ICESP X – Australia 2006
Paper 4B1

A FRIENDLY TOOL TO ASSIST PLANT OPERATORS AND DESIGN ENGINEERS TO CONTROL FLY ASH EMISSIONS: ORCHIDEE

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ABSTRACT

Either in the Operation Control Room, the Handling/Logistics Department, the Maintenance Department…or even in the Environmental Section, the operating personnel can contribute to control the dust emission of a power plant unit.

To satisfy current regulations, the efficiency of the electrostatic precipitator must always be mantained greater than 99.5%. These high performances require continuous control of the impact of possible malfunctions on the emission level, by adjusting the process conditions from the coal yard to the stack, including the electrostatic-precipitator itself.

To evaluate quickly the impact of coal characteristics, combustion parameters and electrical malfunctions on dust emission the operator can use a user-friendly software based on physical modelling of the dust collection process: ORCHIDEE. Without using experimental databases or manufacturer's empirical data, the operator becomes able to get a better real time understanding of the problems, and to react efficiently.

Version 2 of ORCHIDEE software offers additional functions, based on the non-linear coupling of different effects (ash layer chatacteristics, particles resistivity, current and voltage rapping processes, etc.)

By proper introduction of all input data, ORCHIDEE 2 makes possible:

- to evaluate the impact of combustion parameters on dust emission (excessive air-leakages, flue gas temperature at precipitator inlet).
- to test blending hypotheses of various types of coal to avoid back-corona.
- to evaluate the impact of rapping sequences or SO_3 injection on dust emission.
- to simulate electrical malfunctions: field or section out of service, wire and plate fouling, electrode misalignment, etc.
- to evaluate the impact of back-corona on precipitator efficiency and voltage-current characteristics.

Validated with industrial precipitators data, ORCHIDEE is a very helpful tool to assist operation and maintenance of electrostatic filters. It is unique for its high scientific content and its user-friendly interface, and it has already shown to fulfil the expectations of industrial users.

1. INTRODUCTION

In coal-fired power plants, the most diffused industrial devices for collecting the fly ashes produced by the combustion process, are electrostatic precipitators (ESP). This technique, born at the beginning of the 20th century, is now technologically mature. It has the advantage of inducing very low pressure drops in the flue gas circuit, and requires less maintenance than other filtration techniques. However, electrostatic precipitation is a process influenced by many parameters, particularly the physical and chemical nature of the fly ash, the flow rate and the composition of the flue gas, the electrical operating conditions, the rapping sequences, etc.

The operation and maintenance of an electrostatic precipitator may prove to be difficult because of the great number of physical processes involved: an electrostatic filter is in the same time a mechanical machine (rapping system, structure of the emitting wire and collection plates), an electrical machine (high voltage power supply, electrical discharge), a fluid-dynamic machine (flow distribution and regulation) and a "chemical machine" (ash characteristics and flue gas conditioning).

The individual physical phenomena which have to be taken into account in the simulation of an electrostatic precipitator are listed hereafter according to their sequential order:

1. Gas flow in the electrostatic precipitator,
2. Calculation of the electrical field between high voltage electrodes and grounded plates,
3. Production of ions at the wires by the corona discharges,
4. Migration of the negative ions from the ionisation region to the collecting plates,
5. Electrical charging of particles depending on their size distribution,
6. Particle migration under the action of electrical, viscous and gravitational forces,
7. Particle Collection onto the plate,
8. Evacuation of the particles into the hoppers.

Actual precipitators require an accurate control of all these physical processes and a deep understanding of their impact on the emissions levels.

Two distinct approaches are usually utilised to comply this goal. The Deutsch equation approach, mainly used by the ESP manufacturers, describes the process as a whole, based on substantial experimental database. The physical simulation approach, mainly adopted by university researchers, accurately describes all the physical phenomena with self-consistent mathematical models.

The two approaches are not really opposite to each other. There is a theoretical continuity between the most complex models and the simplified Deutsch's formula: by introducing appropriate simplifying hypotheses, it is possible to de-couple the various physical processes and to linearise the multi-dimensional equation system; then, step by step, it is possible to calculate averaging integrals over most of the independent variables, and to reduce the equation system to one single equation in one dimension (distance along the precipitator length): its integration over the whole precipitator leads to the Deutsch's formula. All the intermediate simplification steps may be assumed as successive approximation levels; each of them may be acceptable if the simplification level is suited to the specific application [1].

The ORCHIDEE package is based on an intermediate level of analysis adapted to the power plant operator's requirements, and implemented into the user-friendly simulation tool. In this paper we present its new functional developments, together with their practical validations. Finally, we will report some examples of its use to support decisions in the operation and maintenance of electrostatic filters.

