Proceedings of the Sixth IASTED International Conference
EUROPEAN POWER AND ENERGY SYSTEMS
June 26–28, 2006, Rhodes, Greece

IMPROVING POWER PLANT ENERGY PERFORMANCES: FROM EXPERTS TO OPERATORS

Benoît Bride Baligh El Hefni Jérôme Durand Véronique Arrondel
EDF R&D
6 Quai Watier
F-78401 Chatou Cedex
France
benoit.bride@edf.fr baligh.el-hefni@edf.fr jerome.durand@edf.fr veronique.arrondel@edf.fr

ABSTRACT
In order to improve the energy performances of the power plant and to generate electricity at the best cost, a Q600 (600 MWe pulverized coal units) numerical model was created in 2003. This physical model was created with a modular solver called LEDA. First a 1-D furnace module was created, then a complete LEDA Q600 model was built.

Only using measures from on-site sensors, the model was able to compute precisely the mass flow rate of coal (poorly measured since it is a solid) and all the efficiencies of the equipment. The uncertainty of mass flow rate of coal was less than ±2%, that is the best available accuracy of all our tools (models, balance sheet, losses method, measurements…).

The model was validated, accelerated (from a one-hour calculation delay to less than 20 seconds) and automated, operators and e-monitoring teams use it to make performance computations and “what-if” simulations through an interfaced software called ηPerf.

Operators, engineering teams and researchers collaborated to write an “energy performances optimization guide” was written: each proposal of operation improvement could be simulated and checked via the Q600 model. This guide gives a methodology to decrease fuel consumption based on five main indicators.

KEY WORDS
Power Plants, Optimization, Modelling, Simulation

1. Introduction

Generating electricity at the best cost, in a context of ever more stringent environmental constraints, is an ambition shared by all Utilities, but above all it is a condition for success in the present energy situation where the market price will determine the profitability of an installation taking into account its generating costs.

In R&D projects dealing with energy performances of fossil-fuel power plants, one of the main needs is to improve the knowledge of the physics running the unit. This knowledge can allow to diagnose the condition of the equipments and to optimize the operation of the plant and to propose ways of improvement when new equipment are to be installed.

This need of knowledge is even more important for pulverized-coal units where the mass flow rate of coal is poorly measured – e.g. ±5% since it is a solid – and ought to be calculated in order to assess the actual performance of the unit (in order to compute the heat rate or the global efficiency).

2. Creation and use of a physical model

2.1 Q600 physical model

In order to meet this need, R&D teams decided to develop and make use of thermo-hydraulic steady-state models simulating the process very accurately. That was specifically realized for EDF Q600 units, which are 600 MWe pulverized coal units characterized by a « once through » (no drum) boiler and a sliding pressure control system. EDF owns three units of this type, in the following text, they will be called unit 1, unit 2 and unit 3.

The model was created with a software called LEDA: it is a modular EDF-owned solving software which enables user to develop numerical modules (representing various equipment) and to link them to form an overall model to be solved using Newton Raphson method for steady state cases (LEDA is also used for non steady state simulations). LEDA models are usually built on Unix or Linux computers, but they can be run on Windows PC as well.

Since EDF has been using this software over decades (LEDA is in use since 1982), it offers the best available physical descriptions, since each improvement - correlations, experimental results or 3D computations – is capitalized into the modules.

In the LEDA library, many types of physical modules are available:

- Furnaces: grid, pulverized coal, fluidized bed, waste burners etc.
- Heat exchanger: walls, convective exchanger, condensers, for water, steam, flue gases, perfect gases.
- Turbines, compressor and pumps: steam, GT, with maps, sonic, subsonic etc.
- Gas control: ESP, scrubbers etc.

LEDA models are used by researcher to improve knowledge on existing or future types of power plants. They are also run by engineers to verify accurate design and to carry out non-steady state studies.

2.2 Description of the model

The LEDA Q600 model was built in 2003, describing the whole unit with an energy point of view (fig. 1).

