ORCHIDEE: Efficiency Optimisation of Coal Ash Collection in Electrostatic Precipitators

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Abstract

In a coal thermal power plant, one of the industrial solutions for collecting the fly ashes produced during the combustion process, is the electrostatic precipitation. However, electrostatic precipitation is a process affected by many parameters, in particular the physical and chemical nature of the ash, the flow rate and composition of the flue gas. In addition, the operation and the maintenance of an electrostatic precipitator may prove to be difficult on account of the great number of physical processes concerned.

To satisfy current regulations, the efficiency of the electrostatic precipitator must always be greater than 99.5%. To sustain these high performances requires good control of the impact of various malfunctions on the level of emissions. For that, two distinct approaches can be described. The first, influenced by the problems the ESP manufacturers, describes the process as a whole and requires a substantial experimental database. The second, influenced by research in universities, accurately describes the physical phenomena.

With the ORCHIDEE software, an intermediate approach is proposed, based on physical modelling of the collection process. This approach enables to estimate the efficiency of an electrostatic precipitator without using an experimental database, and to be independent on manufacturer's empirical data. The operator is then able to have a better real time understanding of the problems, and to react efficiently. By introducing properly all input data, ORCHIDEE makes it possible:

- to evaluate the impact of combustion parameters on dust emission rapidly (too much air inleakages, flue gas temperature too high in the electrostatic precipitator).
- to test the hypotheses of blending types of coal to avoid back-corona.
- to evaluate the impact of unfavourable distribution of the flue gas in the electrostatic precipitator.
- to simulate electrical malfunctions: a field or section out of service.

The Maintenance Department can optimise its actions. The Technical Department can make a better assessment of slow drift in operation. The Engineering Department can better appreciate actions for renovation, as the ORCHIDEE physical model makes possible to verify the effect of changes in internal components (height, plate-to-plate distance, and type of wires), changes in the electrical power supplies, the addition of a new field, for both existing units to be retrofitted, and for new units that to be designed.

ORCHIDEE is a tool to assist operation and maintenance of electrostatic filters, that is unique for its high scientific content and its user-friendly interface: it has shown to fulfil the expectations of its users.

1 Introduction

In coal thermal power plants, the most diffused of the industrial solutions for collection of the fly ashes produced by the combustion process, is electrostatic precipitation (ESP). This technique is technologically mature, and dates from the beginning of the 20th century; it has the advantage of causing only very low pressure drops in the flue gas circuit, and requires less maintenance than other filtration techniques. However, electrostatic precipitation is a process affected by many parameters; in particular the physical and chemical nature of the ash, the flow rate, and the composition of the flue gas have great influence.

The operation and the maintenance of an electrostatic precipitator may prove to be difficult on account of the great number of physical processes concerned: an electrostatic filter is at 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 fluido-dynamic machine (flow distribution and regulation) and a "chemical machine" (ash characteristics and flue gas conditioning).

Actual precipitators require a good control of all the physical processes and of the impact of various malfunctions on the level of emissions. For that two distinct approaches are usually utilized. The Deutsch approach, influenced by the problems of ESP manufacturers, describes the process as a whole, based on substantial experimental database. The physical simulation approach, influenced by research in universities, accurately describes the physical phenomena with self-consistent mathematical models.

After having presented the potential uses of these two approaches and their limits, we describe an intermediate level of analysis adapted to the power plant operator's requirements. Finally we present ORCHIDEE, an user-friendly simulation tool developed to support decisions in the operation and maintenance of electrostatic filters.

2 Two extreme approaches

2.1 Deutsch's law: simple but restricted in use

On the macroscopic scale, the electrostatic filter is considered as a “black” box. The input data can be linked to the output data by a transfer function that covers the whole ash collection process.

The most widespread approach, in particular among ESP suppliers, is that known as Deutsch's law. This law expresses the efficiency of an electrostatic precipitator as a function of three variables: the Collecting Area A of the collecting plates, the flue gas flow rate, Q and a parameter ω, with a velocity dimension, called "migration velocity", which summarizes all the physical phenomena:

$$\eta = 1 - e^{-A * \omega / Q}$$ *Equation 1*

The migration velocity is a “overall” semi-empirical parameter, that can be deduced simply and quickly from on line or test measurements: concentration at inlet C_{in} and outlet C_{out} , and flue gas flow rate Q. Knowing the electrostatic filter collection specific area A, the associated migration velocity is obtained by inverting Deutsch's law.

