The electrostatic precipitator external parameters at the heart of dust collection efficiency performance: coal characteristics, combustion quality and SCR chemical process.

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1 Summary / Abstract:

Since January 1st, 2008, the coal power plants are subject to new stricter European Environmental Regulations. To fulfil these new stakes, new and existing units were equipped with denitrification system (such as Selective Catalytic Reduction processes) in addition to the electrostatic precipitators (ESP) and wet-flue gas desulphurization (wet-FGD).

The ESP particle collection process performances mainly depend on:

- The residence time of dust inside the ESP
- The physico-chemical properties of dust (size, chemical composition, resistivity),
- The voltage applied to the dust collector

Only this last point is linked to the ESP itself while the other two depend on other external parameters.

This article focuses on these external parameters and makes the analyses of their impacts on the collection performances.

In particular, we describe and analyse the impact of:

- Coal characteristics through more than 500 reliable coal chemical analyses (from South Africa, Australia, China, Poland, Indonesia, Norway, Poland, Russia, USA coal supplies),
- Residence time, resistivity and collection performances of the 500 coals analysed through software simulation,
- SCR process impacts on the resistivity and the particle size through SO_2 oxidation into SO_3 as well as the possible production of ammonia sulphate and bi-sulphate species.

2 Introduction

Since January 1st, 2008, coal power plants are subject to new and stricter European Environmental Regulations. To fulfil these new requirements, new and existing units were equipped with denitrification system (such as Selective Catalytic Reduction processes) in addition to the basic electrostatic precipitators (ESP) and wet-flue gas desulphurization unit (wet-FGD). Located downstream from the ESP, the FGD requires a threshold concentration of dust at its inlet to maintain its performance.

Each unit can only be run 120 hours a year with one of its pollution control systems not operating. This requires careful management in daily operation and of maintenance.

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Only the last point is linked to the ESP itself while the two former points depend on other external parameters.

This article focuses on these external parameters and analyses their impacts on collection performance.

In particular, we describe and analyse the impact of:

- coal characteristics,
- combustion quality,
- SCR process.

Coal characteristics are evaluated using a coal analyses database carried out on samples taken during the unloading of the vessel. This database compiles data of more than 500 different coal types, mainly bituminous coals supplied to EDF between 1998 and 2008.

The parameter impact quantification was simulated by the ORCHIDEE software [2], [3], [4] on a 600 MW coal fired unit, equipped with an electrofilter (with 2 casings; each casing is made by 4 fields). The main parameters of a 600 MW unit configuration are given in Annex.

3 Coal characteristics impacts

Coal is at the heart of the combustion process. It has an organic and mineral composition. The organic materials are oxidised during combustion, principally into gases (CO, CO_2, H_2O, N_2, NO_x…). The mineral part remains in a solid form as ash. However, although approximately 10% of the ash is recovered at the base of the combustion chamber, 90% is blown out with the fumes. Such fumes cannot be released into the atmosphere. The dust must be removed to allow the downstream flue gas desulphurization process to operate properly and to comply with environmental dust emission thresholds.

3.1 Coal analysis and residence time

At the moment of ordering, the available coal characteristics are Humidity, Ash, volatile matter, Sulfur, Chlorine, Nitrogen, Carbon, Hydrogen, Fluoride contents, LHV and HHV, Hardgrove index, Ash analysis (Fusibility temperatures, % of ash in SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, K_2O, Na_2O, SO_3, P_2O_5, MnO_2).

Among these coal characteristics, those having an influence on the particle level are as follows:

- the ash content,
- the sulfur content,
- the moisture content, due to the coal's inherent nature and to storage conditions,
- the chemical composition of the ash.

The heat value, carbon, hydrogen and nitrogen contents are not considered. Indeed, for a given electrical power production, the higher the Heat Value the lower the coal flow rate will be. Conversely, increasing the Heat Value is generally accompanied by an increase in the production of gas. So, a variation of the Heat Value, by compensation between the 2 above effects, actually has a little impact on the flue gas flow rate and, therefore, on the residence time in the DES.

The residence time of dust is the time interval during which particles are submitted to an electrostatic field (charging, migration and collection).

