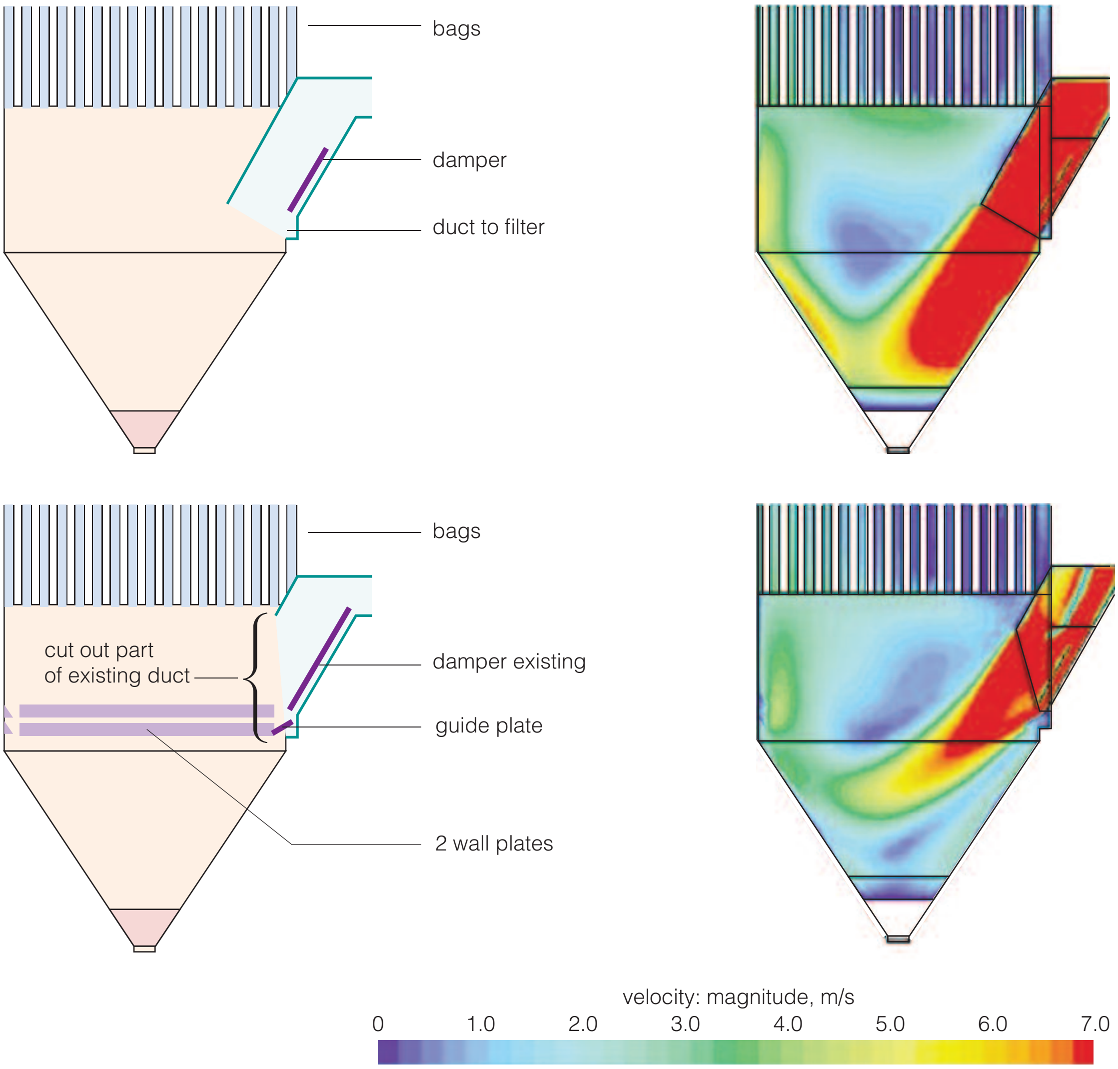

Figure 14 CFD analysis of PJFF (Nielsen and others, 2011)

shows before and after pictures of CFD analysis on a PJFF by FLSmidth, the computer model is on the left and the simulation is on the right.

The 'before' pictures clearly show high flow rate near the hoppers, causing re-entrainment, and non-uniform flow at the top, overloading the bags in the centre. The 'after' pictures show the modified inlet duct and addition of guide plates, which guide the fastest part of the flue gas away from the hopper walls, avoiding re-entrainment, and providing more uniform face velocity and laminar flow towards the bags (Nielsen and others, 2011).

Enviroserv (Germany) offer a state-of-the-art CFD modelling and simulation service for FF. The model is similar to the one described in Chapter 3, apart from EHD force is not accounted for. The pressure drop across the filter (Darcy's law) and filter cake development are accounted for instead (Feldkamp and others, 2008).

