

Dynamic process simulation as an engineering tool – A case of analysing a coal plant evaporator

by Jari Lappalainen, Harri Blom and Kaj Juslin

Dynamic process simulation as an engineering tool – A case of analysing a coal plant evaporator

Jari Lappalainen, Harri Blom and Kaj Juslin

Abstract

Dynamische Prozesssimulation als Methode für Engineeringaufgaben – Fallanalyse für einen Verdampfer eines Kohlekraftwerks

Methoden, die auf mathematischen Modellen beruhen, wie z.B. Simulationen zur Optimierung, sind in der Prozessindustrie üblich, wo sie für verschiedene Engineeringaufgaben routinemäßig eingesetzt werden. Der vorliegende Beitrag befasst sich mit dem aktuellen Stand der Simulation, insbesondere der dynamischen Simulation (DS), bei der technischen Bearbeitung von Projekten. Dadurch wird es möglich, den Prozessverlauf sowohl unter gleichbleibenden Bedingungen als auch bei Übergängen zu untersuchen.

Als Beispiel wird die Lösung eines technischen Problems in einem Kraftwerk vorgestellt. Entwickelt wurde das Modell eines Zwangdurchlaufkessels in einem Kohlekraftwerk, mit dem sich das thermische Verhalten der Verdampferrohre analysieren lässt. Untersucht wurde in erster Linie, ob Zusammenhänge zwischen durchgeführten Veränderungen der Regelungsstrategie und aufgetretenen Rohrbrüchen erkennbar sind.

Das Hauptinteresse betraf die Unterschiede der Rohrtemperaturen bei zwei unterschiedlichen Regelungsstrategien: Wasserstandsregelung oder Überhitzungskontrolle. Neben der Simulation des Normalbetriebs dieser Varianten wurden auch dynamische Vorgänge simuliert, z.B. das Drosseln eines Rohrs oder die Zuflussverringerung. Für Modellierung und Simulation wurde APROS genutzt, eine hochentwickelte Softwareplattform für effizientes Modellieren und DS von industriellen Prozessen. Modellentwicklung und die interessantesten Simulationsergebnisse werden beschrieben.

Authors

Jari Lappalainen Licentiate of Science (Technology) VTT Technical Research Centre of Finland Senior Scientist Espoo/Finland

Harri Blom Bachelor of Science (Technology) Fortum Power and Heat Oy Mechanical Maintenance Manager Naantali/Finland

Kaj Juslin Doctor of Science (Technology) VTT Technical Research Centre of Finland Key Account Manager Espoo/Finland

Introduction – Multi-faceted simulation

Process and automation engineering projects utilise different kinds of mathematical modelling and simulation related software tools. These tools are typically used for obtaining information about a new process plant under construction, or analysing and developing a current one [3]. The common need is to support decision-making in engineering work.

Steady state flow sheet simulators provide the state information in various locations of the process system. The state comprises typically pressure, temperature, flow, enthalpy and fluid composition. The inputs to the model are process connections and equipment specific parameters, but no detailed dimensioning information is needed. The steady state studies demonstrate how different options in the process concept affect on the performance of the plant. This enables evaluation about the feasibility of the concept in the pre-design phase, and to roughly optimise the efficiency of the power plant within the given economical limits.

The detailed dimensioning of equipment, crucial part of an engineering project, is typically done using proprietary dimensioning programs, e.g. by a boiler manufacturer. These include steady state mass and energy balance solvers, and a great number of experience-based correlations for specific process features as mass and heat transfer, combustion and emissions [3].

Computational Fluid Dynamics (CFD) is used to predict flow of fluids inside a piece of equipment. Heat transfer is often included in the studies. For example, boiler suppliers are interested in temperature and flow fields inside the furnace with different designs. The CFD programs help to optimise boiler geometry, and fuel and air feed locations for efficient combustion and heat transfer.

A dynamic process simulator differs from steady state simulation with its capability to predict dynamic behaviour. It differs from CFD by using coarser discretisation thus being able to capture larger scope of the process system. It aims to provide a virtual tool that can be operated similarly to the actual plant. Usually however, substantially more information about the system is obtained, than by normal process measurements (which naturally do not exist in design projects). The increasing number of successful simulation applications grows confidence that a sufficiently accurate simulation models can be built up, in an economically feasible way, entirely based on design data.