2. A USER-FRIENDLY TOOL BASED ON PHYSICAL MODELLING

The objective of an electrical power producer is to dispose of a tool to improve the performances of the plant, and in particular of the electrostatic precipitators. That tool should make possible to follow the modifications of the plant operating conditions, to obtain real-time diagnosis of malfunctions, and rapid verifications of the possible alternative solutions. The main expectations of users regarding that tool are to the following ones:

- the use of the plant parameters to test operator or maintenance actions;
- the possibility of verifying changes in the design of the electrostatic precipitator;
- the computation velocity, for rapid scenario simulations and quick "what happens if" answers;
- the user-friendly interface of the tool;
- the possibility to be run on a Personnal Computer.

To meet these expectations, the tool should have an intermediate approximation level, containing sufficient physics to evaluate the impact of most of the ESP operating parameters: it should be a compromise between the time needed for numerical resolution and the details demanded for the description of the physical processes.

After a deep examination of the different complete models simulating ESP operation, and after a validation test on an industrial unit [8], EDF and IRS (Ingegneria Ricerca Sistemi) decided to develop jointly a code on PC, retaining the physical description of the process, but requiring only a few minutes of calculation, based on the IRS - SPES simulation code [2-7].

In order to reach computation times adequate to power plant applications a procedure was developed to separate the detailed calculations based on the physical modelling, from the instantaneous prediction of the collection efficiency in the power plant. This procedure is twofold:

- preliminarily, a parameter-based variational analysis (Calibration) of the ESP model results is carried out, for the main parameters of the electrostatic precipitator: flue gas velocity, applied voltage, and particle size; this analysis is extended over the whole range that the parameters may assume under usual operating conditions.
- then a multidimensional non-linear interpolation algorithm is applied, to obtain collection efficiency predictions. The interpolation can be realized at level of single elements (cells, slabs or ducts): the overall ESP performances are derived by combining the efficiency of each cell, taking into account the local conditions (flow velocity, applied voltage, particle size distribution).

The interpolation algorithm realizes instantaneous calculations of efficiency, within the parameter range covered by the Calibration step. The accuracy of the interpolated particle concentration values with respect to the full model predictions is always better than 10 % for cells located at the field centre, but may admittedly reach 20 % at the field border.

With the ORCHIDEE software (French acronym for Efficiency Optimisation of Coal Ash Collection in Electrostatic Precipitators), an intermediate approach is proposed, based on physical modelling of the collection process [11]. This approach enables to estimate the efficiency of an electrostatic precipitator without using an experimental database, and without depending on manufacturer's empirical data.

ORCHIDEE is a stand-alone simulation tool, that makes possible to estimate the dust emissions at the stack of a power plant. It is at the moment not connected to any one-line data acquisition system of the plant. It is equipped with a user-friendly interface, with pop-up menus, dialog boxes, buttons, etc., which allows to use the software quickly and easily (

Figure ***1***).