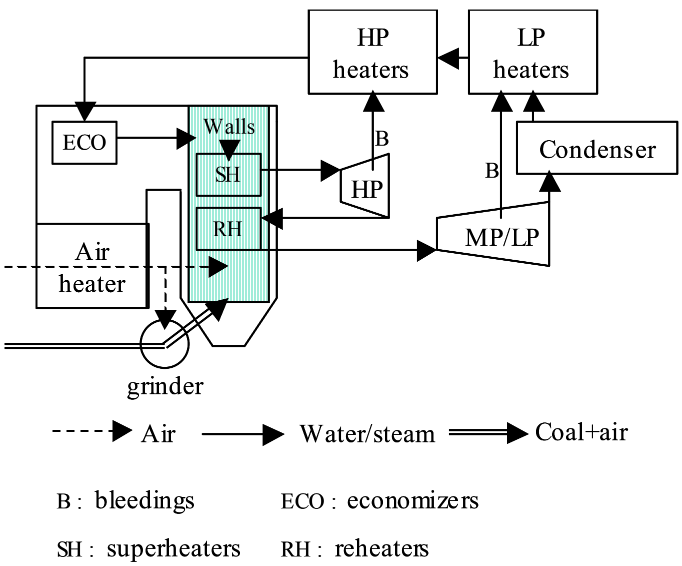

Fig. 1: simplified process flow diagram of the LEDA - Q600 model

The model includes:

- Air/coal circuit: grinders, air heater and preheater.
- Water/steam cycle: economizers, waterwall, superheaters, reheaters, turbines, condensers, water heaters and pump-turbine.
- Furnace and boiler: combustion module, flue gases exchangers.

It contains about:

- 36 types of modules,
- 86 modules (piece of equipment),
- 680 geometrical data,
- 650 variables,
- 200 equations.

Every variable can be set either as input or output variable.

The equations set in the modules take into account non-linearity and the state-of-the-art on physical behaviour of each physical phenomenon:

- The furnace is a 1-D thermodynamic module, divided in 7 layers or cells, three of them can receive pulverised coal, the others can receive some when the burners change angle. Radiation equations rely on gas grey spectrum correlations validated with experiments.
- Waterwall, Economizers, superheaters and reheaters also contain precise and up-to-date correlations for heat exchange coefficients and pressure loss. Convection and pressure loss correlations are set and valid for any flue gas composition, for water as a liquid phase, vapour phase or both. Conduction equation is adapted with a fouling coefficient. To feed these equations each module contains a very accurate set of geometrical data (number of tubes, diameters etc).
- Steam turbine stages modules are based on an ellipse law and an isentropic efficiency.
- Water heater are KS-type modules, taking into account condensate cooling.

2.3 Calibration and first use

The maximum convergence duration of the model is about 20 seconds on a Unix, linux or PC computer: although it is fast, the model remains an expert tool, and the computation should be launched from an initial reference solution quite close to the final one. If a reference solution is absent, the calculation should be done step by step or input variable by input variable and could last up to one hour.

The calibration phase consists in setting the maximum number of variables to measurement values: doing this we can compute all the performance parameter and the outputs data we need.
The main computed performance parameters are:

- Fouling coefficients,
- Ellipse law coefficients,
- Isentropic efficiencies,
- Radiation coefficient,
- Pressure drop coefficients.

The main computed outputs are

- coal mass flow rate (and consequently the heat rate and the global efficiencies),
- thermal power of exchangers,

- temperatures and pressures in places where no sensor are installed,
- bleedings mass flow rates.

The first calibration of the model was made with data from the acceptance test of unit 3 in 1984. Then we used measurements taken from on-site sensors during performance tests of 2004 (on units 1 and 2), the model was then able to compute precisely the mass flow rate of coal and the performance parameters of all internal equipment from the whole unit down to a single heat exchanger.

The ability of choosing the input variables of the model appeared then very valuable since in relatively old units, Many sensors are damaged or inaccurate. Even during prepared performance test, values – retrieved through our EDF internal website – were missing or wrong. For this last reason, the use of a simpler model or balance sheet was more complicated since it could not give the choice on the input variables. For these preliminary computations, the number of input data is about 100 and the uncertainty of coal mass flow rate has proven to be less than 2%: that is quite satisfactory since no sensor had been renewed or added.

