

Modelling and dynamic co-simulation studies of oxy-fired power plant

Hannu Mikkonen^{1*}, Mikko Jegoroff¹, Jari Iappalainen² and Jouni Savolainen²

¹ VTT Technical Research Centre of Finland Ltd, Jyväskylä, Finland

² VTT Technical Research Centre of Finland Ltd, Espoo, Finland

*Hannu Mikkonen, +358 40 5953 909, hannu.i.mikkonen@vtt.fi

Abstract

What kind of dynamic characteristics a new process concept will have? Is it easy to operate? Which control strategy is the best? Suitable simulation tool will give answers to these kinds of questions. Modelling and simulation software provide an environment for process modelling and accordingly, the process phenomena can be simulated and design solutions can be evaluated. This paper focuses on dynamic process simulation with one dimensional models. With simulations it is possible to carry out process optimization, solve process bottlenecks and evaluate, for example, different alternatives to integrate process areas before building the plant. The use of simulators for training is increasing nowadays when the target is to make operators familiar with the process well before the commissioning. There are different modelling environments for different needs. It depends on the case and targets what kind of modelling would be the most fruitful, and finally, on financial issues what kind of simulation, if any, will be implemented. The best cost-efficiency can be achieved when simulation tools are used early in the engineering project, and the use is continued throughout the project, for design, testing and analysis, for training and operation support as well. This article presents a study, where Circulated Fluidized Bed Boiler (CFB), Air Separation Unit (ASU) and CO₂ Purification Unit (CPU) were modelled dynamically using the Apros and Aspen Plus Dynamics programs. The dynamic simulation of the whole CCS capable production chain ASU+boiler+CPU was achieved by combining the tools, in other words, co-simulating the system.

Keywords: CFB, ASU, CPU, CCS, modelling, dynamic simulation, oxy-firing, co-simulation, Apros, Aspen

Introduction

Depending on the development history of different simulation tools, there are plenty of differences in solution methods, material properties, chemical reaction capabilities, ability to handle different phases (solids, fluids, gases), and naturally, in the unit operation model libraries available for the users. Thus it is quite common that a single tool does not fit all the requirements needed to fulfil the simulation study targets. In this study Apros was used for boiler and turbine side, and Aspen Plus Dynamics for the air distillation and CO₂ purification side. Apros is very powerful tool for dynamical modelling of the power plant and turbine islands, including solid, liquid and gaseous material streams, and it has also large automation and electrical libraries. Aspen has very large chemical libraries as it has been developed mainly for the needs of chemical industry. In this case the modelling tools were communicating through the Matlab Simulink program.

This paper will present an overview of the novel CCS capable power plant concept, the modelling of the process areas, the communication principles behind the co-simulation, and illustrative simulation results of an operational transient. Finally, conclusions and future prospects will be given.

Process description

The boiler island design is based on Amec Foster Wheeler's technology. The boiler island includes feed systems for fuel, sand and limestone, primary and secondary oxidant streams, furnace, cyclone, return leg, baghouse, heat recovery system to preheat the gaseous oxygen streams, flue gas recirculating system, and different types of heat exchangers to transfer heat from flue gas and fluidized solids into water, and on the other hand, from the water cycles to the gas streams. Flue gas circulation is used only in the oxy firing mode. The circulated CO_2 rich flue gas is mixed with the O_2 feed, thus diluting the formed synthetic oxidant gas into a reasonable range of O_2 content, to control the combustion temperature and guarantee safe and economical operation of the boiler. The boiler model gas side and the turbine island are illustrated in Figure 1.