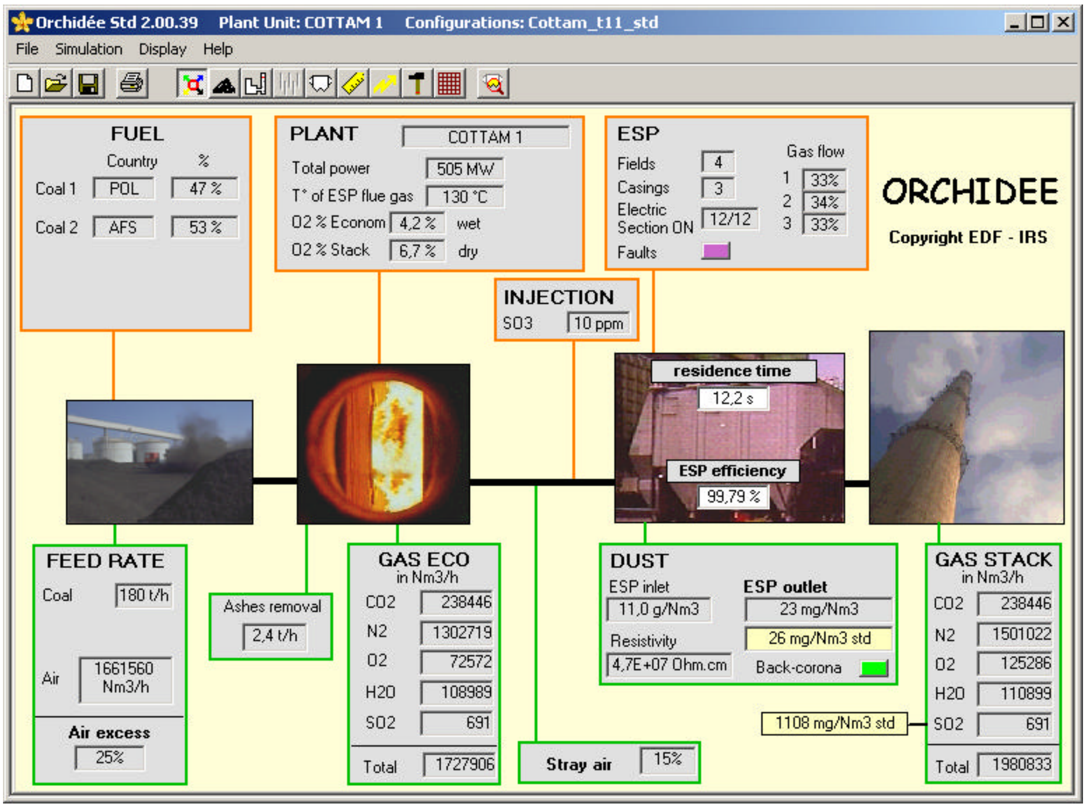

Figure 1: Main screen of ORCHIDEE software

The operator is then able to get a better real time understanding of the possible problems, and hence can react efficiently. By introducing properly all input data, ORCHIDEE made possible:

- ➢ to evaluate the impact of combustion parameters on dust emission rapidly (excessive air leakages, flue gas temperature at the precipitator inlet).
- ➢ to test blending hypotheses of various types of coal to avoid back-corona.
- ➢ to evaluate the impact of unfavourable distribution of the flue gas at the precipitator inlet.
- ➢ to simulate electrical malfunctions: field or section out of service.

3. NEW FUNCTIONS

In version 2 the ORCHIDEE software has been enhanced with new functional features, in order to represent a wide range of thermal plants (including prefiltration and SO_3 flue gas conditioning), to assist in the optimisation of the rapping sequences and in the interpretation of the current-voltage curves.

3.1 Pre-filtering module

The use of mechanical filters, most often cyclones, to decrease the inlet dust concentration before the electrofilter is not systematic. The modelling of the cyclones is difficult due to the variety of technologies and configurations encountered; consequently two different approaches have been implemented in ORCHIDEE 2:

Zenz model: based on the calculation of particle dwell times in the cyclone, this model establishes a correlation between the geometry of the cyclone and the cut-off diameter, taking into consideration the gas velocity. This correlation can be applied only to cyclones that respect accurate sizing rules, in particular the condition of tangential gas flow.

Fixed Yield model: for the cases where the Zenz model cannot be applied, a semiempirical fixed yield model has been has been introduced. This enables the user to apply to each particle size class, yields derived from the manufacturer manual or from in situ measurements.

3.2 SO_3 injection module

SO_3 is usually injected upstream to the electrofilter and is adsorbed after condensation on the ash particles; this phenomenon occurs merely at low temperature (where condensation may occur). SO_3 injection is often used to compensate the low sulphur content or the lack in the coal of other alkali elements that contribute to decrease the ash resistivity.

The resistivity model used in ORCHIDEE 2 is based on that proposed by Bickelhaupt [12], [13]. It has been improved to manage the discontinuities encountered in the initial model and to extend the interpolation ranges. Accordingly, the concentration of injected SO_3 is added to that previously calculated for the composition of the flue gas in the combustion chamber.

3.3 Dust layer module

Mathematical models of the physical phenomena related to the basic steps in dust capture (gas flow, corona discharge, ion production and migration, particle charging and migration) are widely described in the literature and have been accurately implemented in ORCHIDEE 1. However, the knowledge about the processes within the dust layer once deposited is very poor; the information on layer dynamics and rapping rate effects on the emission levels derives mainly from empirical manufacturer know-how. No scientific quantitative data and models about these physical phenomena were available until the experiments performed on an industrial pilot as part of the ABRICOS European project [14]. The different effects on and within the dust layer have been quantified (mass balance, particle re-entrainment, dust sliding over the collecting plates, effect of back-discharges, etc). The coupling of EDF and IRS theoretical studies with the pilot experiments performed within that project has resulted in the definition of a straightforward model about layer dynamic evolution.

In order to take into account the influence of the dust layer on the efficiency of an electrofilter, the ORCHIDEE model simulates the non-linear coupling between the thickness

of the layer, the resistivity of the particles, the electrostatic pressure, the vertical stability of the layer, and the possible presence of back-corona [9, 10].
The thickness of the dust layer deposited on the plate is estimated taking into consideration two phenomena (Figure 2) [15]:

- a continuous process of increase of the layer thickness due to the balance between the particle deposition flow Φ_p (according to the physical and electrical parameters within the precipitator), the particle re-entrainment flow Φ_r, produced by fluid-dynamic erosion, particle impact and ionic wind, and the vertical layer sliding on the plate surface Φ_h [14].