4.5 Cohesivity

Highly cohesive fly ash can lead to problems with high pressure drop, due to lack of pores, and bag cleaning. Excessive ammonia slip from upstream SCR can increase the cohesivity of the filter cake, potentially causing blockages. Lower cohesive particulates can create large pores in the bag, leading to particulate ‘bleeding’ through. FGC can be used to increase FF performance by creating a certain cohesivity for optimum porosity filter cake, allowing for high collection efficiencies at low pressure drops. Elemental sulphur (S), ammonia (NH_3), and sulphur trioxide (SO_3) are the main conditioning agents currently used. Agglomeration could be used to make the fly ash more cohesive. However, Yao and others (2008) at the particle and combustion engineering group at Tsinghua University have found that charging particulates before a FF has mostly adverse effects on pressure drops and collection efficiency.

4.6 Humidification

To minimise thermal deterioration of the filters, the flue gas temperature at the FF inlet duct can be regulated through the addition of ambient air. However, some days there is a combination of high ambient temperature and high PCC plant load. These combined factors can produce high flue gas volume flow rates which reach limitations of induced draught fan capacity and pressure drop across the filters. Bayswater PCC plant (4 x 660 MWe, New South Wales, Australia) experienced these limitations. In response to this, HRL Technology developed a humidification system to reduce flue gas temperature and hence flue gas volume flow rate, thus avoiding limitations of induced draught fan capacity and pressure drop across the filters. The humidification system accurately controls the flue gas temperature at the FF inlet duct using a very fine water mist, avoiding the acid dew point. The humidification was installed at Bayswater PCC plant in 2005 and has been operating reliably since. Other benefits have included added flexibility in maintenance, ability to bypass the combustion air pre-heaters when required and reduction of parasitic loads. The choice of filters and hence cost of replacement has been reduced as bags with lower temperature limits can be specified (Patterson, 2013).

4.7 Sorbent injection

Solid sorbents react with certain gaseous chemicals to form solids. Sorbents can be injected directly into the flue gas upstream of FF. The sorbent mixes into the flue gas and then forms part of the filter cake with the other particulates. Some of the sorbent will react whilst in the duct but the majority of sorbent will react when in the secondary filter cake, as the sorbent will be in direct contact with the flue gas for a long time. Proven and effective sorbents include ammonia for NOx control, activated carbon for mercury control and sodium based sorbent or lime for sulphur dioxide control. Sorbent addition coupled with FF is known as multi-pollutant control. In some versions of multi-pollutant control, the sorbent is injected into a spray dryer or circulating fluidised bed dry scrubber, possibly with filter cake reuse for higher sorbent reaction rates. Supporting equipment for the sorbent injection system includes in-duct injection lances, sorbent receiving, handling and storage facilities.

The disadvantage with sorbent injection is that the fly ash is contaminated with sorbents and pollutants, such as activated carbon and mercury, making it unsaleable. Instead it may have to be treated or land filled which incur additional costs.

Sorbent injection systems are not effective with an ESP, as they can overload the ESP and excess particulates will simply pass straight though the constant efficiency device. However, a FF is a constant emission device and compensates for increased fly ash loading with increased cleaning frequency. Also, the majority of sorbent reaction occurs in the filter cake – ESP do not have a filter cake that the flue gas passes through.

Discussion of multi-pollutant control leads to discussion of sorbents, additional process equipment and possible wastewater treatment processes. These are all large and complex areas outside the direct enhancement of ESP and FF, therefore discussion of multi-pollutant control is beyond the scope of this report.

4.8 Replacing ESP with FF

Some PCC plant may find that only a FF system will be capable of meeting ELV and the existing ESP will be removed. If so, it maybe possible to remove the ESP internals and replaced them with a FF system providing the following criteria can be met: the casing is large enough to accommodate the required cloth area, the case has sufficient structural integrity, the case metal is not excessively corroded and there is enough area around the casing for the work to be undertaken. Removing the ESP internals leaves the duct work, casing, access, hoppers and conveyor belt intact and available for use with a FF retrofit. The induced draught fan may have to be upgraded or replaced to allow for the greater pressure drop with FF. No two projects are the same, but in most cases the work can be done in one outage at a cost approximately half that of a new build. There have been many successful conversions: two examples are given below.

Big Stone PCC plant

Big Stone PCC plant (USA) have converted their ESP to a PJFF. The work was done by the Buell Division of Fisher-Klosterman. The ESP casing was large and strong enough to accommodate an intermediate pressure, long bag PJFF design. The turnkey cost of conversion was half that of an entire replacement. Another advantage was that the existing ESP was compartmentalised, so the PJFF was installed in separate stages which allowed short outages for conversion. In 2008, unit 4 set an annual record for low emissions (Lugar and others, 2012).