This parameter, where the gas passage distance (usually 300 or 400 millimetres) may be disregarded, can be considered as a re-formulation of the well-known SCA (Specific Collecting Area) parameter. The similarity between the two parameters is well understood if the residence time is redefined as the inner volume occupied by one cubic metre per second of gas. From a user perspective, the operating parameter is the flue gas velocity.

Residence time has an exponential effect on electrostatic precipitator efficiency. For example an increase of 20% in flow rate doubles the particle concentration at the ESP outlet.

However for a given electric power load, residence time does not significantly change using different coals. *Figure 1* illustrates residence time variations over the coals database for a 515 MW electric power load. It shows that the estimated value varies from 19.5 to 20.5 second over all the coals. The estimated values were computed using ORCHIDEE simulation software.

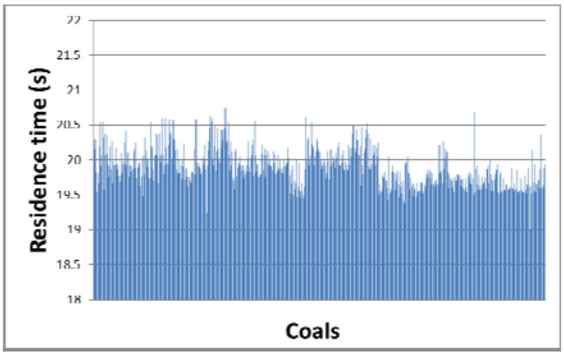


Figure 1: Residence time inside the ESP of a 600 MW unit for different coals.

A higher heat value is related to a lower ash content.

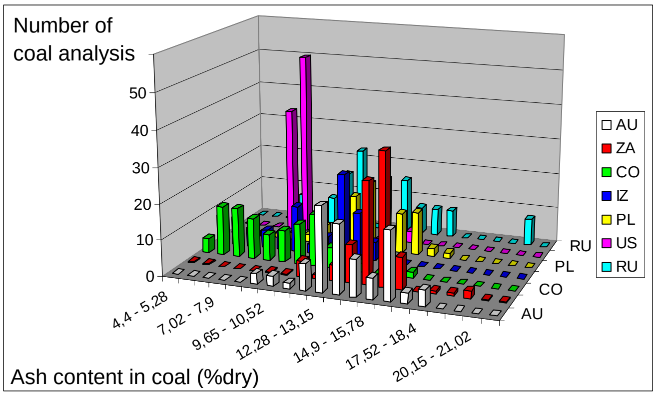
3.2 Influence of ash level

"All other things being equal" (characteristics of the ash, conditions of grinding and combustion), dust emissions at the ESP inlet are proportional to the ash content in the coal.

Higher inlet concentration means higher concentration at the outlet. This obvious concept can transform a well performing precipitator in a “bad” performing one by simply changing the type burned coal in the furnace.

As illustrated by Figure 2, ash content varies from 4.4 % to at least three times that value. It means that for the same collection efficiency the output level will triple using one kind of coal in spite of another one (*Figure 3*). However, the ESP performances are assessed by the outlet concentration, which is regulated and monitored.

Another effect of a coal ash content is a modification in voltage-current level. The presence of charged particles in the flue gas lowers the electric field at the emitting electrodes. The higher the particle concentration, the higher the voltage needs to be at the emitting electrodes in order to maintain the same current level (the control parameter used by T/R set). [5], [6], [7], [8]



Au: Australia, ZA: South of Africa, CO: Colombia, IZ: Indonesia, PL: Poland, US : USA, R: Russia

Figure 2 : Répartition de la teneur en cendres en fonction de l’origine des charbons.

Most of the provided coal has an ash content below 15% on dry basis (db). However, it is found that some coals from Australia, South Africa and Russia could have an ash content higher than 15% (db).

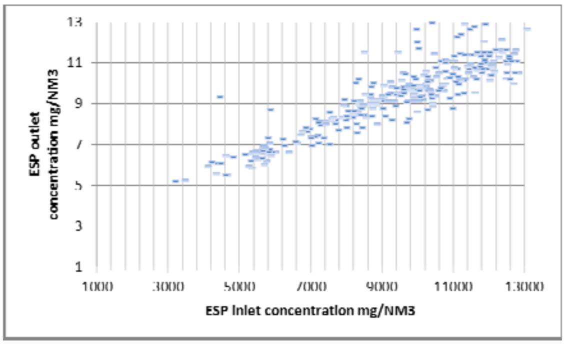


Figure 3: ESP particle concentration outlet regarding the inlet concentration.