However, the migration velocity depends on many parameters, as the characteristics of the fly ash (chemical composition, resistivity, size, density), the characteristics of the gas (composition, pressure, temperature), the ESP design (geometry of the emitting wires, distance between the collecting plates), etc.

Deutsch's law has the advantage of producing correct result by using a pocket calculator, when the flow rate of the flue gas in a defined electrostatic precipitator is changed. However, the area of validity of this migration velocity is not known, and even less is known its behaviour when the operating conditions of the electrostatic precipitator vary (change of coal, clogging or misalignment of wires, etc.), unless correlations have been made for the various possible conditions. Although this know-how is generally available to the suppliers, electrical power producers rarely have it.

2.2 Physical Simulation: accurate but expensive in computer resources

The principle of electrostatic precipitation is relatively simple: the flue gas to be cleaned is passed into ducts, where small radius wires at high negative voltage (from 40 to 80 kV) are placed in front of grounded plates; the intense electric field generates corona discharges near the wires and ionises the flue gas; the ion charges move under the action of the local electric field, and attach to the surface of the fly ash particles; in turn, the charged particles migrate in the electric field, and are collected on the plates; the collected dust layer is then evacuated into the hoppers by plate rapping.

In order to estimate the efficiency of an electrostatic precipitator, models may be used: they describe in details the physical phenomena, right down to the molecular level. The geometry of the electrostatic precipitator, the path followed by the flue gas and the particles are accurately described. The collection process is described taking into account six dimensions: (Figure 1):

- Space ($\mathbf{x_1, x_2, x_3}$): to account for spatial distributions of ions and particles,
- Time (**t**): to calculate the dynamics of the different physical processes,
- Particle size ($\mathbf{r_i}$): to account for the dependence of particle charging and transport upon their mass,
- Particle charge ($\mathbf{q_k}$): to calculate the dynamic charge transfer from ions to particles.

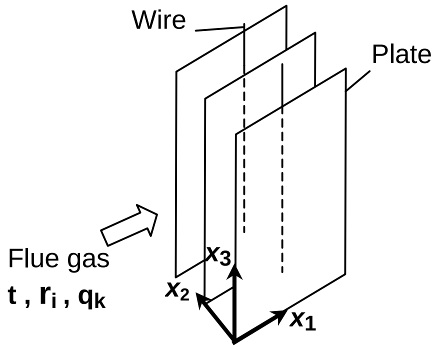


***Figure 1**: Six dimensional representation of ESP*

Physical modelling consists of expressing each of the stages described above as equations and solving these differential equations in a coupled manner:

1. Gas flow in the electrostatic precipitator
2. Calculation of the electric 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. Electric charging particles depending of their size distribution
6. Particle migration under the action of electric, viscous and gravitational forces
7. Particle Collection on the plate
8. Evacuation of the particles into the hoppers

As may be observed, these different points cover several different scientific fields: fluid mechanics, electrostatics, plasma physics, classical mechanics, structural mechanics, inorganic chemistry.

The coupling between electrical phenomena, turbulent gas flow, charged particle transport and space charge effects make the resulting set of equations strongly non-linear. Therefore it needs sophisticated numerical methods to obtain reasonably accurate solutions, with a high cost in terms of memory allocation and computation time.

In spite of the numerical difficulties (non linear coupled equation sets to be solved in a six-dimensional space) and the computation costs (memory allocation and computation time), the basic principle of this approach is that the more detailed the model is, the more general and accurate the results will be. Therefore, it offers many advantages:

- Reduced experimental data required to obtain the collection efficiency,
- Deep understanding of the physical processes affecting the efficiency,
- Flexibility of modification of the operating conditions,
- Access to a large amount of rarely available data, such as dust resistivity, particle size distribution, etc., that make possible a variational analysis of the physical parameters.

However, the six-dimensional non-linear calculations need very long computer time to converge to acceptable solutions, even for "supercomputers": much too long for "real-time" applications in the control room of power plants.

3 A level of analysis designed for plant operators and engineers

Although Deutsch's law, together with the long term experience of the ESP manufacturers, makes possible to dimension new installations, it proves much more limited to forecast the operation of an existing installation, to understand the origin of possible malfunctioning, and to plan the maintenance actions. In fact, this law assumes ideal functional conditions that may be different in real operation (non-uniform gas velocity, variable temperature, aging of the equipment, etc.), and it does not give access to the physical variables necessary to understand the basic physical processes inside the ESP.