Traditionally, the data in different engineering systems has been stored in heterogeneous formats. Simulation software does not make an exception, as usually it comes from different providers than CAD systems. Deployment of simulation has suffered a lot from this separation aside of the main stream of the engineering work flow. During last years, there has been active development to dramatically improve tools interoperability in engineering. A key to interconnect and re-use data in different engineering tasks and phases is to apply common well-defined semantics for the data. The software products used must be open to enable export and import of the data contents and models. This need has been widely recognized and the development work is undergoing [10].

Dynamic process simulation provides virtual plant

The demands of the task at hand, and the modelling approach (somewhat equal to software used), determine the accuracy and level of details in the simulation. Input data for a plant scale DS model are process connections, physical dimensions and positions of process equipment and pipelines, equipment-specific parameters (e.g. pump and valve curves), automation concept diagrams, control parameters and initial condition information. In engineering projects, part of the input data is produced by steady state simulation, various dimensioning calculations, and even CFD. The engineering work flow and interchange of data play important role to squeeze down the costs of model building [2]. The input data partly overlaps the input data of the steady state simulation, which some simulator products utilise by offering export of the steady state model into a dynamic version.

The major uses of plant scale dynamic process simulation can be summarised as follows. The different use types are accompanied with a reference to an example study.

- Development of control strategies. This is the classical use of DS where simulator is used as test bench for control development [8].
- Analysis of the system operation. A key benefit of DS is to conduct "what-if experiments" that are not possible in the real plant. This enables detailed studies of different transients, such as load or grade changes, but also disturbances, malfunctions and accidents. The model can be used for tuning parameters or developing the system and work practices, in a manner that planned transients are in tight control, and disturbances are detected earlier, and the plant is recovered faster [6].
- Verification of design. Benefits are gained at two levels: integrated verification of the process and automation design, and verification of equipment dimensioning. Process and automation interconnections make DS the only way of evaluating a novel process concept and its controls, if plant scale experiments are not possible [4].
- Testing of control system. By connecting the actual DCS (Distributed Control System) to the process simulator, functionality of the system can be tested and commissioning of the system can be simulated and find automation system flaws can be identified which would otherwise not be detected until on the plant. Also the controllers can be pre-tuned with the simulator. This can lead to a significantly shorter commissioning time of the automation and earlier start of production [5].
- Training of operators. Simulation training is an efficient tool to speed up the start-up curve of a new plant, to imbed best operational practices for all operators, and to ensure the safe operation of the plant in all circumstances [7].
- Development of operational practices and the control room. A simulator can be used for developing the control room in a manner that the operator has the right information at hand at the right time thus improving plant safety and economy [9].

The ultimate benefit of DS is gained when it is incorporated in the engineering workflow, supporting different phases of the life span of a process plant in a cost-effective way. The model is constructed in the basic design phase, used in evaluation of design, also in developing of operator displays, then re-used within DCS checkout, and finally in operator training. Later on, the simulator can be utilised in different process and control analysis tasks, and in planning of plant modifications. The simulation case presented here, describes an example of an ad-hoc type of simulation project, where rapidly built, tailored simulation tool assists in solving a specific problem at a power plant.

Case study – Evaporator with pipe ruptures

Problem formulation

The case study assesses conditions of evaporator pipes in a pulverised coal power plant in Naantali, Finland. History of the 315 MW power plant origins to the 1970s, with a number of small retrofits taken place during the years. One such a project was undergoing in summer 2010, including reconstruction of some evaporator pipes that had suffered damages, including pipe burst, since the last plant maintenance shut-down. The material analysis suggested that the damaged part of the pipe had experienced high temperatures (over 500 °C) for substantially long times. Questions arose of circumstances for excessive heating, and, their connection with the recent changes made in control strategy.

The circumstances were too challenging for experimental study, so the plant engineers proposed modelling and simulation might give answers to the questions. The potential tool for the task, APROS, was known because it is widely used in the company.

The modelling environment

This simulation tool provides easy on-line access for configuring and running the simulation models, solution algorithms and model libraries for full-scale modelling and DS of processes, including combustion power plants, nuclear power plants, and pulp and paper mills. Besides the process, also automation and electrical systems can be modelled in detail. The extent of the applications varies from small computational experiments to models for full-scope training simulators. The model libraries have been comprehensively validated against data from physical process experiments.