3.3 Influence of sulfur content

Sulfur contained in the coal is an important criterion for the choice of its supply. Sulfur content greatly varies from one origin to another, even within the same geographical area. (Figure 4).

Beyond 1250 °C, all the sulfur present in the coal in various forms (pyritic, mineral and sulfates) is found in the gaseous states: SO_2 and SO_3. Sulfur trioxide (whose quantity varies with the kinetics of cooling, the ash content and composition) then combines with the moisture present to form sulfuric acid. It is lain down on the ducts surface and inside the air heater, also on the dust particles, which thus creating a conductive layer. This reduces the dust's resistivity (Figure 6).

However, it is noted that for a 130 °C fume temperature at the inlet of an electrostatic precipitator, the estimated dust resistivity exceeds 2.10^{10} Ω.cm, if the sulfur content is below 0.6 % db (Figure 7).

Usually the flue gas contains les than 100 ppm of SO_3, instable molecule, (see Figure 5). Bickelhaupt model [9], [10], predicts that SO_3 concentration in flue gas should be less than 2,5 ppm. Most of coals from South Africa and Norway produce few SO_3, unlike coals from Colombia and Indonesia.

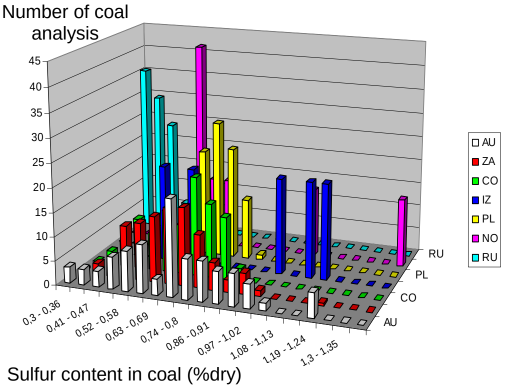


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Figure 4: Distribution of total sulfur content depending on coal origin.

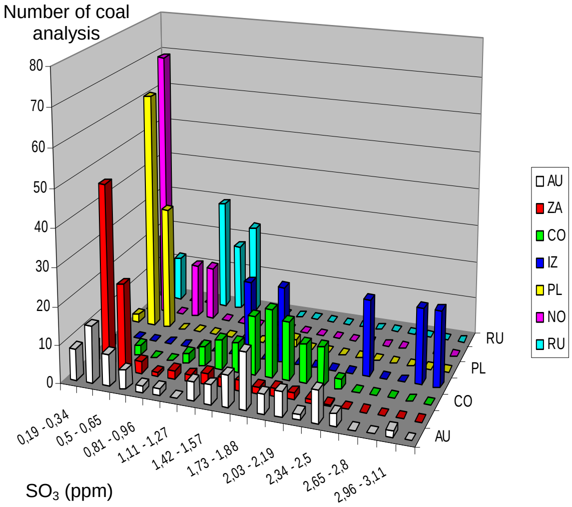

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Figure 5: Distribution of SO_3 content of fumes after combustion of coal sulfur depending on coal origin.

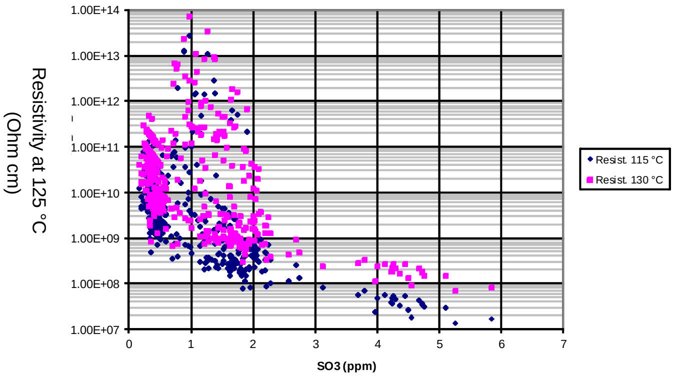
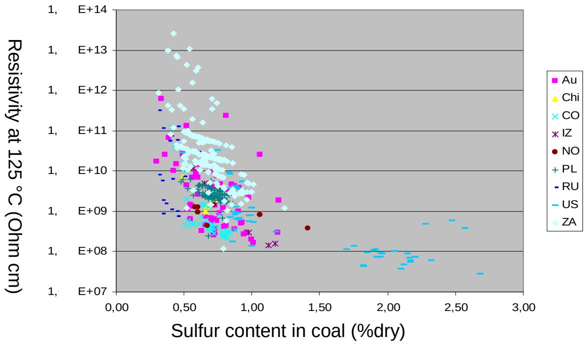


