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Computer-Aided Analysis of Industrial Energy Systems Applied to a Paper Machine

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Over a third of the worldwide CO_2 Emissions are attributable to the industrial sector (Metz et al., 2007). Appropriate software systems can help engineers optimizing production processes in order to reduce CO_2 Emissions or costs. The TOP-Energy toolbox is tailored to the analysis of energy systems with a partial focus on the industrial sector. An important tool included in TOP-Energy is the simulator. It is capable of calculating characteristic figures for an energy system.
The methodology of the simulator was designed to make the process of data acquisition, data analysis and optimization of energy systems more efficient. These tasks are often performed by energy consultants and have to be efficient and easy-to-use. The simulator was developed to close the gap between very complex simulation tools for production planners and very simple spreadsheet calculations that are usually performed by energy consultants and do not deliver detailed results.
To make the process of analyzing more efficient, methods for debugging equation based models have been integrated in the methodology. Additional modules allow benchmarking of different variants against each other.
The methodology is used to analyze the production of hygienic paper in a paper mill. It was investigated whether investing in a larger heat exchanger or a shoe press will reduce the energy consumption perceptibly.

1. Introduction

The decrease of energy consumption in industrial processes is crucial to almost all industrial facilities from small-scale enterprises to global corporations. Increasing costs and ecological considerations boost the need for energy consultants at industrial facilities. The professional analysis of energy systems often reveal measures for higher efficiency at lower production costs.
The term industrial energy system covers the energy related aspects of the production process, as well as the energy supply system. As energy systems consist of multifaceted technologies that interact closely with each other, the analysis of these systems is a complex task. Furthermore there is more than one objective in energy system analysis. Constantly rising energy prices have made energy costs a process key issue for operating companies. Governmental regulations and marketing strategies are drawing

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the attention of process operators to the reduction of CO_2-emissions. The objectives "energy cost reduction" and CO_2-reduction" do not always lead to the same optimum. So finding a good trade-off is also an area of activity. An efficient methodology for energy analysis is also crucial because the results have to pay-off the costs of the analysis itself.
There are a lot of tools focusing on process planning and analyzing process costs. A good example is Aspen, by Aspentech (Aspen, 2010). Tools like these are developed for specialists who have expert knowledge in production planning and simulation environments. In most cases energy consultants have neither the time nor the expert knowledge, to deal with such complex software systems.
Software tools especially designed to analyze energy supply systems like ebsilon (Ebsilon, 2010) for example are in a similar way unsuitable for the given task. They can provide an optimized energy supply system based on a given load. They do not consider the impact of changes to the production process on the primary energy consumption or the CO_2-emissions.
In this paper a software tool for the analysis of energy supply systems is presented, to overcome the hurdles of an efficient analysis. It caters for energy consultants and energy managers who lack a simple and efficient tool in order to optimize the energy relevant figures of an industrial process. Focus is laid more on efficiency than on accuracy of the analysis, as the available input data quality for these kinds of tasks is often very bad.

2. Basic Concept

The tool is best suited for continuous energy intensive production processes like in the pulp and paper, chemical or food industry. The methodology has no limitation on continuous processes, but it is not applicable for very discontinuous production processes like in mechanical deformation for example.
Furthermore the tool focuses on the interactions between different process steps and not on optimizing single devices in the systems. Possible applications are the optimization of internal heat recovery, dimensioning of cogeneration systems or the evaluation of new technologies in a concrete production environment.
Special attention was given to usability of the tool. As energy consultants often just have a few days to analyze a facility, simulation results have to be gathered fast and cheap.

2.1 Modeling and the simulation algorithm

The most complex component of the analysis toolbox is the simulator, which is capable of calculating energy consumption, CO_2 emissions and other key figures for a given energy system. The simulation is performed based on simple models of the technical components including mass and energy balances and in most cases a simplified component behavior. Time dependent simulation is done by simulating multiple time steps, which are considered steady-state. The models of different technologies are organized in so called components. New components can be modeled using a modeling language and extend the component database.

2.2 Framework

To make the analysis easy to use, a graphical user interface is needed. The lack of a GUI is often the reason, that tools developed an academic context do not suit the needs of energy consultants although they are technically superior to commercial solutions. The presented software is therefore tied to the TOP-Energy Framework (Wrobel, 2007). This framework provides a GUI which is intuitive to use and provides different services to the user that assist the user in analyzing complex data. The framework has a flow sheet editor, which allows graphical assembly of the energy system model and can illustrate results qualitative. Furthermore the framework provides unit conversion operations and check values for plausibility and validity. These tasks are taken from the energy consultant to make the results more reliable.