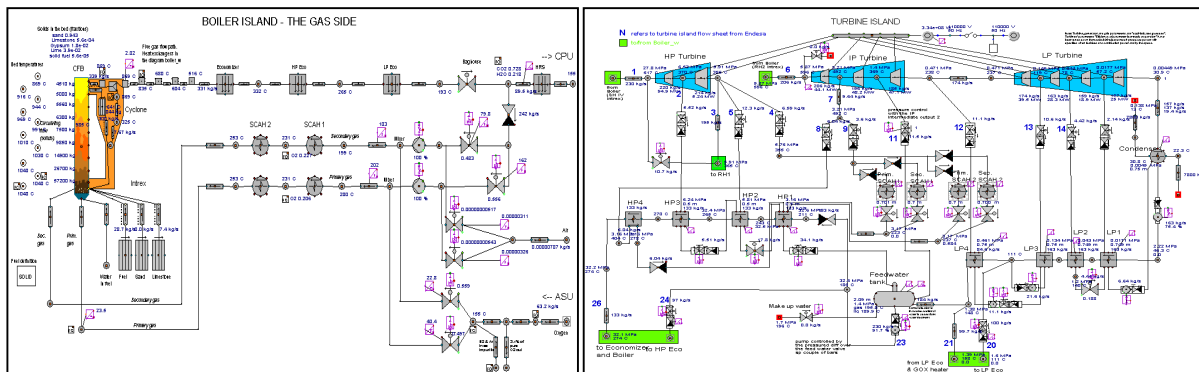


Figure 1. The boiler and turbine island (Apros).

The furnace side heat transfer is separated in convection and radiation heat transfer and the user can define the heat transfer coefficients or alternatively Apros will calculate them depending on the gas and sand concentrations and flow velocities. During the load changes the bed solid material profile is changing which causes characteristic dynamics for the heat transfer phenomena like in real boilers. Also additional materials like iron and boiler masonry were included into the model to more accurately achieve realistic boiler dynamic behavior. In the process side all the needed main equipment like pumps, fans and valves were included in the simulation model.

From the control point of view there was a need to develop sliding pressure control for the main steam pressure. Main steam temperature was controlled by using three spraying water valves. Feed water amount was controlled by using a pump for pressure and a control valve for flow controlling according to the boiler load. The boiler side control system included also a main load controller, which was measuring the turbine power (MW) and controlling the fuel feeding. According to the fuel feed, the total air/oxy demand was calculated and divided further for the primary and secondary air/oxy controllers. Flue gas oxygen content was controlled by using separate controllers depending on which mode (air/oxy) was in use.

The turbine island was separated in high, intermediate and low pressure part. In every part of the turbine section efficiency and the taps were defined according to initial information acquired from the turbine supplier. After the turbine, condenser level was controlled by a pump as well as condenser cooling water amount. The condensate was then pumped to the low pressure preheating system where it was preheated in four sections. There was also additional low pressure economizer where part of condensate water was circulated and which was taking heat from the flue gas duct. The feed water tank pressure was controlled by using a turbine tap valve. After the feed water pump and valve, feed water was circulated partly via parallel high pressure economizer and high pressure preheating system up to the main economizer and back to the boiler riser tubes.

The ASU plant operation is based on the cryogenic distillation. Distillation was made in a three column system including low, intermediate and high pressure columns. At first, incoming air was compressed

in three sections. After compressing pressurised air was flowing to the HP and IP columns, where the first distillation step was carried out. One part of the air flow was circulated via turbine which was flashing air to lower pressure and at the same time cooling air to acquire colder conditions. Cryogenic distillation is based on the evaporation temperature difference between oxygen and nitrogen. The evaporation point of O_2 is higher ($-183^\circ C$) compared to N_2 ($-196^\circ C$) and this is why O_2 is taken out from the bottom of the column as liquid and N_2 from the top of the column as gas. Finally in the first step purified gases from the HP and IP columns were flowing to the LP column where final distillation was made. For all distillation columns pressure and flow controllers were implemented in the model. The pressurizing consumes a lot of energy and for this reason integration of waste heat from the compressors to the boiler is necessary. The model included also the heat exchangers which are used for inlet air cooling with the product flows (O_2 and N_2).

The CPU also consumes a lot of energy because of flue gas pressurizing. The pressurizing as well as cooling is needed for incoming flue gas liquefaction. Also in this case waste heat energy has to be integrated to the boiler part in order to improve the plant economy. The ASU and CPU models are illustrated in Figure 2.

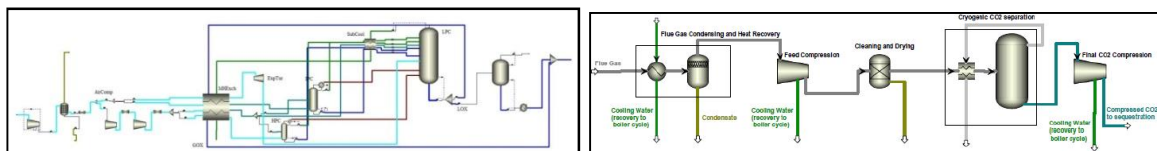


Figure 2. The Air Separation and CO₂ Purification Units (Aspen Plus Dynamics).