- a discontinuous process of layer modification due to the rapping impact: a block of dust is instantaneously detached from the plates; a fraction of it is evacuated towards the hoppers M_{hr}; however, under the effect of the electric field, part of it is re-collected on the plates while the rest is released again into the gas flow M_{rr} [15].

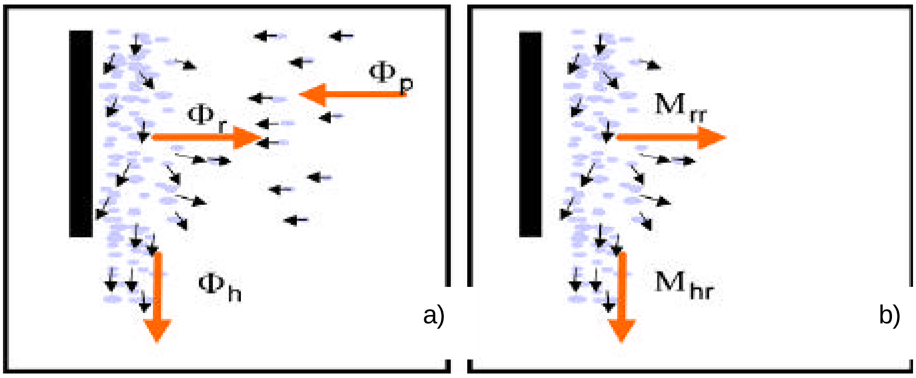

Figure 2: Schematic representation of the dust layer dynamics: a) continuous mass flow; b) instantaneous mass transfer during rapping.

3.4 Back Corona module

For high resistivity ash, two different electrical effects occurring into the deposited dust layer have to be taken into consideration (Figure 3):

- the resistance of the particle layer produces a potential drop (V_c) across the layer itself, which decreases the voltage across the gap (V_d). This last one sustains the corona discharge.

- depending on the fly ash characteristics, a back-corona effect may occur. It takes place when micro-discharges appear within the dust layer deposited on the plates; these discharges create positive ions moving into the electric field towards the emitting wires. The back-corona current (J_{CE}) adds to the glow corona current (J), because the positive and negative ions move in opposite directions. However, the corresponding positive and negative space charges cancel each other, leading to lower particle charging rates and therefore to lower collection efficiencies.

These electrical effects are represented hereafter in an equivalent electrical circuit [16]: both current J and J_{CE} are non linearly related to the corresponding voltages V_d and V_c. After the solution of the non-linear equation system of the equivalent circuit, the back corona module estimates the variation of the collection efficiency according to the variation of the net space charge, and of the corresponding particle charging rate.

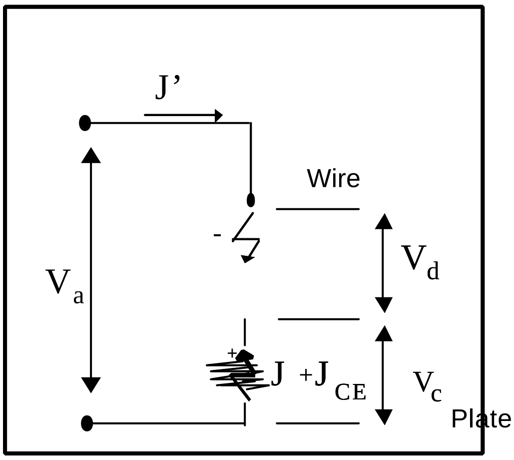

Figure 3: Equivalent electrical circuit of an electrofilter including the layer voltage drop and the back-corona current

3.5 Precipitator fault module

Most of the electrical and mechanical failures in a precipitator would affect both the collection efficiency and the Voltage-Current characteristics. The major faults have been introduced into the ORCHIDEE 2 simulation:

- wire or plate fouling;
- wire to plate misalignment;
- High voltage insulators surface currents.

The operator can use this model facility either to analyse the precipitator performances in presence of an identified fault, or to identify an unknown fault by comparing the actual V-I characteristics with the predicted ones.

3.6 Non-linear process coupling

All the new modules have been assembled around the original core of ORCHIDEE 1 (Figure 4), in order to evaluate their impact on the dust emission. Due to the non-linearity of the system, the precipitator efficiency is estimated with a main loop calculation (red arrows in Figure 4) until convergence of the solutions is obtained.

The physical modelling method used in ORCHIDEE 2 makes therefore possible to estimate instantly and quantitatively the impact on efficiency of the real operating conditions of the electrofilter, including flue gas conditioning, fouling of wires or plates, rapping frequencies, back corona, and mechanical and electrical failures.