Craig PCC plant

Due to a poorly performing hot-side ESP, a PJFF system was retrofitted to the 455 MWe units 1 and 2 at Craig PCC plant (CO, USA) in 2003-04. Significant modifications included uprating the existing induced draft fan with new rotors and motors to handle the larger pressure drop, upgrading the combustion air pre-heaters and duct work to bypass the retired hot-side ESP. The work was completed by Hamon Research-Cottrell. The PJFF could have been retrofitted inside the hot-side ESP casing, however the maximum six-week outage on each unit was insufficient to complete the work. The PJFF is a low pressure, high volume design with bags arranged in circular bundles. The filter bags are 8 m long by 12.5 cm wide made from 2.7 denier PPS felt, the A/C ratio is 4 and each unit has 15,744 bags. Project costs were 72 US$/kW according to Hamon Research-Cottrell and 35 US$/kW was the breakout price for the PJFF. After three months of operation, test results on unit 1 showed pressure drops remained the same or decreased and opacity was 3.6%. Performance deteriorated with some punctured bags due to abrasion caused by poor design, but subsequent CFD simulations and additional flow control devices solved this (Wolf and others, 2004).

5 Hybrid systems

Hybrid systems combine ESP and FF to benefit from the advantages of both technologies – high collection efficiency for all sized particulates with low pressure drop.

5.1 Energy and Environmental Research Center (USA)

Figure 15 AHCP photo (Lugar, 2012)

The advanced hybrid particulate collector (AHPC) technology was developed at the Energy and Environmental Research Center at the University of North Dakota (USA). The project was funded by the US DOE. The AHPC combine ESP and FF in the same space, however the plate electrodes are perforated. The system is designed to collect 90% of the fly ash in the ESP section and just less than 10% in the FF section, allowing for high face velocities and longer bag life.

The AHPC has been tested for several years at laboratory scale. A successful pilot AHPC was demonstrated in 2001. A full-scale AHPC demonstration was carried out at Big Stone PCC from 2002 to 2004, funded under the DOE power plant initiative programme. Initially the AHPC saw good results. However, problems were soon encountered with high pressure drops, bag life under six months, and emissions and opacity regulations not being met. The technology has not received funding for further development since 2004 (Lugar, 2012).

5.2 Allied Environmental Technologies (USA)

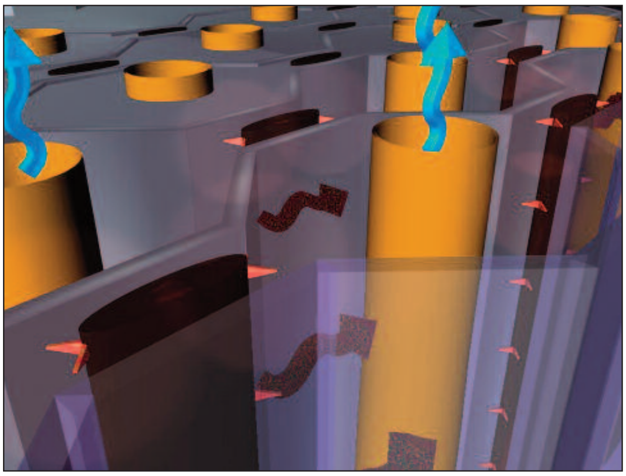

Figure 16 MSC schematic (Krigmont, 2011)

The multistage collector (MSC) was developed by Allied Environmental Technologies (USA). The MSC combines single stage and two stage ESP with barrier filtration. The MSC collection efficiency is independent of fly ash resistivity and has high collection efficiency of $PM_{2.5}$.

In 2006, a proof-of-concept pilot demonstration for the technology was completed. Initial results showed collection efficiency of 99.99% at face velocities of approximately 0.04 m/s. Another advantage of the MSC is that particulates will not follow the gas streamlines that cut past the filter cake but instead follow the electric field lines which direct the particulates into the filter cake. Up to May 2012, Allied Environmental Technologies has been unable to find a sponsor for a full-scale demonstration (Krigmont, 2011).

5.3 Electric Power Research Institute (USA)

Electric Power Research Institute (EPRI) in the USA have developed the following hybrid systems, compact hybrid particulate collector (COHPAC), COHPAC II, TOXECON and TOXECON II. Figure 17 shows schematics of these hybrid systems and the following sections explain their operation.