We could notice that unit 1 had a smaller gross heat rate than unit 2, and that the reference curve did not fit anyone of the computed heat rates (fig. 2). The reference curve was given by the manufacturer in 1984, hence it is logical that it does not fit the computations anymore. The difference between the two units could be analysed precisely through the model, and we noticed that control system on reheating and desuperheating behave differently : this is one main cause of the difference.

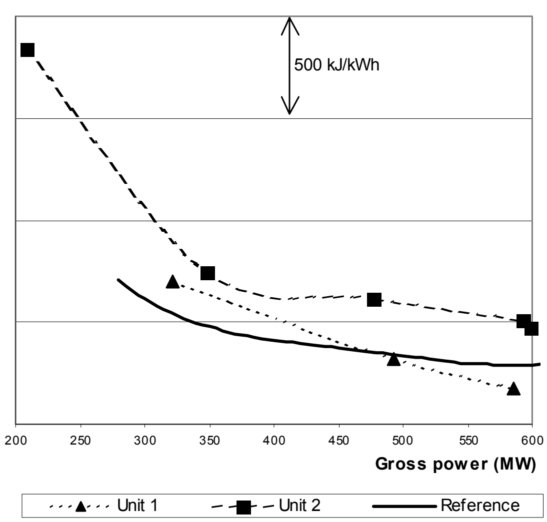

Fig. 2: gross heat rate as a function of gross power for energy performance test on unit 1 and 2

The curve heat rate as a function of gross power as a typical decreasing shape. The calibration made for the 210 MW test gave the first heat rate computed at this power: indeed, the minimum available power of the unit was 300 MW and the test at 210 MW was made in order to reduce this minimum available power.

3. Validation and uncertainties

Validation of the relative use of the model was possible thanks to the performance test computations. We compare the measurements and the computation made out of the measurements to the "what if" simulation results. This validation was performed on five cases starting from a calibration on unit 2: the range of gross power was 210 – 600 MW, one case was on unit 2 and one had an isolated HP line.

We compared 15 parameters: global efficiencies of the unit, temperatures, pressures, flow rates and powers. The two values (measurements or complete computations and model) were always closer that the uncertainty of the parameter. For instance, the maximum heat rate difference was around 2% (fig. 3).

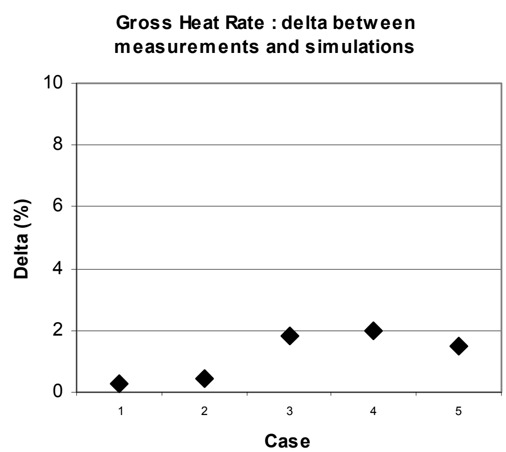

Fig. 3: relative difference (delta) between gross heat rate computed on calibration mode during performance tests and gross heat rate computed with "what-if" simulation

As a consequence, the model was validated for its relative use for any power and any unit. Validation of the model for an absolute use could not be done since it needed a good measurement of the coal flow rate: nevertheless, the results were close (within uncertainty range) to the ones given by other balance sheets or standard methods (for instance the coal flow rate computation proposed by NF EN 12952-15 standard).

The uncertainty is computed with a Monte-Carlo method: using as first hypothesis the uncertainties of all the input parameters, random calculations are launched in order to plot gauss-type curves and compute the uncertainties of the outputs. This work also gives what we call a sensitivity analysis on the uncertainty of the results, which is a hierarchical list of influent parameters for each output.