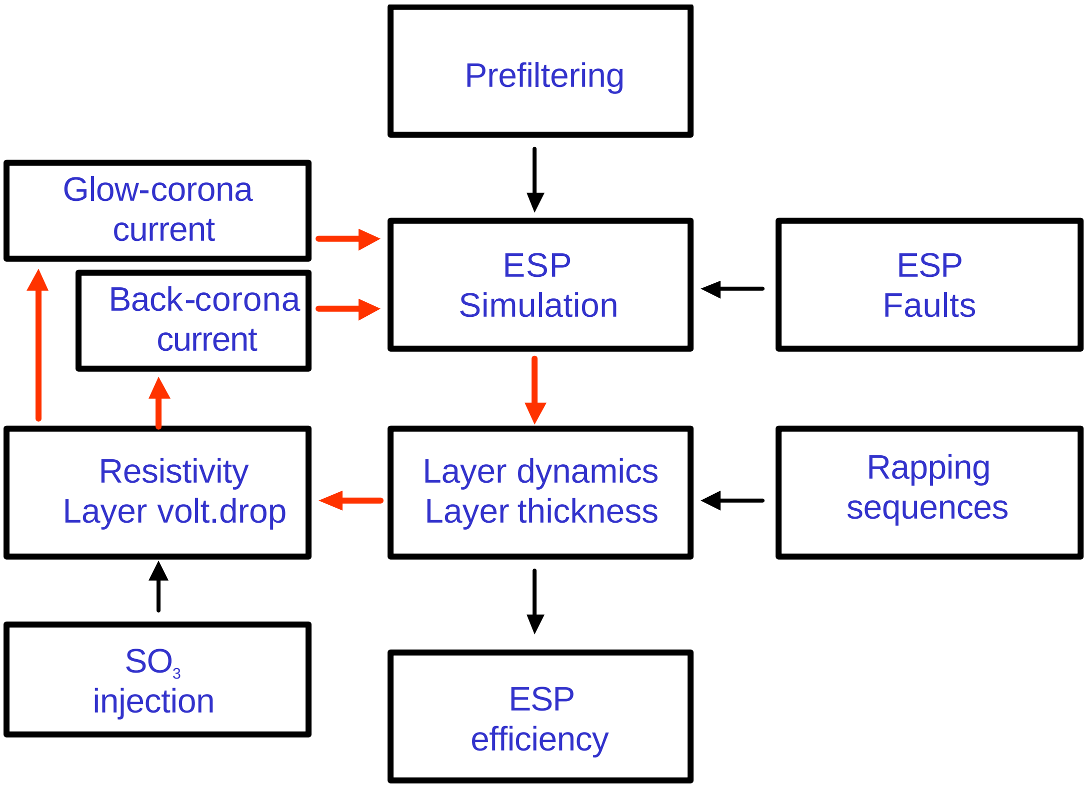

Figure 4: Non-linear coupling between the different physical process in ORCHIDEE 2.

4. COMPARISON WITH LITERATURE AND INDUSTRIAL DATA

4.1 SO_3 injection

The effect of SO_3 injection on dust resistivity has been validated with data available in the literature. Table 1 shows the coal and ash analytical data used for the resistivity calculations.

Figure ***5*** shows the results obtained with the ORCHIDEE simulation code, compared with the results reported by Bickelhaupt [13]. In ORCHIDEE, the SO_3 injected is added to the SO_3 produced during the combustion. The Figure 6 show the quality of correspondence.

Coal	Ash analysis
Humidity : 5,0% On dry: C : 65% H : 4% 0 : 9,3 % N : 1,0% S : 0,7% Ash : 15%	Li2O : 0,04 Na2O : 0,47% K2O : 2,73 MgO : 0,81% CaO : 2,83% Fe2O3 : 9,1% Al2O3 : 26,29% Si02 :54,4% Ti02 : 1,82% P2O5 : 0,51% SO3 : 1,01%

Table 1: Coal and ash analytical data used in the resistivity calculations.