The simulator offers predefined component models that are conceptually analogous with the actual devices, such as pipes, valves, pumps, heat exchangers, reactors, tanks, measurements, signal processing, controllers, electric devices, etc. The user drags and drops appropriate process components from model library palettes, draws connections, and enters process related input data. Parameterisation is straightforward, and most importantly, the tool hides all solution algorithms.

The model libraries include models from simple to high fidelity. This way one can create an optimal model structure in respect of model fidelity needs, development time available, and simulation speed requirements. Several types of solvers for thermal hydraulic networks can be used, depending on the demanded fidelity level. The mostly used thermal hydraulics solver is based on dynamic conservation equations of mass, energy, momentum and component mass fractions. It provides means for solving of fluid mixture flows, heat conduction in solid structures and between fluids and structures. Other solvers comprise of a sequential flow solver, solver for forced single phase flows, and solver for non-equilibrium separate phase flows. By using very short time steps even fast transient phenomena can be studied. Usually the user lets the time step vary based on process conditions. This enables increased accuracy whenever needed, i.e. during fast transients, but fast calculation during normal, more stable process conditions.

In the solution, the model is considered as a network of nodes, i.e. control volumes, and branches, i.e. connections between the nodes. This calculation level network is managed automatically by the process component level, which is the level where the user operates. The primary state variables of the thermal hydraulic nodes are pressure, enthalpy, and component mass fractions, and flow velocities for branches. Material property functions are used in calculating various quantities, such as density, viscosity and heat capacity according to the state variables. The equation solver processes the large systems of linear equations, which arise from the discretisation and linearisation of partial differential equations with respect to space and time. A powerful feature is that the simulation run can be continued promptly after any configuration change. Also, the complete model information can be saved into a model snapshot file containing the full model configuration and its momentary state data at the specified time instant. Accordingly, at any time, the user can backtrack to a snapshot once saved in the past. The openness of the simulation platform allows the inclusion of the user's own models in the calculation, as well as easy connection to control systems.

In addition to model configuration, the modelling interface provides tools to manage simulation experiments, and to visualise the dynamic behaviour of the simulated system. The user can freely select any component variables to be displayed on the flow sheet diagrams as numerical values (monitor fields) or as trends in separate windows. During a simulation run, the model diagrams can be used for modifying component properties, e.g. controller set values, controller tuning parameters, starting/stopping devices. Any variable data can be logged to file for post-processing purposes.

Building the model

Simulation projects typically contain modelling at different levels of accuracy, even



Figure 1. Model diagram of an individual tube line in one half of the evaporator. The numbers next to the circular thermohydraulic points show steam volume fractions in the tube location (0 = liquid, 1 = steam). The orange coloured numbers give the approximate length of the tube line in the position.

within a single process model. The main reason for this is cutting down project time and costs, yet capturing the relevant behaviour of the process. The parts included in the modelling are selected for different reasons. For example, controls often play a major role in the plant dynamics, and one cannot even run a rigorous process simulation for a longer time without them. There are, however, automation functions that can usually be omitted. The suitable accuracy level of utilities modelling varies from case to case. Recirculation streams, even small ones, can potentially cause meaningful dynamics, thus forcing the modeller to consider extension of the modelling further than just the main stream. Then, major simplifications may be justifiable for that part of the model.

Real life processes take place in 3D, which challenges the process modeller, and leads to simplification in dimensions. Naturally CFD simulations would capture the space more realistically, but consequently, the scope of simulation would be much more limited. Typically understanding of what is relevant for solving the problem evolves during the work. Possibility to vary the modelling accuracy according to the needs is an absolute demand for efficient simulation engineering. This can be tackled by hierarchical model description, by offering different thermo hydraulic models for calculation of flows, by different accuracy options for process unit models, by offering fundamental mechanistic building blocks for the model development, by offering flexible interface to link user's own routines in simulation, by supporting also transfer function type of modelling, etc. And it is important that the different options are available within a single model. In this case study, the scope of the modelling covers half of the evaporator, including 16 tube lines. The evaporator comprises two identical halves. The half with most tube damage was selected. The model starts from a point downstream the economiser, before the header that distributes the individual evaporator tube lines. The length of each tube line inside the evaporator is approximately 260 m, and this length was discretised into 65 pieces in the model. Additionally, there were two tube lines that had more accurate discretisation. After evaporator, the tubes are combined in a header, and the resulting flow is lead to a water-steam separator (Sulzer bottle), which acts as an end boundary for the model.