Modelling the physical phenomena at molecular scale, taking all the dimensions into account (space, time, particle size and charge distributions), requires considerable computer and human resources, but it can answer to most of the questions of ESP operation and maintenance.

The two approaches are not really in opposition 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 physical processes and to linearise the six-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 dimension (distance x1 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].

For an electrical power producer, the objective is to dispose of a tool to improve the performances of his 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 future users regarding that tool are related to:

- 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 calculation velocity, for rapid “what - if” answers;
- the user-friendly interface of the tool;
- the possibility to be executed on a PC.

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 for numerical resolution and the details for the description of the physical processes.

4 Design of an industrial tool

4.1 Simplification method

The coupling between the electrical phenomena and the flow of the medium is a sensitive area. In fact, the gas is ionised under the action of the corona discharge. It is therefore subjected to the electric field effect and produces an ionic wind to which submicronic particles are highly sensitive.

The coupling between turbulent fluid mechanics and electrostatics, known as electrohydrodynamics, is possible only on very powerful computers and leads to very considerable calculation times to solve the equations. It is therefore not possible to envisage using this to resolve an operational problem.

In spite of this decoupling, the model still has 6 dimensions: the 3 dimensions of space, time, the charge and the particle size distribution. To simplify, we propose that two hypotheses be accepted. The first concerns the absence of interaction in the vertical direction (x_3). In fact gravity is negligible in relation to the other forces, the velocity of the gas stream has no vertical component, which does not mean that the velocity is uniform; the discharge electrodes are identical in the vertical direction; and diffusion is negligible in this direction. The phenomena can then be described in 2 dimensions in a horizontal plane.

The second hypothesis concerns the charging of the particles. At a fixed point, at a given time, all the particles of one same size have approximately the same charge. In other words, the particles that are not charged at the inlet of the electrostatic filter have practically the same history. The distribution of the charge is close to a Dirac law.

To pursue the simplification and reach Deutsch's law (1-D), it would be necessary on the one hand to assume that the electric field is uniform in the space between wire and plate and on the other hand that the particle density is uniform in the direction x_2. We felt that these last two hypotheses were excessive, so we decided to develop a simplified 4-D tool: space in 2 dimensions, time, and particle size distribution.

4.2 An industrial code

After a deep examination of the different complete models simulating ESP operation, and after a validation test on an industrial unit [6], EDF proposed to IRS (Ingegneria Ricerca Sistemi) 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 [2-5]. The original complete SPES code was developed by IRS for scientific purposes during a long-term collaboration with ENEL, and required several tens of hours of calculation for a case study.

The original model has 6 dimensions (the 3 dimensions of space, time, the charge and the particle size distribution). And its flow chart is given in Figure 2.