The uncertainties computed by the model are lower than that computed with other performance tools (balance sheet, losses method):

- Heat rates and coal flow rate: ±1.7%
- Boiler efficiency: ±0.9%
- Flue gases and air flow rate: ±4%
- Boiler exchangers power: ±1.5%
- Water station power: ±2%
- Condenser power: ±2.4%

The sensitivity analysis on the uncertainty of the results gave a list of important sensors: this list enables us to reduce the number of input parameter keeping the initial accuracy. It has been possible to limit the number of important inputs (and sensors) to about fifty.

4. Results

4.1 Simulations and curves

Once calibrated on an actual situation of a unit and then validated, the model can simulate any change of operation: it was interfaced on a simple graphic tool called COGENE®, it was then easier to launch a large amount of "what-if" simulations. A sensitivity analysis of the model ("what-if" simulations for each input variable) has been done in order to know the influence of each operation parameter. This work also gave a hierarchy of the influent parameters.

The correction curves, given by the manufacturer, could then be cross-checked with the model sensitivity analysis and we could prove that some of them had become wrong (fig. 4). These curves were corrected in the tools used by operators: on-line performance monitor, monthly performance sheet.

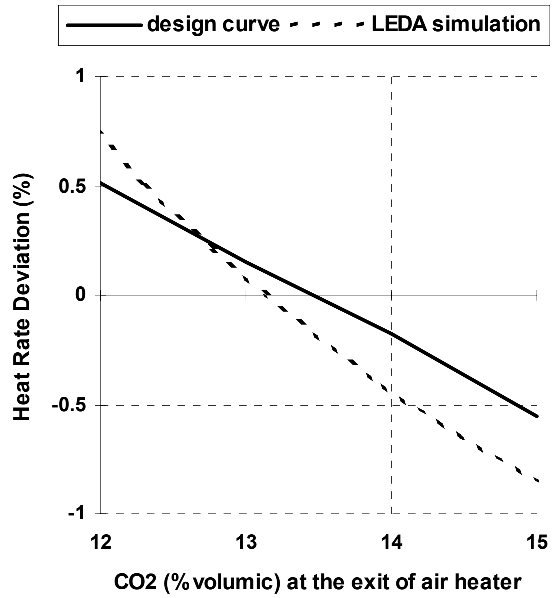

Fig. 4: comparison of design and simulation curve for CO2 fraction (equivalent to excess air).

4.2 Creating a optimization method

The sensitivity analysis of the model was shared with operators and engineering services, and the team work provided knowledge to write and validate an "energy performance optimization guide": each proposal of operation improvement could be simulated and checked thanks to the Q600 model.
This guide delivers a methodology capable of helping to decrease the fuel consumption of the unit:

- It is based on only five main indicators which are available in the control room and are easy to check.
- The quantification of the over-consumption is given.
- A first-level diagnosis table (fig. 4) is proposed to operators for a fast action of correction.
- A second-level diagnosis table is then available for maintenance actions or other long-term economic strategies.

Means of detection (measurements, alarms, tests/trials)

probable causes	D1	D2	D3
C1	x	x	
C2		**X**	
C3	x		**X**

Fig. 5: shape of the diagnosis table proposed in the optimization guide to assess the causes of over-consumption

An example of optimization is given in fig. 5, where we suggested that the operator should use a set of curves created through the Q600 model simulations. These curves enables us to assess any gain or loss due to a combined change in excess air and unburned carbon rate. Since it is very difficult to forecast the relationship between the two parameters – only possible with 3D computations and very dependant on coal analysis, burner angles and load – the operator can get the values of the two parameters thanks to the sensors and see the gain or loss with the curves.