Figure 6: Resistivity depending on SO_3 and temperature in fumes



Au: Australia, Chi : China, CO: Colombia, IZ: Indonesia, NO : Norway, PL: Poland, US : USA, R: Russia ZA: South of Africa,

Figure 7: Total resistivity at 125°C of ash from coal procured between 1998 and 2008 depending on the coal sulfur content (SRI correlations)

The overall tendency of the Figure 7 demonstrates that resistivity decreases when the sulfur content of the coal rises.

This graph reveals clusters of coals depending on their origin: generally, coals from South Africa have higher resistivity than Polish or Colombian ones.

However, although the sulfur content is an important parameter regarding the ash resistivity, the data dispersion underlines that it is not the only one (figure 6). Indeed, the sodium, lithium and/or iron contents can balance a low sulfur content.

3.4 Influence of the chemical composition of the ash

Although the ash and sulfur contents are part of the specifications applying to coal procurement on the international market, it does not apply to the resistivity of the dust.

The resistivity of ash coming from coal combustion partly depends on the properties of the coal and also on those of the fumes, which have to be estimated by models [9], [10].

The various chemical elements in the ash from the raw coal actually have an impact on the resistivity of the dust:

- <u>silica and alumina</u>, which represent more than 50 % of the whole, tend to increase the resistivity ;
- <u>magnesium and calcium</u> also tend to increase resistivity, as they facilitate SO_3 collection;
- <u>lithium, sodium and iron</u> instead tend to reduce resistivity, since they promote high conductive elements.

Hereunder, Fe, Na, Mg, Ca contents are expressed as a percentage of oxides (respectively of Fe_2O_3, Na_2O, MgO, CaO) found on dry basis in the ash.

3.4.1 Total resistivity

The ash resistivity of coals provided between 1998 and 2008 varies, between 6 10^6 Ω.cm and 1.10^{14} Ω.cm, depending on the evaluations made using correlation by SRI. These resistivity variations cause considerable performance changes in electrostatic precipitator performances.

The Figure 8 reveals the coal ash resistivity distribution in the database according to the coal origin for a fumes temperature of 125 °C.

At 125°C, Polish and Norwegian coal supplies therefore do not entail any back-corona problem. For the other origins, the provenance of the coal alone is not considered to be sufficient information regarding the resistivity.

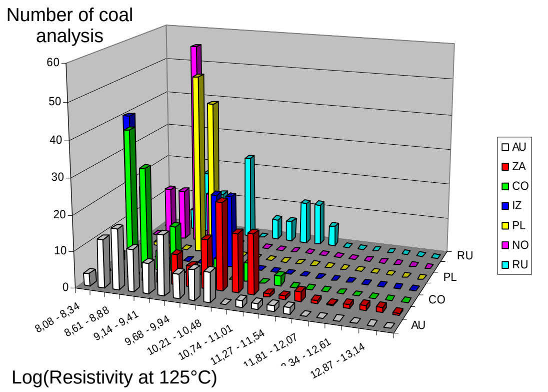


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Figure 8: Coal ash resistivity at 125°C regarding the coal origin

The database analysis reveals 5% of the coal can provoke excessive resistivity for a given electrostatic precipitator operating at 125°C. This percentage reaches 25% if electrostatic precipitators operate at 140°C. High resistivity are mainly observed for South African coals, but also from Russian and Australian coals, and for some Colombian coals.

3.4.2 Resistivity and Sodium content

The Na_2O content of coal procured by EDF between 1998 and 2008 varies between 0.05 and 4.1% dry basis (db), with an average value of 0.6% db.