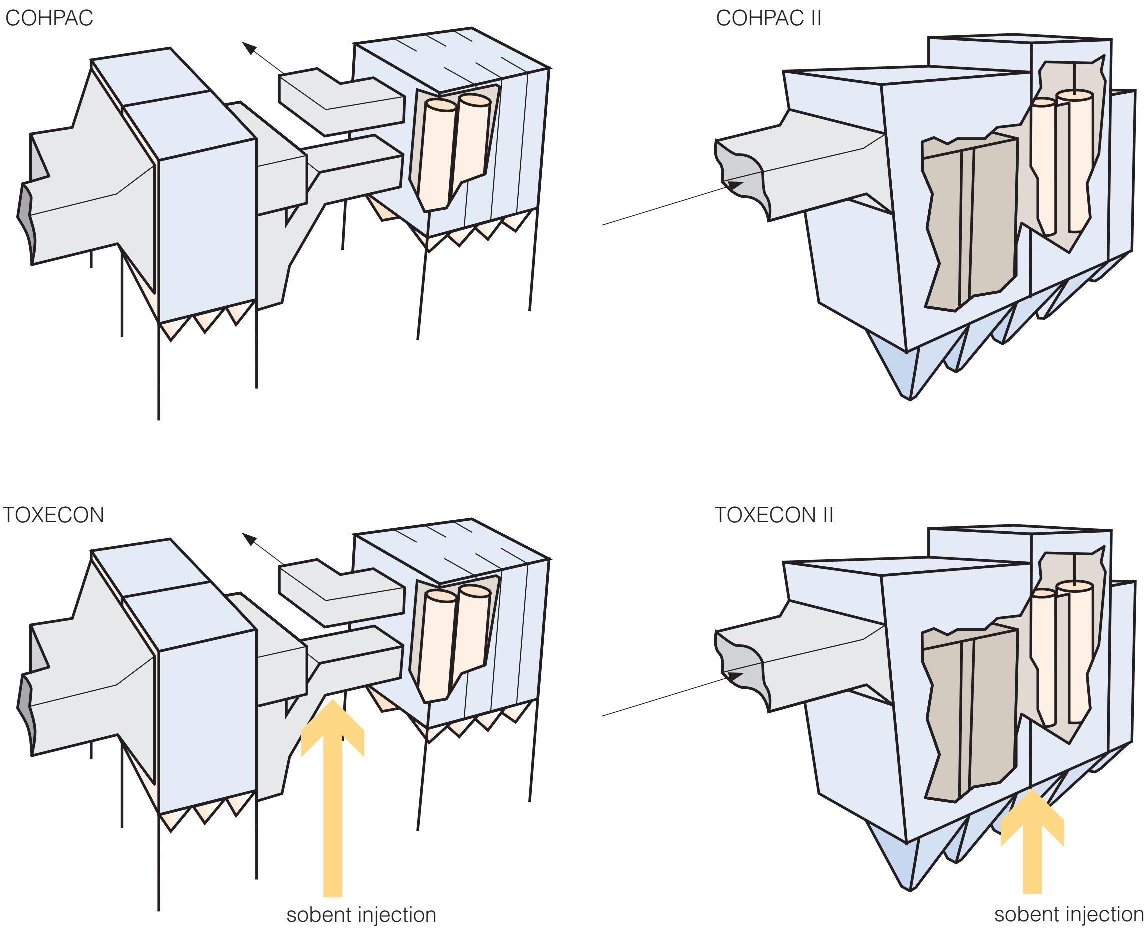

Figure 17 Schematics of COHPAC, COHPAC II, TOXECON and TOXECON II (Zhu, 2003)

5.3.1 Compact hybrid particulate collector

Developed and patented by EPRI in 1991, the compact hybrid particulate collector (COHPAC) contains a PJFF downstream of an existing ESP – acting as a 'polishing filter', eliminating the need for possibly more expensive and underperforming ESP retrofits. COHPAC collection efficiencies equal FF at >99.95%. Depending on the design, the ESP will remove most of the fly ash. The low fly ash loading on the FF allows for a high air-to-cloth ratio of 1.52 to 2.44 m/min (5 to 8 ft/min), allowing a small footprint on-site, longer bag life, lower pressure drops and lower parasitic load. The ESP can act as pre-charger helping to agglomerate the particulates. Another advantage is that the PJFF will capture any emission peaks from the ESP due to re-entrainment or a sudden change in flue gas. The unit outage for installation is a few weeks (Salib and others, 2005). There are two design variations. COHPAC has a separate FF system to the ESP. COHPAC 2 replaces the last plate electrodes in an ESP with a FF system.