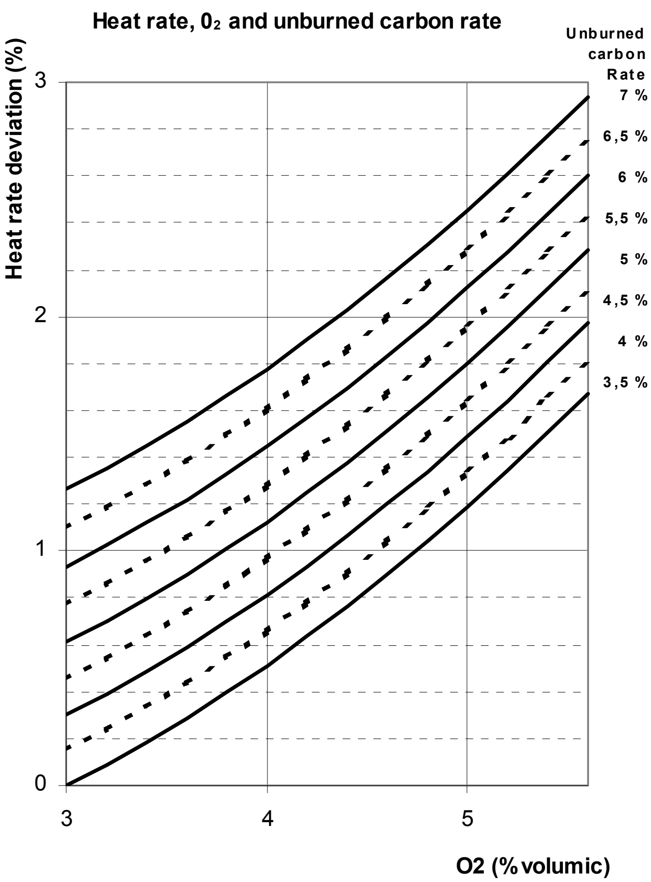

Fig. 6: curves of optimization for O2 and unburned carbon

4.3 Transfer of methods to operators and engineering teams

The R&D project has proven to be profitable, and each improvement or knowledge is now being transferred to operators or engineering teams.

- A list of the most strategic sensors , given in hierarchical order, was issued and a standard for maintaining or improving their accuracy was created.
- The "energy performances optimization guide" (called GOPE according to its French acronym) is now on every operator's desk and computer. It is also available in the help topics of the operators' on-line performance monitoring system and its interface is being changed to fit to this new method.
- All the correction curves are updated with the ones created by the sensitivity analysis of the model.

4.4 Transfer of model to operators and engineering teams

Operators needed a tool to carry out performance test and simulate the behaviour of their units, for this purpose the last model has been accelerated and automated and integrated an interfaced software called ηPerf (pronounce EtaPerf).

The integration of the model in the software rather than a balance sheet or a losses method tool was decided because of its three advantages:

1. We can easily choose the input variables of the model and let it calculate the missing parameters,
2. We could reduce the number of input parameters without degrading the accuracy,
3. Only the model can make "what-if" simulations.

Besides LEDA models can be compiled into Windows executables files: inputs and outputs are written in a text file, it is then easy to use the model embedded in any software.

Based on our expert experience, we built a database of initial reference solutions. The software created can then choose the closest reference – regarding gross power and HP line condition – before launching the Q600 model : by doing this it can change all the variables and converge in only one step, as a consequence the calculation for a complete performance test lasts 20 seconds in the most difficult case. This calculation time is achieved both for performance calculations (calibration mode) and for "what if" simulations. Plant data recovery and treatment could be automated through our intern website and several functionalities could be created to answer operators' needs.

The ηPerf software includes four functionalities :

1) data recovery and processing of a reduced number of data (around 50);
2) performance calculations with the validated model and boiler efficiency in compliance with NF EN 12952-15 standard and with a known uncertainty (fig. 5);
3) what-if simulations on 18 main operating parameters (fig. 6);
4) tests database and pre-built data processing.