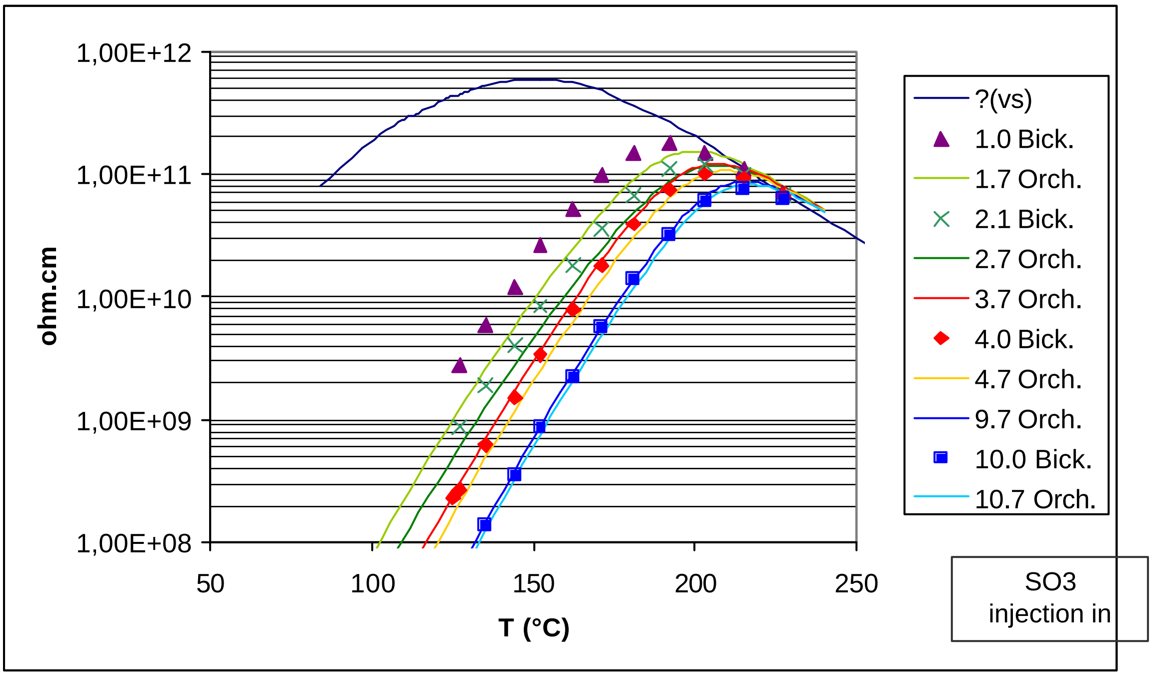

Figure 5: Comparison of the ash resistivity obtained by Bickelhaupt [13] and by ORCHIDEE 2.

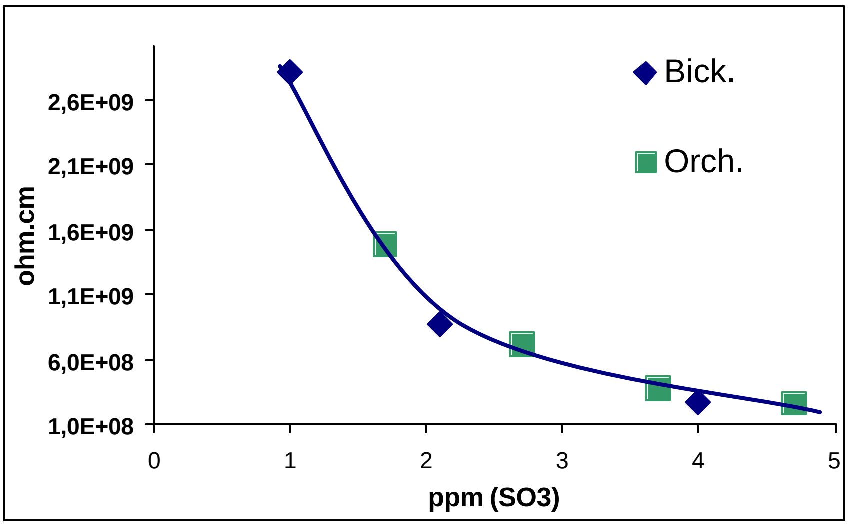

Figure 6: Evolution of the ash resistivity obtained by Bickelhaupt [13] and by ORCHIDEE 2 with SO3 injection at 130°C .

The effect of SO_3 injection on precipitator efficiency has been validated with the data collected in the electrostatic precipitators of two different industrial sites:

1) <u>Unit 4 at Le Havre Power Plant (France)</u>:
The 600 MW coal fired unit is equipped with a Lurgi electrofilter with 2 casings; each casing is made by 4 fields. A new SO_3 injection system makes possible to burn high resistivity coal. The acceptance tests have supplied a complete set of data for testing the ORCHIDEE software. The test conditions and the coal and ash characteristics are listed in Tables 2 and 3.

These data have been loaded into the ORCHIDEE DataBase (including the out uf service of a few sections, and the flow un-balance between the two casings – 45 to 55 %). Without SO_3 injection this coal would have given rise to an ash resistivity of 2 10^{11} Ω.cm, and to a dust emission much higher then the prescribed limit of 50 mg/Nm3. With 15 ppm of SO_3 injection, the dust emissions simulated by the ORCHIDEE software are around 28 mg/Nm3, while the measured ones over a period of four hours are 32 mg/Nm3. The agreement is within the measurement error.