E C Gaston PCC plant has a capacity of 2 GWe, it burns low sulphur coals and runs hot-side ESP. Sodium sulphate was introduced as a FGC agent to overcome the sodium depletion problem. However this was not effective – the plate electrodes often needed cleaning and boiler deratings were required to meet emission standards. In 1996, utility-scale COHPAC was operational on unit 3 of the E C Gaston PCC plant (USA); a second was operational in 1999 on unit 2. The COHPAC units were installed in abandoned cold-side ESP casings which were directly underneath the running hot-side ESP. Both are low pressure and high volume PJFF installed by Hamon Research-Cottrell. The filter bags used in this COHPAC system are shown in Figure 12 on page 34.

COHPAC can be controlled by a MBC system, which can be integrated with a remote monitoring system for real-time monitoring, data logging and subsequent performance analysis, accessible from any web browser. Both installations have seen a move from the original 2.7 and 3.0 denier Ryton felt fabrics to more permeable 7.0 denier PPS felt fabrics. Average tube-sheet drag force dropped by 40%. Changing the filter bags did not compromise collection efficiency. The pulse cleaning rate was reduced from 0.7 to 0.2 pulses per bag per hour. Average bag life for all filter types is two to three years or 19,000 to 27,000 hours. Various felts are continually being tested and new tests have found that a dual-density Torcon 9058 felt is effective. It is important to remember that this PJFF is placed after an ESP, so the fly ash loading primarily consists of finer particulates. Therefore, the felts proving successful in this application may not prove so without an ESP upstream.

In a decade of operation, COHPAC has halved stack opacity and has reduced the number of hours per month the opacity has exceeded 20% by 95%. COHPAC has allowed fuel flexibility, resulting in decreased overall operating costs. The FGC system is not needed with COHPAC, the plate electrodes need cleaning less and there is no need to derate the boiler. The last one or two fields of an ESP can be removed and replaced with a PJFF in that area of the casing, this arrangement is known as COHPAC II.

During its operation, powdered activated carbon (PAC) was injected upstream of the PJFF of the COHPAC systems at E C Gaston, to capture mercury. Tests found that 90% of the total mercury was captured COHPAC and sorbent injection led to the development of TOXECON, which is discussed below (Cushing and others, 2008; Zhu, 2003).

5.3.2 TOXECON

TOXECON is COHPAC coupled with a sorbent injection system upstream of the FF. The sorbent injection is to capture other pollutants, such as mercury. The existing particulate control will capture approximately 99% of the fly ash, which can be sold as normal. This leaves 1% of unsaleable fly ash caught in the FF.

Figure 18 TOXECON photo (NETL, 2008)

TOXECON allows high sorbent residence times and therefore efficient sorbent use. Just COHPAC, TOXECON retains the PJFF advantages, a small footprint and high collection efficiency of fine particulates. TOXECON was demonstrated between 2006 and 2009 on a total of 270 MWe at Presque Isle Power PCC plant (USA). A labelled photo of the site is shown in Figure 18.

Providing TOXECON can be scaled-up successfully for commercial application then it will be a technically and economically viable process for $PM_{2.5}$ and mercury control. As

TOXECON is a retrofit, capital costs are site-specific and will vary dramatically. NETL (2008) estimate that the average capital cost will be $34.4 million or 270 $/kW and operation and maintenance will cost 0.81 $/MWh. Approximately 75% of the total cost is due to activated carbon and increased induced draught fan power.

In TOXECON II, sorbent is injected into a cold-side ESP just before the last field. The majority of ash is collected before sorbent injection, leaving the majority of ash for sale without need for treatment or landfilling. TOXECON II avoids the need for a new build FF. EPRI have tested TOXECON II with injection of activated carbon and found 50–70% mercury removal. EPRI estimates that the cost for TOXECON II will be similar to that of conventional activated carbon injection, which is within 2–3 $/kW (Offen, 2004). However, land filling fly ash is expensive. ADA-ES have tried milling activated carbon to reduce injection rates, whilst maintaining sufficient mercury removal; however the resultant fly ash would still have to be landfilled. Fly ash friendly sorbents have also been tested without success so far (Sjostrom and others, 2008).

5.3.3 PM screen

EPRI have developed another type of polishing filter, the PM screen. The flue gas must pass through a screen of filter material that is installed on the outlet of an ESP. The filter material is mounted on a belt-driven system that continuously cleans the screen of accumulated fly ash and avoids excessive pressure drops. The electric charge on outlet particulates is utilised for effective capture on the screen. Screen materials will require high mechanical strength (mainly fatigue strength).

Miller PCC plant (USA) is operating a PM screen on a 1 MW slipstream. Filter materials and possible sorbent injection are being assessed. Initial results show that 40–57% of the ESP outlet emissions can be caught with acceptable pressure drops. Materials include 325-mesh and 500-mesh stainless steel and a felted material yet to be decided (Fisher and others, 2010).