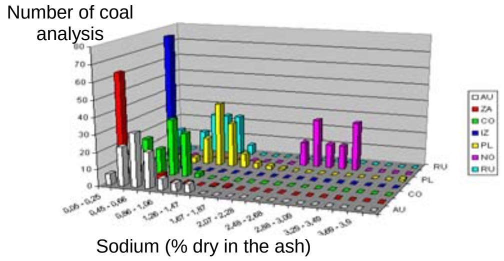

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Figure 9: Distribution of coal sodium content depending on its origin.

Data analysis (Figure 9) reveals that some Norwegian coals have a sodium content higher than 2.3%db. The coals generally have less than this percentage. It is mostly ranked between 0.05 and 2% db.

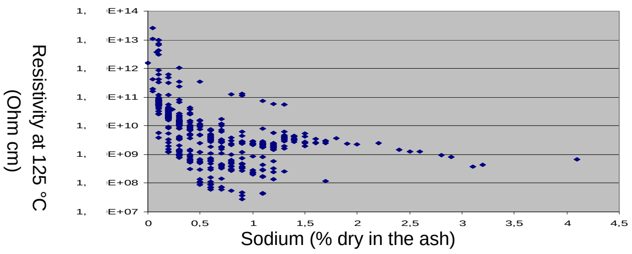


Figure 10: Coal ash resistivity at 125°C depending on sodium content

As shown in the Figure 10, the higher the sodium content, the lower the resistivity will be. Sodium tends to bring resistivity down because it is a highly conductive element.

3.5 Resistivity impact

Resistivity variations have been investigated in the reference configuration (see details in Annex) and on the existing coals in the database described in the previous chapter.

The graph (Figure 11) points the particle density leaving the ESP is a function of the resistivity and the temperature of the ESP. The graphic underlines:

- the link between the particle concentration at the ESP outlet and the resistivity (higher resistivity means a greater resistive drop in the dust layer on the anodes, and the triggering of back-corona if the resistivity exceeds a value of around 2-5 10^{10} Ω.cm) [11], [12], [13], [14], [15],
- the link between the particle concentration at the ESP outlet and the temperature (a lower temperature decreases the residence time),
- the variability of the particle concentration at the ESP outlet depending on a parameter other than resistivity and temperature.

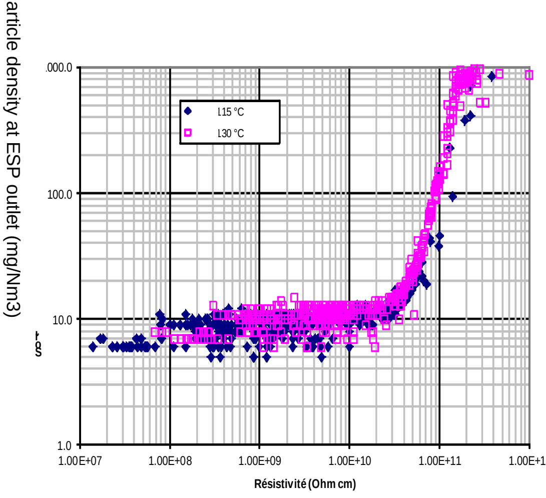


Figure 11: Particle density leaving the ESP outlet as a function of resistivity and temperature of the DES.

3.6 Conclusions

The characteristics having an influence on dust emission levels are therefore ash content, sulfur content, humidity content and ash chemical composition.

To control dust emissions during production, the ash and sulfur contents are the most efficient parameters to define a coal blend, but they are not the only ones: insufficient contents of sodium, iron or lithium can cause high resistivity of ash.

From analysis of our coal database, we conclude:

- The high resistivity of South African coal is explained by the combination of low sodium and iron contents of the ash, with its high calcium content,
- The low resistivity of ash from Polish and Norwegian coals is due to the combination of high sodium and iron contents in the ash, with low calcium content.

4 Combustion impact

The imported coal is conveyed to the mill, dried and ground into powder to improve its combustion in the boiler. Downstream, the precipitator cleans the flue gas according to its characteristics: flow rate (§ 3.1), particles concentration (§ 3.2), particles size, unburned carbon in the ash and SO_3 level (§3.3 & 5.3).