2.3 Flexible evaluation of component models

Most simulators assume that the input data for the model of a technical component can be fixed before knowing the actual use case. This is true for many academic applications of simulators, where almost every data can be measured or calculated before the actual simulation. In energy system analysis this is not the case. Energy consultants have to perform simulations with the data that can be collected in reasonable time. These data sets are often incomplete, redundant, inconsistent and fit fixed input data sets only occasionally. Therefore the simulator has to react flexible on the input data that is available.

The simulator contained in TOP-Energy is designed to be as flexible as possible according to the available input data. Therefore the model is based on nonlinear equation systems that can be used to calculate different sets of output data, as long as enough input data is available.

2.4 Debugging equation systems

As the models of energy systems are not always portable between different use cases, almost every energy system requires customizing of technical component or property models. The process of modeling new components is often time consuming and requires knowledge of the underlying simulation algorithm. To make the modeling process as efficient and beneficial as possible, great importance has been attached to debugging algorithms.

Debugging in this context means debugging of component models and debugging of input values. Simulation errors may occur, because there are wrong equations in the model of the energy system. Errors also occur, when input values are wrong, conflicting of missing.

3. Simulation Algorithm

To implement a debugging of equation based simulation models, the equation system describing the energy system have to be decomposed in smaller parts that can be reviewed by the user. As described above, equation systems are often under- or overconstrained, because data required for the simulation is missing or redundant. Therefore the decomposition is done using an algorithm described in (Dulmage, Mendelssohn, 1969). This algorithm partitions the set of all equations in three subsets that contain the over-, under- and well constrained equations of the model. The well

constrained equation systems are solved using a Newton algorithm. Overconstrained equation systems are solved using QR decomposition with householder transformation (Golub, 1989). If the solution of an overconstrained equation system is not unique, an error message is generated. Simulation models of energy systems are supposed to always have a unique physical solution.
The underconstrained equations are analyzed to provide the user with information, what variables he would have to measure in order to calculate a certain result variable that is part of an underconstrained equation system.

4. Evaluation Tools

Unlike most simulation software tools TOP-Energy provides evaluation tools, to extract characteristic figures out of the simulation results that allow benchmarking several variants against each other. These tools include the calculation of economical key figures like payback period and capital value, sensitivity analysis and qualitative analysis of simulation results.
The calculation of economical key figures is implemented analog to the German industry standard (VDI 6025, 1996). It calculates common characteristic values based on the energy cost savings calculated from the simulation and investment costs and declining values for technical components given by the user. The sensitivity analysis allows the user to study the influence of one input parameter on certain output parameters. Thereby it is possible to investigate the influence of exogenic or unknown parameters (like prices) on simulation results.
The simulator allows the illustration of simulation results as so called enhanced energy and process diagrams. These diagrams show the material flow like in Figure 1, and contain in addition qualitative information of the flows like in sankey diagrams by varying the thickness of the arrows connecting the components.

5. Production of Hygienic Paper

The methodology has been used to analyze the production of hygienic paper in a paper mill. One of four different paper machines of a production site in Germany has been analyzed and simulated. The simulation has been performed only for the paper machine. The preparation of the fiber, and manufacturing has not have not been analyzed.
The paper machine holds the potential of heat recovery and technology upgrades. Therefore it is interesting for the given kind of analysis.
A descent reasonable model for pulp had to be developed, which is not too complicated to measure and detailed enough to deliver the requested results. Also the heat transmission between the paper and yankee cylinder respectively hot flue gas had to be modeled in an easy-to-use manner.

5.1 Material properties

The most complex task modeling the paper machine was modeling a component model for the paper suspension that reflects all relevant properties of the material. Especially the sorption enthalpy of the water that is bound to the fiber had to be modeled. To calculate the sorption enthalpy the sorption isotherm has been used. It can approximately be calculated using the following equation (Prahl, 1968):

$$\phi = e^{\beta_1 T_P + \beta_2} \tag{1}$$

In this equation ϕ is the relative humidity of the air surrounding the wet paper and T_p is the temperature of the paper. The parameters β_1 and β_2 can be approximated as given in (Karlsson, 1982):

$$\beta_1 = e^{-15.03 x_P - 1.37\sqrt{x_P} - 3.14}; \beta_2 = e^{-13.53 x_P - 2.9\sqrt{x_P} - 2.9} \tag{2}$$

where x_P is the loading of the paper. The specific sorption enthalpy can therefore be calculated as:

$$h_S(T_P, x_P) = R_S e^{-15.03 x_P - 1.37\sqrt{x_P} - 3.14 T_P{}^2} \tag{3}$$

Other material properties are calculated using simplified models like ideal liquids or gases.