5.4 General Electric (USA)

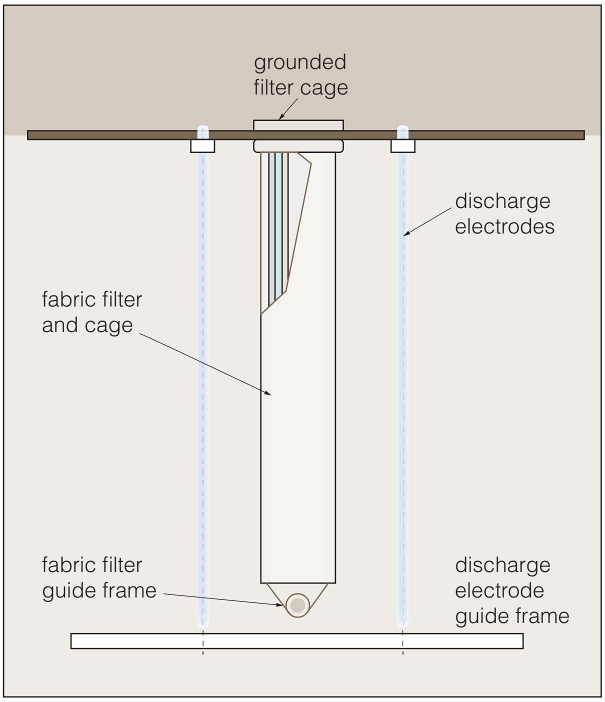

Figure 19 Max 9 schematic (Taylor, 2006)

The electrostatically stimulated fabric filter (ESFF) is patented by the US Environmental Protection Agency (EPA). General Electric is the exclusive licensee for the ESFF, marketed as Max-9.

The operating and cleaning principles are exactly the same as a FF, with the addition of electrostatic charge for enhanced collection. The ionising electrodes are located between the filter bags on the side of the fly ash laden flue gas. The collector electrodes can either be the filter bag itself or the filter bag cage. The particulates are all negatively charged by a low DC current from the ionising electrode. A low current is used to eliminate risk of fire or filter puncture from sparking. Particulates accumulate on the filter due to air pressure differential and electrostatic attraction to the collector electrode. As the particulates are all negatively charged they repel each other creating a porous filter cake. A porous filter cake allows for a low pressure drop, low frequency cleaning, prolonged bag life, higher A/C ratio and can eliminate the need to install a bigger induced draft fan. Also, low cleaning frequency allows more effective use of sorbent injection.

Testing has shown collection efficiencies of 99.99%. When combined with a GE combustion process that maximises the amount of particulate mercury, Max-9 can capture 85% mercury without PAC injection. Fly ash can be treated to remove much of the mercury to reduce disposal costs. As with COHPAC and TOXECON, Max-9 can be used as a polishing filter for finer particulates and mercury. GE was building commercial-scale units in 2005 (Taylor, 2006; Modern Power Systems, 2005).

5.5 Fujian LongKing (China)

The electrostatic-fabric integrated collector (EFIC) developed by Fujian LongKing (China) is similar to COHPAC II – ESP fields are removed and replaced with a PJFF system. EFIC has patented 13 of its advanced technological features. These features include pulsing valves, step-down arrangement of bag compartments, sizing of clean air chamber exit valve, large clean gas chamber, and a filter bag bypass system for online overhaul.

In 2009 EFIC was installed in the last three fields of a four-field ESP on a 660 MWe unit at Boasham PCC plant. Historical ESP efficiencies average 80% due to varying coal types. After the retrofit, EFIC guaranteed a collection efficiency of 99.8% (30 mg/m^3 outlet emission) with low pressure drops of 900–1000 Pa and lower parasitic load . In 2012, Fujian LongKing successfully installed 91 EFIC units with 87 on order for PCC plant units of 15–660 MWe. A side view schematic of the retrofitted EFIC is shown below. EFIC is operational on Henan Xinmi PCC plant (2 x 1000 MW units) (Zheng and others, 2011).