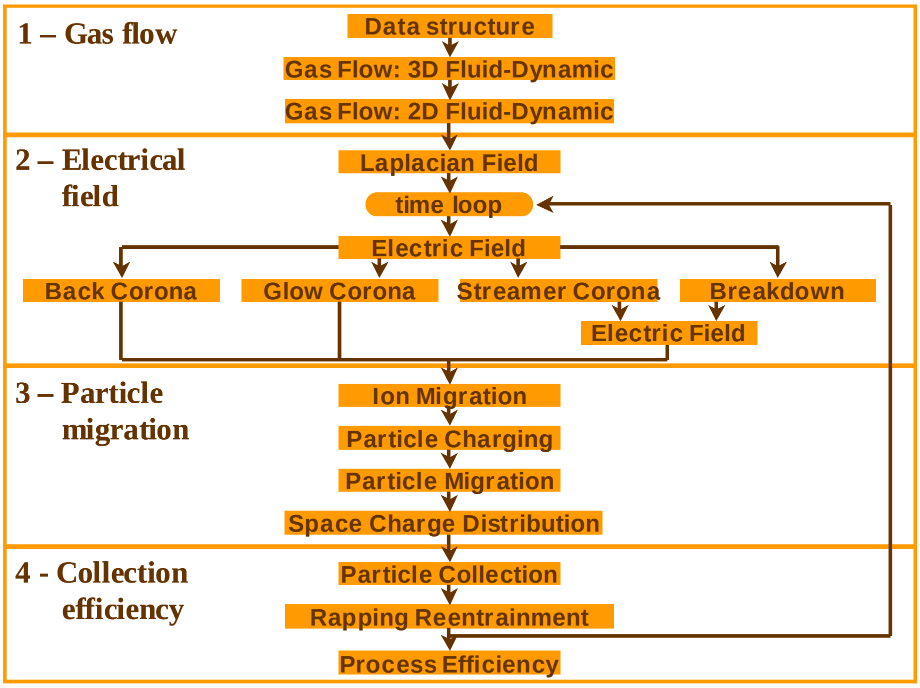


***Figure 2**: Flow chart of the ESP model*

For the first simplified assumption the ESP ducts are subdivided into parallel “slabs” and “elementary cells” (Figure 3): as gravity is negligible with respect to other forces, it is assumed that there is no interaction between slabs in the vertical direction (x_3); as turbulent re-circulations are limited, backward interactions between cells in the flow direction (x_1) are neglected; therefore, the electrical and transport equations may be solved in two dimensions on horizontal planes, in a simple forward integration scheme. In fact, the vertical transport of gas and particles is re-introduced simply as boundary conditions between slabs.

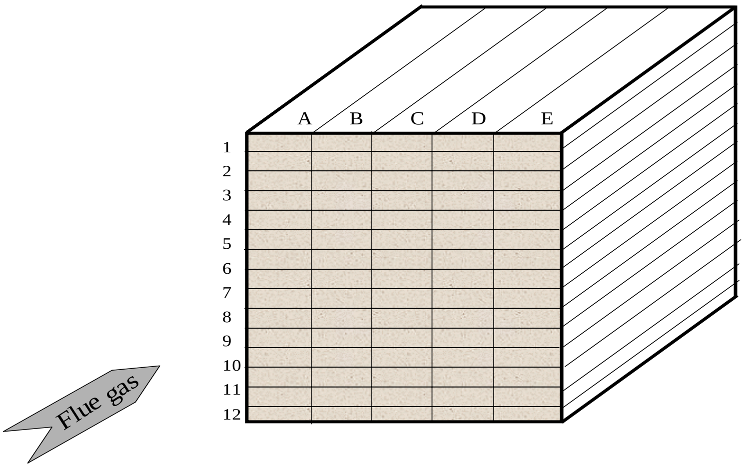


***Figure 3** : Example of subdivision of ESP into 60 channels for a simulation*

The next assumption fixes the charging laws of the particles: at a given position and time, all the particles of the same size are charged at the same value; the particle charge is no more an independent variable, but can be calculated as a local state variable.

The model has been therefore simplified to four dimensions: 2 in space, time, and particle size. Considerable work was undertaken to linearise the equations and to reduce the computation resources: in particular, the number of equations to be solved has been minimized, and the numerical algorithms have been optimised to increase the time step**.** By these means, the calculation time on a PC has been reduced from tens of hours to tens of minutes, still maintaining a detailed description of the ESP physical processes. This simplified code has been considered quite satisfactory for engineering design; however, the computation time has been still considered too long for real-time applications in a power plant control room.