Most of the input data was taken from the original design drawings, including mainly locations and physical dimensions of process equipment and tube lines. The length and friction losses due to tube bends were studied and modelled in detail from the design drawings, in order to reveal any differences among the individual tubes due to their different routes in the boiler walls. Appropriate data for defining the model boundaries were also needed i.e. pressures, temperatures, and the heating power to the evaporator tubes.

The selected thermo hydraulic model for this simulation study was the non-equilibrium separate phase flow (so-called 6-equation) model, which calculates dynamic mass, energy, and momentum balances for both liquid and gas phases of water. This choice guaranteed that the modelling should capture any thermo hydraulically meaningful phenomena taking place in the evaporator tubes.

Model diagrams were used to organise the model configuration into suitable sub-processes (Figure 1). The diagram shows tube line number 14, which is part of the water wall. In order to provide a realistic model for surface temperatures of the evaporator tube inside the furnace, it was essential to model the tube route on the walls including accurate positioning of turning points and elevations. The route of the tube can be easily followed. It comes in at the back wall, goes down to the cone, and starts to zigzag horizontally until the bottom part is fully covered. Then it rises upwards in the front wall, and zigzags the whole half of the furnace up and down, until comes back in the starting point and exits the furnace. The burners and air ducts in the corners are marked in the figure, too. The tube model composes of a series of heat tube modules, having a thermo hydraulic point in between. The heat tube component includes also the tube wall's heat structure. The average length of the tube parts is four meters in this case. In addition, the heat structure of each tube module is axially divided in two parts. The input and output points in the graphics allow one to jump to the specific diagram(s), where the model continues.

There are 16 individual tube lines that travel throughout the furnace half, installed next to each other. An own graphical diagram for each tube allowed use of copy-and-paste after completing the first one. Thus, manual editing work was minimised. Naturally, the tube lines created this way, appear to be identical in their parameters, too. Modifications to achieve the real tube parameters, i.e. lengths, friction losses, and turning point elevations, were easily performed with the aid of Excel sheets that had been filled with the relevant data for each tube line. This data, and modification that might be needed subsequently, was updated to the model database by using automatically created command scripts.

The modelling did not include the burning and flue gas side of the boiler. Accordingly, the heating power from combustion is defined as boundary condition to the evaporator tubes. Initially, the heating power was considered as a constant value throughout the water wall. The first simulation results revealed that the approximation was not realistic. The heating power was then modified to depend on the tubes' position inside the furnace, including seven heating power levels, ranging from 150 to 500 kW/m^2 . Thus the bottom part of the evaporator, for example, was treated with the lowest power. We were fortunate to get useful data from a recent CFD study to derive the power profile of this boiler. If this knowledge is missing, applicable informa-



Figure 2. Control mode 1. Step change (10 %) upwards in heating power at time 60 s, returning to the original level at 240 s. Blue colour marks liquid flow.

tion from the boiler supplier or literature will have to be used instead.

es, as well as 4430 heat structure nodes. Despite of the rigorous thermo hydraulic model used, it runs three to four times faster than real time in a typical laptop PC (2.40 GHz, 3 GB RAM, Windows XP).



model used, it runs faster than real time i (2.40 GHz, 3 GB RAM



Figure 3. Control mode 1. Step changes up and down. Individual mass flows inside the 16 evaporator tube lines.

VGB PowerTech 1/2 2012

Results

The simulation study focused on the peak temperatures and their localisation in the evaporator tubes in different situations. Two different control strategies to operate the evaporator were to be emphasized:

- Control mode 1: Level control of the water-steam separation bottle
- Control mode 2: Superheating state control

The traditional operation mode (Control mode 1) keeps part of the outcoming water from the evaporator in liquid phase, and accordingly the water-steam separator is run with liquid level in closed-loop control. In the other mode (Control mode 2) the outcoming steam is superheated, and the level of superheating is controlled. The reference states representing operation in these control modes were taken from historical data, being steady operation periods in the plant some weeks before the modelling project. To reach an operational state like this in the model, the boundary pressures and flow conditions were firstly set according to the reference state. Then, the heating power was adjusted to produce a proper match with the plant measurements. While the level of heating power was adjusted, its relative profile was kept unchanged.