2) <u>Unit 1 at Cottam Power Plant (Great Britain)</u>:
The 500 MW coal fired unit is equipped with a 3 casing electrofilter; each casing is divided in 4 fields. The test conditions and the coal and ash characteristics are listed in Tables 2 and 3.

These data have been loaded into the ORCHIDEE DataBase. Without SO_3 injection this coal from South of Africa would have given rise to an ash resistivity of 6.4 10^{10} Ω.cm and to a dust emission around 260 mg/Nm3. With 11.6 ppm of SO_3 injection, the dust emissions simulated by the ORCHIDEE software are around 36 mg/Nm3, while the measured ones are 38 mg/Nm3. Also in this case the agreement is within the measurement error.

	Le Havre 4	Cottam
Coal (on dry)	South Africa	South Africa
PCS (kJ/kg)	28424	28156
PCI (kJ/kg)	27546	27446
C %	73,24	70,5
H %	4,13	3,9
0 %	5,81	7,6
N %	1,64	1,8
S %	0,56	0,64
Humidity	7,0	3,3
Ash	14,62	15,7
Ash analysis		
Na_2O %	0.08	0,2
K_2O %	0.74	0,5
MgO %	1.56	1,7
CaO %	7.52	8,4
Fe_2O_3 %	3.64	3,7
Al_2O_3 %	28.6	29,6
$Si0_2$ %	51.29	47,2
Ti02 %	1.56	1,5
P_2O_5 %	1.58	2,1
SO_3 %	1.86	5,2

Table 2: Coal and ash analyitical data during Power Plant tests

	Le Havre 4	Cottam 1
Date	13 January 2006	7 February 2005
Load	580 MW	505 MW
O_2 economiser	3,6% on wet	4,3% on wet
O_2 stack	7,9% on dry	6,6% on dry
ESP inlet temperature	130°C	126°C
SO_3 injection	15 ppm	11,6 ppm
Particles Emission level	32 mg/Nm^3 (on dry at 6% O_2)	38 mg/Nm^3 (on dry at 6% O_2)
Simulation	28 mg/Nm^3 (on dry at 6% O_2)	36 mg/Nm^3 (on dry at 6% O_2)

Table 3: Power Plant operating conditions during the tests

4.2 Influence of rapping sequences

The effect of the variations of the rapping sequences has been tested on the electrofilter installed at Cottam Power plant on Unit 1. With respect to the usual rapping sequence, the rapping motor pause times have been multiplied by 2 (slow rapping) or divided (fast rapping) by 2.

The observed emission values for usual rapping rate were 27 mg/Nm^3 (on dry at 6% O_2) compared with 25 obtained by the ORCHIDEE simulations. Both, faster and slower rapping caused an increase in the emission level (Figure 7).

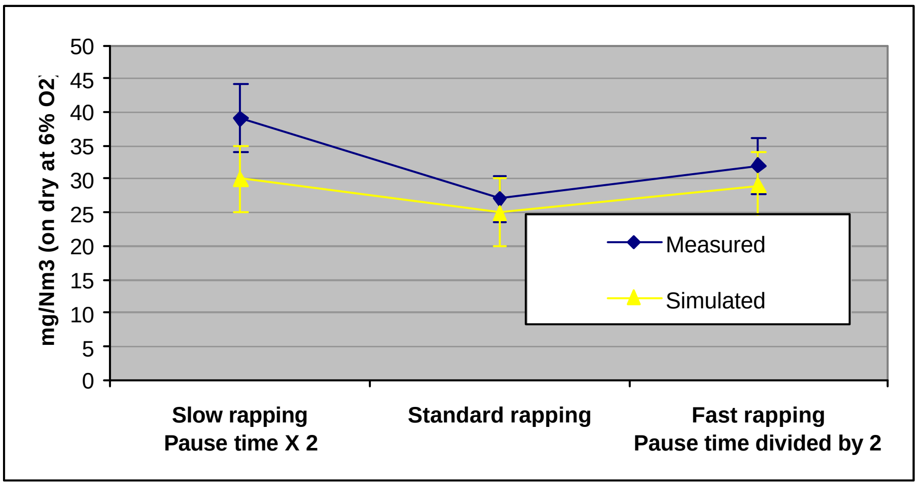

Figure 7: Experimental and simulated dust emissions at Cottam Unit 1 electrofilter as functions of the rapping frequency

4.3 Influence of observed failures on V-I curves

In the electrofilter of Unit 5 of the Cordemais Power Plant, sets of current-voltage curves were determined, using direct oscilloscope measurements. The analysis of the curves was followed by internal inspection of the filter casing, is a mean to link observed defects to the curve characteristics.