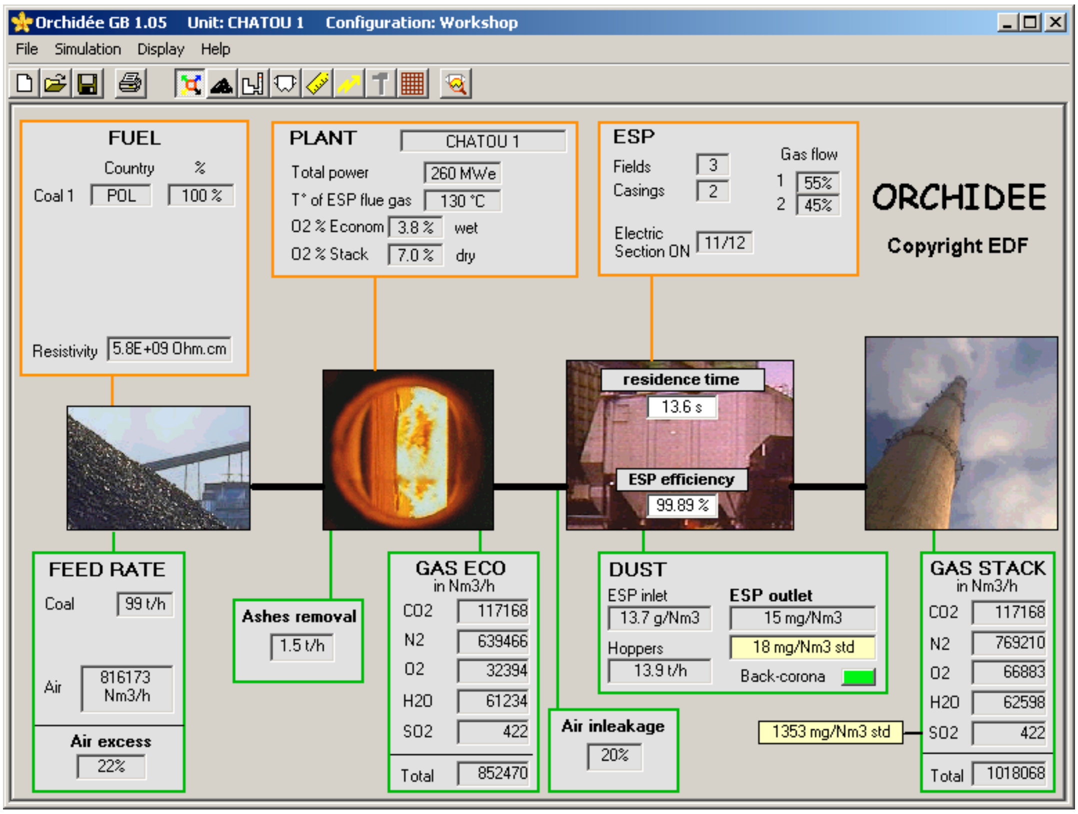
In order to reach computation times adequate to power plant applications a procedure was developed to separate the detailed calculations based on the physical modelling, from the instantaneous prediction of the collection efficiency in the power plant. Preliminarily, a parameter-based variational analysis (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; the analysis is extended over the whole range that the parameters may assume under usual operating conditions. Then a multidimensional non-linear interpolation algorithm is determined, 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. 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, and may reach 20 % at the field border.

5 ORCHIDEE:

5.1 An user-friendly tool for decision support in ESP operation and maintenance

ORCHIDEE (French acronym for Efficiency Optimisation of Coal Ash Collection in Electrostatic Precipitators) is a stand-alone simulation tool, that makes possible to estimate the dust emissions at the stack of a power plant. It is actually not connected to any data acquisition system of the plant. It is equipped with a friendly user interface, with pop-up menus, dialog boxes, buttons, etc., that allows to use the software quickly and easily (Figure 4).



FUEL
Country %
Coal 1 POL 100 %
Resistivity 5.8E+09 Ohm.cm

PLANT CHATOU 1
Total power 260 MWe
T° of ESP flue gas 130 °C
O2 % Econom 3.8 % wet
O2 % Stack 7.0 % dry

ESP
Fields 3
Casings 2
Gas flow
1 55%
2 45%
Electric Section ON 11/12

residence time 13.6 s
ESP efficiency 99.89 %

FEED RATE
Coal 99 t/h
Air 816173 Nm3/h
Air excess 22%

Ashes removal 1.5 t/h

GAS ECO in Nm3/h
CO2 117168
N2 639466
O2 32394
H2O 61234
SO2 422
Total 852470

Air inleakage 20%

DUST
ESP inlet 13.7 g/Nm3
Hoppers 13.9 t/h
ESP outlet 15 mg/Nm3
18 mg/Nm3 std
Back-corona 🟩