The following sections will describe in greater detail the impact of the particle size distribution, the unburned carbon and how they relate to the combustion conditions on ESP performance.

4.1 Particle Size distribution

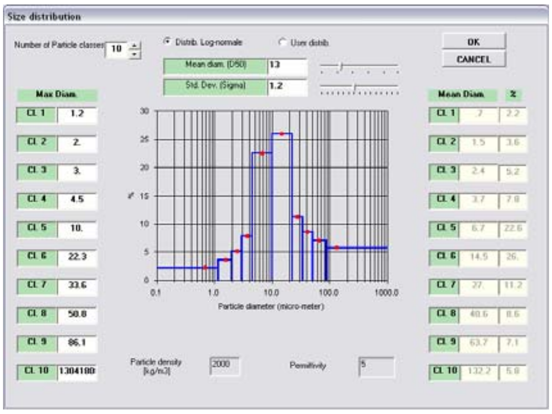
Particle size distribution at the ESP inlet is a function of several parameters: fineness of the grinding, char macro-porosity, combustion temperature and condensation mechanism (level of fouling in the fume circuit and air intakes).

Coal mills and classifiers mainly define particle size distribution entering the boiler where combustion occurs. Smaller particles while more easily burned, are difficult for the electrostatic filter to collect.

Particle size distribution is one of the main parameters affecting ESP performance. Collection efficiency decreases with particle size and reaches a minimum between 0.2 and 0.6 micron. Particles smaller than 0.2 micron are easier to collect. This minimum collection efficiency region is also observed in other collection systems such as bag filters (even if the underlying physical processes are different).

In a coal power plant, the mass particle size distribution is conventionally described by a log-normal curve centered on a specific value. The number particle distribution is defined using a bi-modal distribution.

ORCHIDEE software uses a typical particle size distribution: the log-normal, Figure 12. This figure also shows the 10 particle size classes. The Figure 13 shows how these ten ESP inlet classes are filtered along the ESP fields using the simulation software. At the first field outlet, 5 of the ten initial classes still have significant particle concentrations. After the second field outlet, only 3 remain significant. After the fourth field outlet just the finest remains significant.



Size distribution

Number of Particle classes 10

● Distrib. Log-normale ○ User distrib.

Mean diam. (D50) 13

Std. Dev. (Sigma) 1.2

Particle density [kg/m3] 2000

Permittivity 5

	Max Diam.	Mean Diam.	%
CL 1	1.2	.7	2.2
CL 2	2.	1.5	3.6
CL 3	3.	2.4	5.2
CL 4	4.5	3.7	7.8
CL 5	10.	6.7	22.6
CL 6	22.3	14.5	26.
CL 7	33.6	27.	11.2
CL 8	50.8	40.6	8.6
CL 9	86.1	63.7	7.1
CL 10	1304180	132.2	5.8

Figure 12: Log-Normal particle size distribution

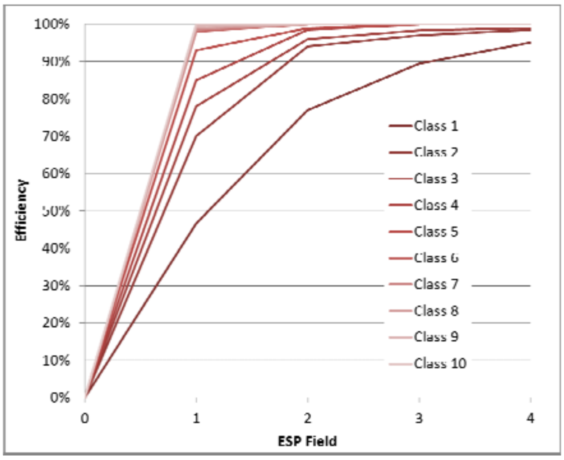


Figure 13: Efficiency of particle collection

4.2 Parameters affecting the production of unburned carbon in ash

The term "unburned carbon" refers to the unburned fraction of fuel, mainly composed of solid carbon in the ash. The unburned carbon content in the fly ash, is usually monitored since it may be an obstacle to upgrading the ash if it exceeds a threshold value (in general 5% or 7% wet, according to contracts signed with cement manufacturers).