Besides the simulation of normal operation in these modes, also transients were simulated, such as throttling of a tube, and reducing feed flow. Special emphasis was put on simulation analysis to the part of the evaporator where the tube damages had taken place. Some samples of simulation results are described in the following.

 Simulation 1: Control mode 1, change in heating power

Figure 2 and Figure 3 illustrate general behaviour of the process, and the flows in the 16 evaporator tubes, when the heating power was first increased by 10 % upwards, and then returned back to the original. It is seen in Figure 2 that the increased evaporation increases the pressure loss inside the tubes, and the feed flow goes temporarily down, until the feed flow control loop corrects the situation (valve position from 41 % to 45 %). As a consequence of the power increase, practically all liquid water evaporates, which is shown as decrease of the liquid mass flow in outlet. Figure 3 gives further details by showing individual flows in all the 16 tube lines.

The differences in total mass flows between the individual evaporator tubes were checked in all simulation studies. It was found that, like in this example, the differences between the 16 tubes were relatively small. Typically, all the flow rates were within \pm 5 % in normal operation. In other words, the original design proved to be of good quality. Therefore, the main emphasis was put on some selected tubes, the simulation data of which were written to files



Figure 4. Control modes 1 and 2, the reference conditions (in steady state). Profiles along the evaporator tube line number 14.



Figure 5. Control modes 1 and 2. Throttling the tube line number 14. Temperature profiles along the tube line length. Dotted lines are for Control mode 1, solid lines for Control mode 2.

and analysed. Tube 14 in Figure 1 was one of those under detailed study.

 Simulation 2: Control modes 1 and 2, reference conditions

Power plants are operated long times in rather steady conditions, and it is impor-

tant to analyse the system in these typical conditions, especially if there is suspicion of harmful condition for process equipment. Figure 4 illustrates the conditions inside the evaporator tubes in control modes 1 and 2. A steam void fraction is presented as well as pressure and temperature as function of the cumulative length of the tube. It is seen that the pressure and temperature are higher in control mode 2, and evaporation starts earlier than in Control mode 1. Furthermore, in Control mode 2, in the end of the tube, all liquid is evaporated and steam gets superheated.

 Simulation 3: Control modes 1 and 2, one tube throttled

In the plant there are manual control valves for each evaporator tube line to adjust possible differences in the flow rates. In this simulation, one such a valve was closed by 25 % to mimic a situation that flow is hindered in the tube for some reason. The flow of the tube decreased by 21 %. The decrease was practically equal in both control modes. As a consequence, the total flow to the furnace decreased slightly (less than 1 %), but only temporarily, as returned to the set point by the feed flow controller. When settled, the flow difference between the largest flow rate and the flow rate of the throttled tube reached 29 %. Figure 5 shows the clear difference between the control modes. There are three temperature profiles along the evaporator tube length shown for both control modes. Control mode 1 is marked with the dotted lines. The lowest temperature profiles are from the water inside the tube. The somewhat higher values are for the surface temperature inside the tube, and the highest temperatures belong to the tube outer surface. The difference between the control modes is clearly seen in the end of the tubes, as in Control mode 2 the tube heats up close to 480 °C, about 35 °C more than in Control mode 1. As the steam is superheated already in the normal conditions in Control mode 2, the buffering effect of two phases is missing, and accordingly the temperature response gets higher in this kind of disturbance.

 Simulation 4: Control mode 2, feed flow decreased with constant heating power

This simulation study illustrates the dynamics of the water wall tubing in disturbance, where the evaporator feed flow rate drops quickly but heating power stays constant. The feed flow was changed simply by setting 30 % lower set point for the controller. The outer surface temperature of one tube was again selected to demonstrate the transient. Figure 6 shows the reference state for Control mode 2 (also shown in Figure 4), and four time instants after the initiation of the disturbance. The new steady state is reached in four to five minutes, and the end of the tube heats up to over 500 °C.