1353 mg/Nm3 std

GAS STACK in Nm3/h
CO2 117168
N2 769210
O2 66883
H2O 62598
SO2 422
Total 1018068

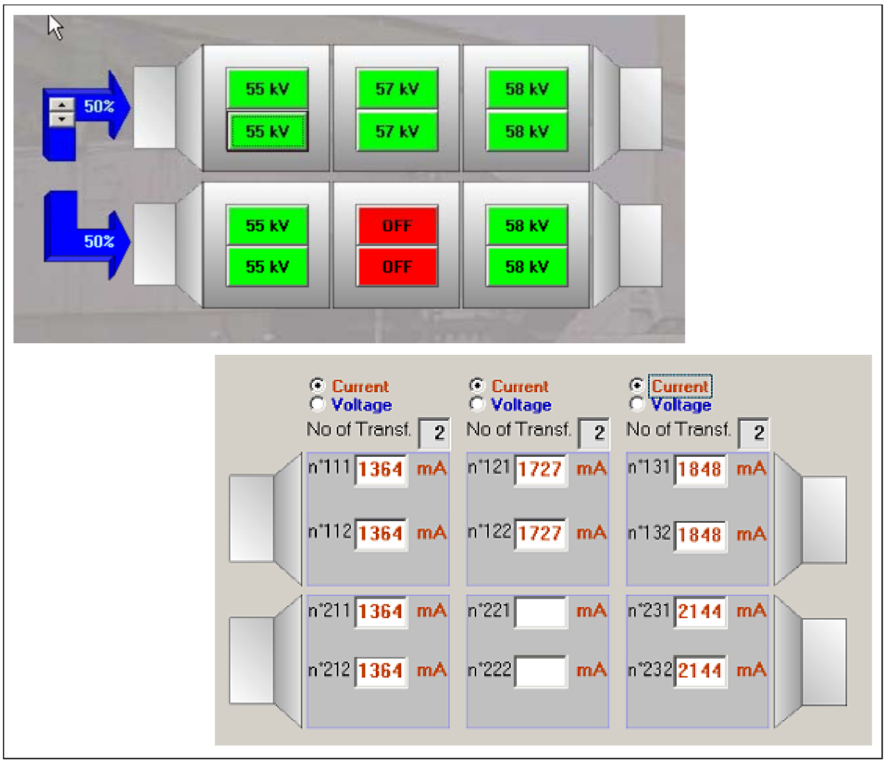
***Figure 4**: main user interface of ORCHIDEE*

The input data of the package are easily available on an industrial unit:

- fuel characteristics (coal analysis, blending up to 4 types of coal, oil admixture)
- power plant characteristics: rated output, energy efficiency of the unit,
- operating conditions of the unit: electrical power generated, O_2 level at the economizer and at the stack,
- electrostatic precipitator characteristics and operating conditions: geometry, electrical power supplysetting (voltage or current), distribution of the flue gas in the casing.

As output, ORCHIDEE supplies data that support decisions for the optimum plant operation:

- resistivity of the fly ash,
- flow rate of combustion coal and air, according to the electrical power load,
- flow rate and composition of the flue gas,
- current from each power supply,
- collection efficiency of each field of the electrostatic precipitator, per class of particles,
- overall dust emissions at the stack, per class of particles,
- back-corona risk.



● Current ○ Voltage — No of Transf. 2
n°111 1364 mA
n°112 1364 mA
n°211 1364 mA
n°212 1364 mA

● Current ○ Voltage — No of Transf. 2
n°121 1727 mA
n°122 1727 mA
n°221 mA
n°222 mA

● Current ○ Voltage — No of Transf. 2
n°131 1848 mA
n°132 1848 mA
n°231 2144 mA
n°232 2144 mA

Figure 5*: ORCHIDEE window on electrical power supplies; it gives also the flow repartition between different casings.*

To facilitate its use, the Data Base has been organized in two sections:

- a coal database, where it is possible to include the characteristics of all the coals that has been used at the plant
- an ESP and unit database, which includes all the characteristics of the electrostatic precipitators and the main unit data.

Help on line is available to facilitate the use of the software and to provide additional information.

5.2 A tool validated on power stations

The ORCHIDEE software has been tested and validated on various installations; two examples on French power plants are given below.

***Figure 6**: ORCHIDEE window for computed results.*

The Cordemais power station has two identical units (Nos. 4 and 5), burning imported coal, with a rated output of 600 MWe. They are equipped with flue gas desulphurisation downstream of the electrostatic precipitator. The emission level must remain below 50 mg/Nm^3 (on dry flue gas with 6 % O$_2$) to enable the desulphurisation unit to operate correctly. 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.

Three tests at different operating points have been realized; the unit and electrostatic precipitator operating parameters have been recorded: complete coal analysis, unit load, oxygen rate at stack and economiser, ESP inlet temperature, voltage for each TR set. The main unit operating conditions are indicated in table 1. A blend of South African and American coal has been burned during the tests. On august 28th, with a voltage of 43 kV, the emissions reached 75 mg/Nm^3; On august 31st , by reducing boiler load and ESP temperature, it was possible to increase the voltage to 47 kV and reduce the emissions to 30 mg/Nm3. On September 6th, the boiler load was increased, but with a rise in the voltage, the emission level was kept to the same level.