Figure ***8*** reports a few records of the current-voltage characteristics for different sections of field 2, together with the curves simulated by ORCHIDEE. In the field section 221 a strong electrode fouling was observed, wich resulted in the offsetting of the corresponding voltage-current curve to the lover current values.

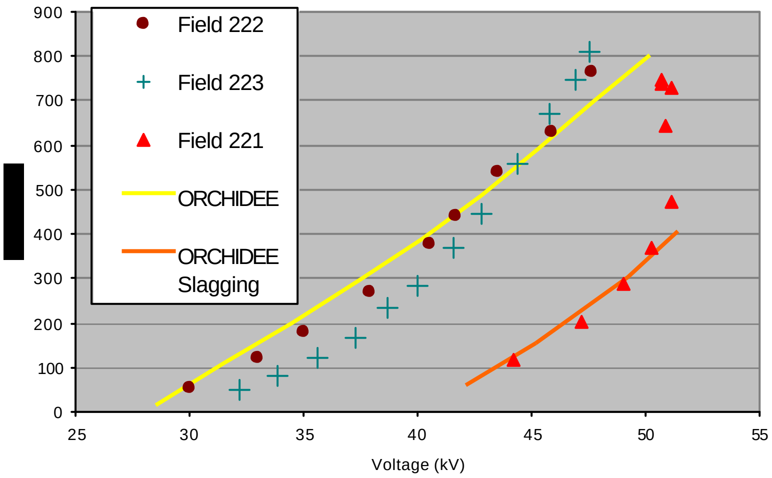

Figure 8: Experimental current-voltage curves for sections of field 2 in Cordemais Unit 5 (15 April 2004), together with the curves simulated by ORCHIDEE.

5. CONCLUSIONS: A USEFUL TOOL TO IMPROVE ESP PERFORMANCES

The actions for the control of dust emissions do not only concern the electrofilter but all the process, from the coal yard to the stack. If the electrofilter is properly maintained, the control of dust emissions may be based on a few simple actions: the control of the gas flow rate and temperature (sealing of any stray air inlets, maintaining air heaters, limiting the combustion excess air, etc.); the control of the electrical performances of the power supplies, to identify eventual failures or trend deviations from the optimal conditions; the control of back-corona effect (burning appropriate coal mixtures regarding resistivity, injection of SO_3, proper regulation of electrical power supplies); the control of the efficiency of the rapping system, to avoid electrode fouling.

All these simple actions can be simulated quantitatively with the ORCHIDEE software. Combined with a minimum maintenance cost, these actions would make possible to avoid expensive load reductions, and expensive renovations, simply by optimising the entire process from combustion to stack emissions.

The ORCHIDEE software has been extensively used in a number of the EDF thermal plants in France. The feedback has shown that the power plant operators have been able to get a better understanding of the problems, and to react efficiently in real time. With the proper data in the Coal and ESP data -bases, ORCHIDEE has made possible:

- to evaluate rapidly the impact of the combustion parameters on dust emission (excess of combustion air, high gas temperature, etc.);
- to verify blending hypotheses of various coal to avoid back-corona;
- to evaluate the impact of unfavourable flue gas distributions in the electrostatic precipitator;
- to simulate electrical malfunctions(a field or a section out of service);

For instance, at the Cordemais Power Station, equipped with two 600 MW units, the possibilities of coal blending have enabled the personnel to use coals with different characteristics (sulphur, sodium…), constantly maintaining medium resistivity fly ash, that does not start back-corona. Combined with the control of the flue gas flow at the inlet of the electro-filter, this strategy has enabled the power station to avoid the reduction of not to be obliged to reduce load because of excessive dust emissions, for the last 3 years.

To be able to burn the cheapest coal on the market, when the site does not have blending possibilities, in injecting SO_3 upstream from the electrofilter. ORCHIDEE can hence be used as a tool to optimise the amount of SO_3 injected according to the risk of back-corona. In addition to the economic aspect, this optimisation avoids the fouling of the electrofilter often observed when excessive injection of SO_3 takes place.

The utilization of ORCHIDEE gives advantages also to other plant Departments: the Maintenance Department can optimise its actions by evaluating in advance the impact of ESP abnormal operating conditions (cut wires, plates and wires fouling, insulators leakages, non uniform flue gas distribution, etc.); the Technical Department can make a better assessment of slow drift observed in operation; the Engineering Department can evaluate renovation strategies, by checking the effect of changes in internal components (height, plate-to-plate distance, type of wires), of changes in the electrical power supplies, of the addition of a new field.

ACKNOWLEDGEMENTS
The authors wish to thank the power plant personnel and the colleagues, for the active participation in the design, realization, validation and use of the ORCHIDEE software.

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