Discussion

Utilising simulation in the projects is decided based on valuations between the value of the sought answers and combined effort of modelling, simulating and interpreting the results. The price of a process simu-



Figure 6. Control mode 2. Decreasing feed flow by 30 %, with unchanged heating power. Outer surface temperature profiles along the evaporator tube line number 14 at different time instants.

lation consists of software licenses and mainly of manpower. Hence, the productivity in the model-building phase determines the costs of the model. In this phase the user interface is important, as well as good interfaces for exchanging data with other engineering systems. Naturally there are questions like technical suitability of the simulation tool for the task, expected accuracy and reliability of the results, as well as speed and robustness of the simulation that must be tackled, too. These questions become easier to be answered when simulation becomes a standard tool in the engineering tool box of the company. This requires determined development of simulation expertise, rather for a team than for one person.

This paper discussed the current status of simulation in engineering projects, illustrated the use of DS, and gave a case example of an engineering problem solved at the power plant. The simulation study was initiated due to the damages in the evaporator tubes, followed timely by a recent change of control strategy. The simulation study showed that operation in superheating control mode does not stress these parts of the tube lines substantially more than level control mode. This was seen both in normal operation and in the transients simulated. In superheating control mode, end of the tube lines heated up more than in level control mode, but the risk for the tube material was still considered low in normal long-term operation conditions. In superheating control mode, however, the end side of the tubing is clearly more sensitive for excessive high temperatures in case of power or flow disturbances. This must be addressed when planning operational practices. The major outcome was a good understanding of the practically meaningful factors in the problem case.

The DS model built in the project will be updated into coming simulator versions, and accordingly may serve in solving future problems in the power plant. Therefore, it is important to document not only the results, but also the strengths and weaknesses of the model. In this model, the strength is the detailed modelling of the tube lines, including the path on the walls, friction losses, heat transfer and thermo hydraulic solution. The simple approach used in modelling the heating power to the evaporator tube lines as static source terms can be considered as a weakness. The power stayed constant regardless of the conditions inside the tubes, and in the tube wall. Simulation experiments with most extreme conditions raised a question if this approach is still valid. A proposed development step is to model the combustion and the flue gas flow in the furnace, too. Then the tube conditions would affect on the heat duty obtained from the hot flue gas.

References

- Apros 2011, Apros Process simulation software, 8.6.2011, Available: www.apros.fi
- [2] Engl, G, Kröner, A, and Pottmann, M.: Practical Aspects of Dynamic Simulation in Plant Engineering, In: Pierucci S, Buzzi Ferraris G, editors. Proc. of ESCAPE-20, 2010, p. 451-456.
- [3] Kettunen, A., and Paljakka, M.: Process simulation in power plant design. Proceedings of SIMS 2006 the 47th Conference on Simulation and Modelling, Helsinki, Finland, 27-29.9.2006, p. 176-181.
- [4] Kokko, T., Huhtelin, T., Ahola, J., and Lautala, P.: Integrated process and control design of new stock preparation system. Proceedings of Control Systems 2000, Pulp and Paper Technical Association of Canada, Victoria 2000, p. 63-66.
- [5] Laakso, P., Paljakka, M., Kangas, P., Helminen, A., Peltoniemi, J., and Ollikainen, T.: Methods of simulation-assisted automation testing, VTT Tiedotteita - Research Notes 2289, Espoo Finland (2005).
- [6] Lappalainen, J., Myller, T., Vehviläinen, O., Tuuri, S., and Juslin, K.: Enhancing grade changes using dynamic simulation, TAPPI JOURNAL, Online Exclusive, December 2003, Vol 2(12).
- [7] Pyykkö, J., and Leppäkoski, J.: A novel training and engineering simulation concept for power plants. 2001. ISA Product Code: TP01POW500 (2001).
- [8] Nissinen, A., Tuuri, S., Rinta-Kokko, P., Airikka, P., Huhtelin, T., and Lautala, P.: Modelling and simulation of web forming process with dilution headbox, Proceedings of the 19th IASTED International Conference Modelling, Identification and Control, IASTED, Innsbruck 2000.
- [9] Näveri, J., Tahvonen, T., and Hakasaari, P.: Testing and Utilization of Loviisa Full Scope Apros Model in Engineering and Development Simulator, Proceedings of International Youth Nuclear Congress IYNC 2010, Cape Town, South Africa, 12-18 July 2010, Paper No. 237.
- [10] Simantics 2011, Simantics, 8.6.2011, Available at: www.simantics.org