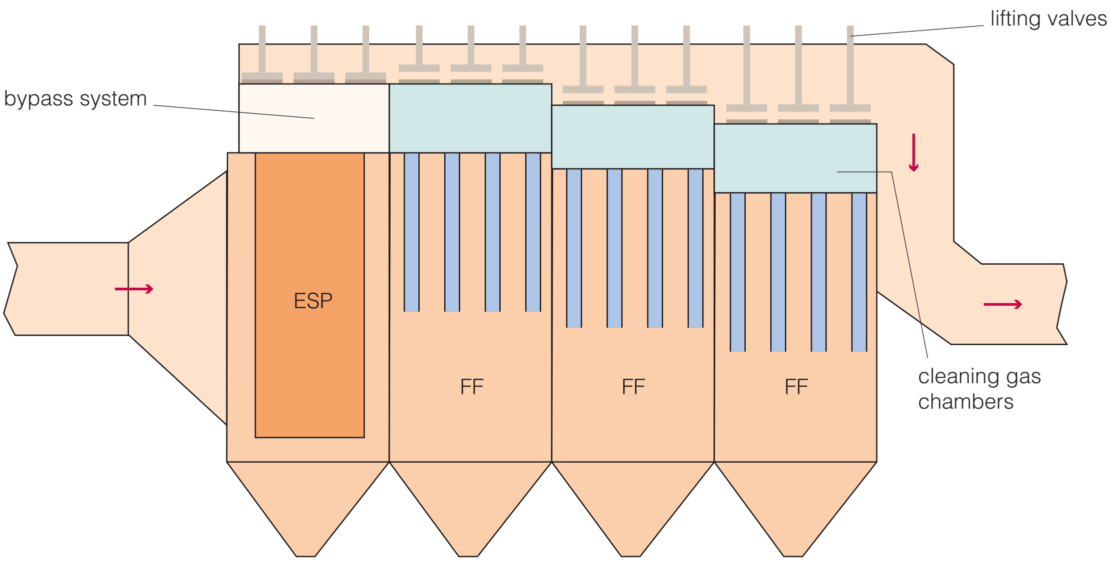

Figure 20 EFIC schematic (Zheng and others, 2011)

6 Conclusions

Emission limit values (ELV) for particulate matter from pulverised coal combustion (PCC) plant are being tightened globally. Some countries are introducing specific limits for hazardous emissions included in particulate matter, for example mercury. Historically, electrostatic precipitators (ESP) have met ELV with up to 99.81% collection efficiency, low pressure drops, reliability and relatively low capital, operational and maintenance costs. Increasingly stringent ELV have been met by enhancing the existing ESP performance. Modern ESP are designed to have high collection efficiencies of all types of fly ash – some are marketed as applicable to worldwide coal firing. However, fabric filters (FF) are becoming increasingly common because of the >99.95% collection efficiency and the ability to capture other pollutants with the use of sorbent injection. A popular example is the injection of activated carbon to capture mercury – this is known as multi-pollutant control. The disadvantages of FF are high pressure drop, and high capital, operating and maintenance costs. The use of sorbent injection will contaminate the fly ash with sorbent and other pollutants, potentially rendering the fly ash unsaleable. New hybrid ESP/FF technologies aim to exploit the low pressure drops of ESP and high collection efficiency FF. Another advantage is that sorbent injection can be utilised in hybrid technology for multi-pollutant control.

Enhancing particulate control has been made difficult by PCC plant operating outside the design conditions. Examples include firing low-rank coals, cofiring biomass, and cyclic operation. Despite this, increases in collection efficiency have been achieved through upgrades, additional features and alternate configurations. Advances in electronics, seen every day in mobile phones and computers, have been mirrored by effective improvements in the areas of fluid flows, control and power supplies.

In all cases, it is essential that mass emissions of particulates are measured at the inlet and outlet ducts of the particulate control, in order to quantify the collection efficiency and optimise operation. Furthermore, the addition of wet FGD downstream of the existing particulate control can more than halve the particulate control outlet emissions.

Electrostatic Precipitator (ESP)

The challenge with conventional ESP (dry, cold-side, parallel plate) technology is to capture fine particulates and maintain high collection efficiencies with high fly ash resistivity. The first port of call to increase ESP performance is to ensure design performance by a full maintenance service. This opportunity can be used to upgrade parts and ensure uniform flow distribution. If space on the site allows, another collecting field can be added for a certain increase in specific collection area (SCA) which therefore improves collection efficiency.

Upgrades include switched mode power supplies (SMPS) for superior charging and microprocessor based control (MBC) for sophisticated operation. Installation of the third/fourth generation of SMPS coupled with MBC will improve collection efficiency whilst decreasing parasitic load. The work will entail a short outage period and a precise capital cost. Also, SMPS can be operated in pulse energisation mode, which has high collection efficiencies with highly resistive fly ash. Discharge and plate electrodes can be upgraded with much improved designs.

Traditionally, uniform flow distribution was worked out from expensive and time consuming physical models or in situ trial and improvement tests. However, the last decade has seen computational fluid dynamics (CFD) revolutionise the way in which fluid flows are analysed. CFD uses numerical methods and algorithms to solve and analyse problems that involve fluid flows – computers are used to perform the calculations. CFD analysis can be used to quickly identify the most effective use of flow control devices in ESP/FF of any shape or size. CFD analysis is quicker and less expensive than traditional methods.