5.2 Model of heat exchange

The two ways of heat exchange relevant to the investigated hygienic paper machine are conductive indirect heat exchange from the Yankee-cylinder to the paper and convective direct heat exchange from the flue gas in the drying hood to the paper.

The conductive drying is modeled assuming a cylindrical layered geometry consisting of a thin water film inside the yankee, the yankee itself and the paper. The convective drying is modeled assuming a sinuous flow of the flue gas perpendicular to the paper.

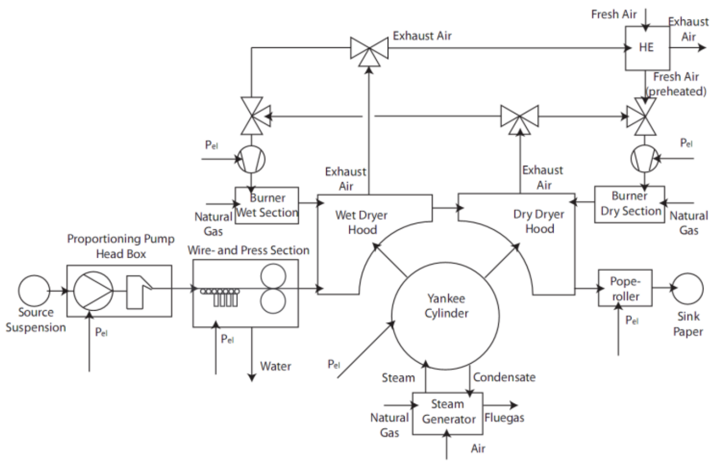

Figure 1: Flow sheet of the paper machine and heat recovery from the dryer hood

5.3 Example

The example investigated in this paper is a hygienic paper machine using two separated drying hoods heated by gas burners and one yankee cylinder heated by steam (6.8 bar). The air from the drying hood with the higher water loading is used to heat fresh air for the dry-side burner, while the air from the hood with the lower loading is used to heat the air for the wet-side burner (Figure 1).

Based on the data measured at 5 different production states characteristic data of the technical components in the paper machine have been determined. Based on the parameters of the technical components and required process parameters like temperature and humidity of the fiber, simulations have been done to verify the model of the current state of the energy system. Some results of the verification simulations have been compared to measurements and it could be shown, that the relative error between the measured and simulated parameters was less than 2.5 %. The parameters are listed in Table 1.

Table 1 Comparison of simulation results and measured data

Parameter	*Measurement*	*Simulation*	*el. Error*
Loading of air leaving dryer hood	33.2 %	33.74 %	1.62 %
Temperature of air leaving dryer hoof	233 °C	235 °C	0.9 %
Dry content paper out	95.9 %	93.7 %	2.2 %
Degrees of effectiveness yankee	88.3 %	86.4 %	2 %

To illustrate the capabilities of the evaluation modules two variants of the current state of the energy system have been calculated. An improvement of the heat integration and the substitution of the press for a new shoe press have been evaluated. The results can be described only briefly in this context.

As the economical data of the paper mill was not exactly known, the evaluation of the shoe press is based on a benefit of 280 €/t of paper. The shoe press was considered to have investment costs of 7 M€. The consumption of steam could be reduced at 14.4 % and the gas consumption of gas could be reduced by 1%. Considering the higher production rate, a payback period of 6.8 y could be calculated.

An inquisition of the heat integration revealed a potential reduction of the gas consumption. A duplication of the area of the flue gas heat exchanger leads to a reduction of gas costs of approximately 120T€ /y.

References

ASPEN, 2010, <www.aspentech.com > (last accessed 21.6.2010)

Ebsilon, 2010, <www.steag-ketek.de>, (last accessed 21.6.2010)

Golub G.H. and Loan C.F., 1989, Matrix Computations, 2nd Edition, John Hopkins University Press, Baltimore, USA.

Metz B., Davidson O.R., Bosch P.R., Dave R. and Meyer L.A., 2007, Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment, Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, USA,

Karlsson M., Soininen M. and Ashworth J.C. (ed.), 1982, The influence of the hygroscopic properties of paper on the transient phenomena during contact drying of the paper webs. In Proc of the Third International Drying Symposium, 494.

Prahl J.M., 1968, Thermodynamics of Paper Fiber and Water mixtures, PhD Thesis, Harvard University, Cambridge, USA.

Wrobel G., Herbergs S. and Augenstein E., 2007, TOP-Energy - A Framework for Software Developement in Energy Engineering in eOrganisation: Service-, Process-, Market-Engineering, Germany VDI 6025, Betriebswirtschaftliche Berechnungen für Investitionsgüter und Anlagen, Universitätsverlag Karlsruhe, Germany (in German).