Regarding electrostatic precipitator collection efficiency, these particles are easily collected but they are also easily re-entrained due to their low resistivity (about 10^6 Ohm.m). A low resistivity particle quickly transfers its charges to the collecting electrodes and so looses the force retaining it on the layer. Consequently, low holding forces allow unburned particle re-entrainment in the flue gas if they do not agglomerate with other particles. In the flue gas, the cycle of particle collection and re-entrained can be repeated a number of times and eventually the particle escape from the ESP. Re-entrainment also happens during rapping as unburned particles have a low cohesion. ESP manufacturers and users usually consider that precipitator efficiency is compromised when the "unburned carbon" is over 10%.

The most important parameters on the production of unburned carbon are:

- Coal ash content and reactivity of coke: they determine the carbon consumption kinetics during the combustion of coke.

- The fineness of milling: it tends to reduce the production of unburned carbon in ash. In fact, it is important to limit the proportion of "large" particles (> 150 microns)

- Burners and boiler design: they define coal-air mixing, temperature and particle residence time. If the temperature, the air excess or the particle residence time decreases, the combustion is less complete and the level of the unburned carbon in ash tends to increase.

5 SCR impact

Nowadays, coal power plants must observed more stringent regulations, including NOx production at stack. Consequently, the installation of de-NOx systems is increasingly common. The impact of SCR (Selective Catalytic Reduction) on the electrostatic precipitator performance can be summarise by three main points:

- Submicron particle formation,
- Particle cohesion increase,
- SO_3 production.

5.1 Creation of submicronic particles

Injection of NH_3 into the fumes in the presence of SO_3 can lead to the formation of submicronic particles of ammonium sulfates.

Particle formation due to chemical reaction between NH_3 and SO_3 species is a complex phenomena. According to Srivastava & al. [16], when the molar ratio between NH_3 and SO_3 is less than 1, ammonium bi-sulfate, NH_4SO_4, is created which promotes ash agglomeration. However, when the molar ratio between NH_3 and SO_3 is more than 1, there is an increase in the ammonium sulphate production, resulting in the creation of small particles.

Submicronic particle creation is a recognised problem arising when a SCR device is added in the flue gas path. SO_2 into SO_3 conversion level in the SCR is indeed a guaranteed value given by SCR manufacturers in order to lower submicron particle creation as well as the opacity increase due to SO_3 presence [17].

Fine particles increase the space charge load and translate the voltage-current curves of electrostatic precipitator. To maintain the same level of current as existed without the fine particles, the voltage must be increased.

In order to quantify the fine particle creation on ESP, simulations using ORCHIDEE were carried out.

With 10 ppm of NH_3 in the flue gas, the ammonia sulfate creation is estimated close to 30 mg/Nm^3. This value is compared to the 12 000 mg/Nm^3 of coal ash at the ESP inlet. However, as submicron particles are harder to collect, particle concentration at the ESP outlet can be slightly modified by such a small quantity of submicron particle coming from the SCR process.

Simulation on a 600 MW power plant while imposing no voltage variation to the power supplies, shows that particle concentration at the ESP outlet has changed from 13 mg/Nm^3 to 15 mg/Nm^3. Although the ultrafine particles do not significantly contribute to the mass based outlet emission of an ESP they might become more important if stricter regulations concerning PM2.5 (particle smaller than 2.5 micron) are imposed.

5.2 Cohesion

Depending on the H_2SO_4/NH_3 stoichiometric rates, ammonia can produce low melting point substances. Low stoichiometric rates produce substances with a high tendency to absorb humidity, promoting cohesion between particles.

To simplify the cohesion mechanisms, only the ammonium bisulfate was considered. As it has a melting point around 150°C, it is in a semi-liquid state at the typical operating temperatures of an electrostatic precipitator and therefore it acts as a particle-bonding agent.

Cohesion has a positive effect on the electrostatic precipitator efficiency by:

- Increasing the average particle size (the larger particles are easier to collect in the electrostatic precipitator)
- Reducing the re-release of particles on the plates.

In order to quantify the particle cohesion effect on ESP, simulation using ORCHIDEE software were carried out with the same configuration described in the annex. A 10 % decrease in re-entrainment parameter reduces particle concentration at the ESP outlet from 13 mg/Nm^3 to 10 mg/Nm^3.