In situations where the fly ash resistivity is too high, flue gas conditioning (FGC) can be added to the existing ESP. FGC adds chemicals upstream of the ESP in order create an optimum fly ash resistivity. FGC is well placed in situations where there has been a switch to firing low sulphur coals. A moderate capital cost and a short outage period is required to install the injection equipment, and an additional operating and maintenance cost will be incurred.

A high loading of finer particulates will decrease collection efficiency for conventional ESP. In order to increase capture of finer particulates, an agglomerator can be added to increase particulate size. Installation of an agglomerator will entail a moderate outage period and moderate capital cost, together with increased maintenance and operating costs.

For an improvement in collection efficiency along with other advantages, the following variations of ESP technology could prove suitable; colder-side ESP, moving electrode ESP, wet ESP, electro-mechanical double-zone ESP and ion blast ESP. These variations of ESP technology can be retrofitted by installing them inside the existing ESP casing or using them as a polishing filter, but most are installed in new builds. In all cases large capital costs are required and utilising existing ESP casing in retrofit cases will entail long outage periods.

Colder side ESP operates in the temperature range 90–100°C and is proven to have higher collection efficiencies and lower parasitic load. Mitsubishi Heavy Industries have now installed colder-side ESP on over 10 GW of Japanese PCC plant, with performance figures of 6.7 mg/m^3 emissions with a 50% power reduction.

Moving electrode ESP (MEEP) by Hitachi, is designed for applications where the accumulated fly ash cannot be knocked off via conventional rapping without causing excessive re-entrainment – instead it is brushed off. The moving parts will wear with high fly ash loading so MEEP is presently installed in the last one or two fields of an existing ESP where there is low fly ash loading. Results from 30 installations in Japan have shown collection efficiencies up to 99.4% with highly resistive fly ash and half the site footprint of conventional ESP.

Wet ESP has high collection efficiencies of particulates of any resistivity and aerosols, and can condense water vapour, leaving plume-free stack emissions. Wet ESP washes accumulated particulate off with a water spray and therefore requires a complicated water delivery and cleaning system. Wet ESP not economically viable on large-scale PCC plant, however it could have favourable economics at small-scale PCC plant or when used as a polishing device. Recently wet ESP has been incorporated into wet scrubbers in multi-pollutant control. Plastic or membrane plate electrodes have not yet been successfully commercialised.

Electro-mechanical double-zone ESP (Fujian LongKing) separates the charging zone from the collecting zone. Recent retrofit applications in China have shown an outstanding performance of 99.96% collection efficiency. In 2011, there were 74 units installed in Chinese PCC plant.

Fabric Filter (FF)

Pulse jet fabric filters have to be well maintained and operated, otherwise pressure drops can get too high and filter bag breakages can result in noticeable drops in collection efficiency. Uniform flow distribution in FF can be ensured using CFD analysis, in much the same way as ESP. Installation of MBC will allow sophisticated cleaning cycles in PJFF, which will guarantee improve overall performance.

Filters using depth filtration benefit from modern synthetic materials and treatments – PPS felt laminated with ePTFE has proven to be effective and reliable. Generally, better performance will be seen from more expensive filters. Surface or membrane filters have not yet been successfully commercialised.

For regions where the flue gas temperature cannot be regulated purely by the addition of ambient air, humidification can be added. Installing a humidification system will entail a moderate outage period and moderate capital cost, together with increased maintenance and operating costs. Using FGC or agglomeration to create optimum fly ash properties is not popular.

Installing sorbent injection upstream of the FF for multi-pollutant control has proved effective. The work involves a moderate outage period, moderate capital cost and increased operating and maintenance costs. Finally, a FF can be installed in an ESP casing, potentially halving the capital expense of a new-build FF.

Hybrid Technology

Hybrid systems combine ESP and FF to benefit from the advantages of both technologies. Low pressure drop and low costs of an ESP combined with high collection efficiency for all sized particulates, ability to capture rapping peaks and sorbent injection capability of a FF. EPRI in the USA is pioneering multiple developments of hybrid ESP/FF plant. Fujian LongKing has developed a hybrid to capture particulates, which is popular in China and has been proved to collect up to 99.8% of the total particulates.

Final remarks

ESP still dominate the existing fleet and new sales of particulate control. However, FF are popular where there are ELV on mercury and possibly other pollutants. Research and development is ongoing in all areas, FF and wet ESP are evolving towards multi-pollutant control devices and hybrid systems look promising.

There is no silver bullet for particulate control as individual PCC plant vary in aspects such as space availability, ELV and labour cost. Performance from a certain particulate control technology on a specific plant cannot be guaranteed on all other plants. However, providing correct assessments are undertaken there will be an effective technology applicable at any site.

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