Date	Coal % on dry	Unit conditions	ESP conditions	Observed emissions	ORCHIDEE predicted emissions
28 august 01	30% SA + 70% USA Sulphur: 0,9% Ash: 13%	600 MW O$_2$ stack 6,6% /dry FGD out of service	Temperature: 135°C ¼ field out of order Mean Voltage: 43 kV	**75** mg/Nm^3 std	**81** mg/Nm^3 std
30 august 01	35% SA+65% USA Sulphur: 0,92% Ash: 11,4%	550 MW O$_2$ stack 6,6% /dry FGD on service	Temperature: 125°C ¼ field out of order Mean Voltage: 47 kV	**30** mg/Nm^3 std	**34** mg/Nm^3 std
6 sept. 01	Sulphur: 0,8% Ash: 13%	600 MW O$_2$ stack 7,2% /dry FGD on service	Temperature: 125°C ¼ field out of order Mean Voltage: 51 kV	**30** mg/Nm^3 std	**26** mg/Nm^3 std

***Table 1:** Comparison of the observed emissions and those estimated by ORCHIDEE, on unit 5 at Cordemais power plant, under different operating conditions.*

By comparing the observed emissions with the ORCHIDEE predictions (Table 1), it has been possible to assess the accuracy of the model within a range of the order of 10 %.

At Blénod power plant the unit 3 has a rated power output of 250 Mwe, and is equipped with an electrostatic precipitator made by 2 casings in parallel. Each casing has 3 fields, with a plate-to-plate distance of 400 mm, equipped with transformer-rectifier sets. In April 2002, co-combustion tests have been carried out with pet coke; the operating conditions of the test are given in Table 2. The results of the tests have shown the positive impact on the emissions of the blend with a sulphured residue with low ash content. Also in this case, the comparison between observed emissions and ORCHIDEE predictions (Table 2), indicates an accuracy of the model of the order of 10 %.

	Coal % on dry	Unit conditions	ESP conditions	Observed emission	ORCHIDEE predicted emission
Without pet coke	Australia Sulphur: 0,49% Ash: 9%	235 MW $O_{2\ stack}$ 6,8% dry	Temperature: 135°C Mean voltage: 55 kV	**100** mg/Nm^3 std	**110** mg/Nm^3 std
With 8% of pet coke: Sulphur: 6,83% Ash: 0,7%	Australia Sulphur: 0,49% Ash: 9%	235 MW O_{2stack} 6,8% dry	Temperature: 140°C ¼ field out of order Mean voltage: 61 kV	**60** mg/Nm^3 std	**64** mg/Nm^3 std

***Table 2**: Comparison of the observed emissions and those estimated by ORCHIDEE on unit 3 at Blénod power plant in different operating configurations*

5.3 Return of experience from ORCHIDEE utilization

The ORCHIDEE software has been extensively used in a number of the EDF thermal plants in France. The return of experience has shown that the power plant operators have been able to have a better understanding of the problems, and to react efficiently in real time. After introduction of all 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 air ingress, high gas temperature at electrostatic precipitator inlet, etc.);
- to verify hypotheses of coal blending 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);

The Maintenance Department can optimise its actions. The Technical Department can make a better assessment of slow drift in operation. The Engineering Department can better appreciate actions for renovation, as the ORCHIDEE physical model makes possible to verify the effect of changes in internal components (height, plate-to-plate distance, and type of wires), changes in the electrical power supplies, the addition of a new field, for both existing units to be retrofitted, and for new units that to be designed.

6 Conclusions

ORCHIDEE is based on physical modelling of the collection process. This approach enables it to estimate the efficiency of the electrostatic precipitator without using experimental databases, and to be independent on Manufacturer's data. ORCHIDEE constitutes a tool to assist the operation and maintenance of electrostatic filters, that is unique for its scientific content and for its user-friendly interface. The return of experience has shown that it has fulfilled the expectations of its users.

Version 1.0 of ORCHIDEE has been installed in all the coal-fired thermal power plants in France, in the Engineering Departments, and in the Cottam power plant in England.

Acknowledgements

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*ICESP: International Conference on Electrostatic Precipitation