5.3 SO_3 production

SO_3 content has a significant impact on particle resistivity, that is one of the main parameters in ESP collection efficiency. For high resistivity ash, SO_3 reduces the back-corona phenomena. But SO_3 is also the source of submicron particles, and the source of higher opacity level at the stack through the production H_2SO_4.

SO_3 production occurs inside the boiler and the SCR process, but the SO_3 quantity, in flue gas, changes along the path from furnace to the stack [18]. SO_3 concentration is modified from the boiler to the ESP: in the SCR if present, and in the regenerative air heater.

If the coal power plant is equipped with a SCR as de-NOx device, the SO_3 concentration in flue gas increases. Most commonly installed SCR installation actually produces SO_3 as a side-effect of de-NOx process. SO_3 production depends on SO_2 concentration, catalyst type and surface, flue gas temperature. SO_3 produced concentration is about some part per million but it is comparable to the SO_3 amount at the boiler outlet.

A third modification of SO_3 concentration occurs in the rotary regenerative air heater. Depending on the type of air heater, the coal type and the temperature, this device captures SO_3 at a rate ranging from 15% up to 70%.

SO_3 concentration variations in SCR and in regenerative air preheater suggest that most popular models for resistivity prediction have to be up-dated.

6 Conclusion

An acceptable dust level at the outlet of the ESP is primarily based on the electrofilter design that takes into consideration both the operating conditions of the plant and the quality of the burnt coal; and secondly, on regular maintenance.

The electrostatic precipitator, located at the end of the fumes circuit, is affected by external parameters such as: coal characteristics, combustion quality, denitrification performance and the state of the ducts.

Using an over 500 coal database, coal characteristics variations have been related to combustion, to ESP inlet particle properties and to ESP performances. Coal grinding and combustion management can change particle collection through variation in ash particle size and the level of unburned carbon. SCR device can create submicron particles, SO_3 molecules and can change particle cohesion.

This means that ESP performances are particularly sensitive to the coal quality. To anticipate any difficulties related to the latter, as grounds for refusing a supply, or to anticipate storage conditions for blending with a more favorable coal, coal ash resistivity is both evaluated with the level of dust at the outlet of the electrofilter.

The analysis has showed that in production, the operator can lower dust level at the ESP outlet by optimizing upstream processes (combustion & SCR) and by taking into account the quality of the burnt coal.

7 Literature

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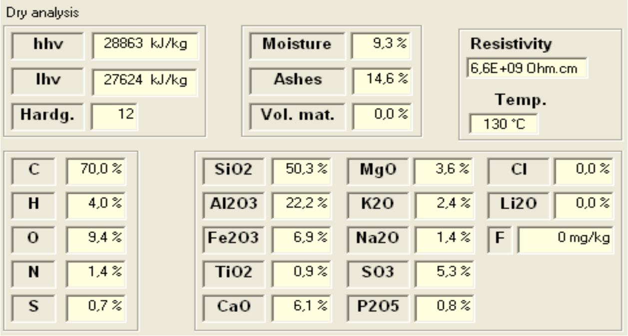
ANNEX 1: ESP of a 600 MW

The unit burns imported coal, with a rated output of 600 MWe. It is equipped with wet-flue gas desulphurisation downstream of the electrofilter. The electrostatic precipitator consists of two identical casings. Each casing contains 4 fields, with a plate-to-plate distance of 300 mm: four independent transformer-rectifier sets supply each field.

The reference ORCHIDEE configuration uses the following Polish coal



Dry analysis

hhv	28863 kJ/kg	Moisture	9,3 %	Resistivity
lhv	27624 kJ/kg	Ashes	14,6 %	6,6E+09 Ohm.cm
Hardg.	12	Vol. mat.	0,0 %	Temp. 130 °C

C	70,0 %	SiO2	50,3 %	MgO	3,6 %	Cl	0,0 %		
H	4,0 %	Al2O3	22,2 %	K2O	2,4 %	Li2O	0,0 %		
O	9,4 %	Fe2O3	6,9 %	Na2O	1,4 %	F	0 mg/kg		
N	1,4 %	TiO2	0,9 %	SO3	5,3 %				
S	0,7 %	CaO	6,1 %	P2O5	0,8 %				