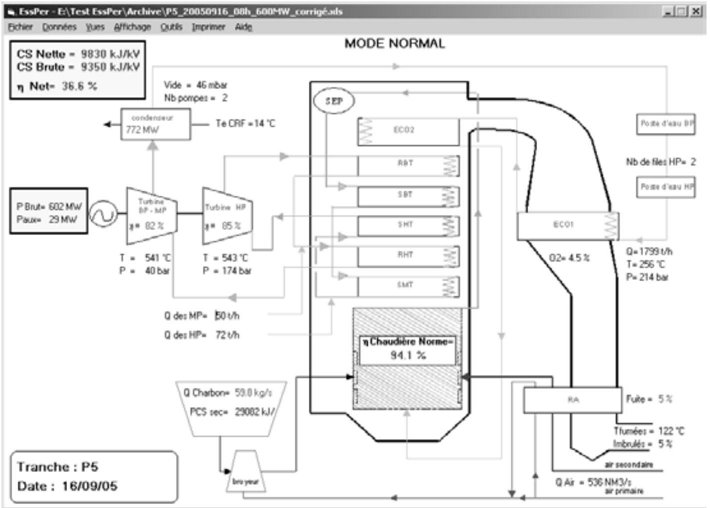

Fig. 7: view of a performance calculation in the ηPerf software

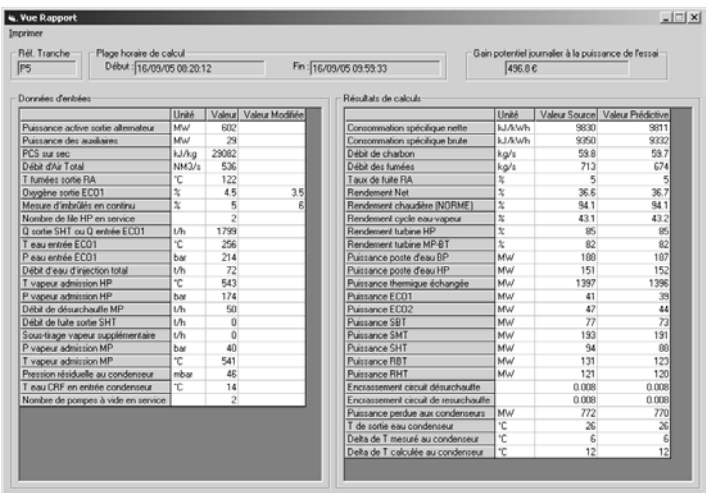

Fig.7: view of a "what-if" simulation result in the ηPerf software

The ηPerf software has been integrated in a toolbox for assessing unit energy performance:

- The on-line performance monitoring system computes energy performances in real time thanks to a losses method: all the computations and reference curves have been updated with the model results,
- ηPerf calculates accurate performances for steady state operation and simulates new operating conditions,
- the monthly performance computations (for steady state and non steady state) are made with a losses method: all the computations and reference curves have been updated with the model results.

From now on, operators and e-monitoring teams can use the model to carry out performance computations and "what-if" simulations. ηPerf allows to assess unit performances with the best available accuracy and computes earnings or over-costs of any technical or investment project.

5. Conclusion

The R&D work focused on energy performances and created an overall methodology to reach its goals. A precise physical model is the starting point of the project, as it is the main tool providing knowledge to the researchers. Though one key of success was that the operators and the engineering teams collaborated to the work from the beginning. First they exposed their needs and their problems to be solved. Then they provided all the data needed. Finally they met with the researcher to form a workgroup which created an optimization guide. As a consequence, the methods and the tool created are modern and fully new, and at the same time they really meet the needs of the main users.

Other R&D works were carried out at the same time on other subject: mainly about environmental issues and electrical network services. They all tried to follow the same methodology: a physical model, then an association with operators to create optimization guides and tools.

The future works will deal with improving the overall knowledge of the unit in its environment (environmental issues + energy + network services +…) and trying to know the real cost of each produced kWh. Besides, the work done on Q600 units may be generalized for any fossil-fuel power plant.

Acknowledgements

The authors wish to thank the power plant personnel and the colleagues, for their active participation in the creation of the "optimization guide" and ηPerf tool.

References

[1] S.S. Munukutla and R.P.M. Craven, Modeling of the Performance of a Coal-Fired Power Plant in Real-Time, *Proc. Power and Energy Systems*, Benalmádena, Spain, 2005, 468-086.

[2] M. Antoine, Extract more value from your plant, *Turbomachinery International, July/August 2005*, 24-25.