In ASU and produced gaseous oxygen amount was controlled in two positions. Firstly, main oxygen demand was calculated according to the boiler fuel load (as earlier described) and was given as a set point for the ASU plant. Secondly, because of delays in oxygen production, O_2 demand was given also as a set point for gaseous oxygen buffer tank. This buffer tank has a capability to respond quickly enough for the boiler load changes in most of the disturbances. The buffer tank consists of the gaseous oxygen (GOX) header and liquid oxygen (LOX) tank. To enable sufficient pressure there were two ways to handle the GOX pressure. When the load was decreasing, the GOX header pressure was controlled by ventilating O_2 out from the header (overpressure). During the load increasing the pressure was maintained by evaporating LOX from the liquid oxygen tank. The evaporating was carried out by using turbine tap steam in a condenser type preheater. Model diagram of the oxygen buffer system is illustrated in the Figure 3.

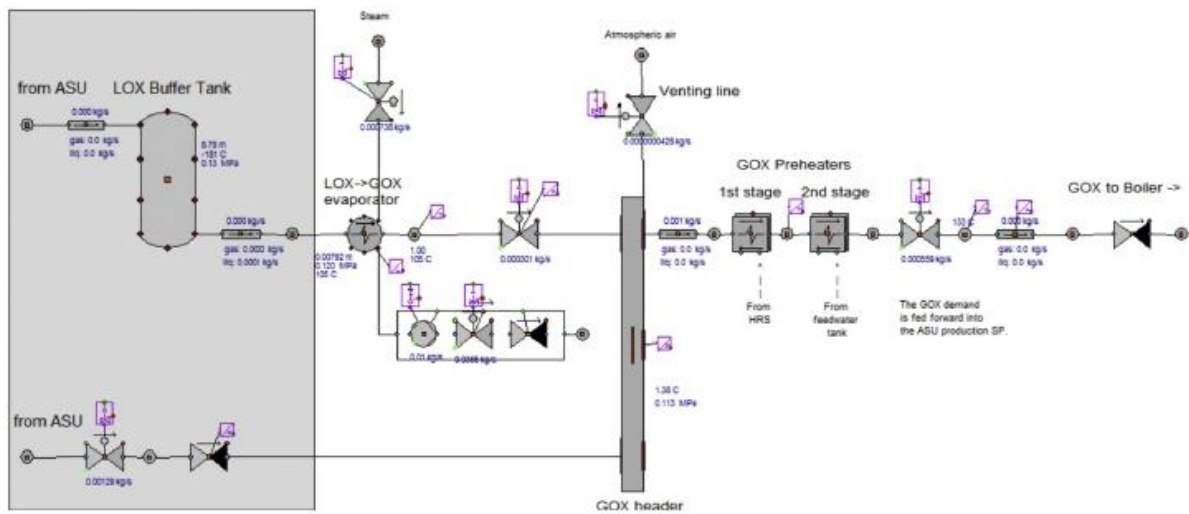


Figure 3. Model diagram of the buffer system in the oxygen supply line (Apros).

The CPU plant was defined as a two train system. Two trains mean two similar compressor rows which included four compressors each with same pressure proportion between the compressors. The cooling was needed after every compressor to enable right gas conditions before the next pressurizing step. After pressurizing, rest of water was removed from the flue gas before the purifying unit. Final CO₂ purification was made in separation tanks in 30 bar and -30°C based on flashing the gaseous impurities out from the tank while CO₂ liquid was taken out from the bottom of the tank. Liquid CO₂ was then pressurized to supercritical condition (110 bar).

As mentioned above these two modelling tools Apros and Aspen were communicating through the Matlab Simulink program. The interface is communicating in two directions so that one program is calculating at the time. The results required for the co-simulation are given to the other program, which uses the result data as boundary conditions in the interface of the models. The Matlab Simulink application works as a master, which is taking care of the time synchronizing.

Connecting Apros and Aspen Plus Dynamics

Initial screening of dynamic linking techniques

Three techniques for linking Apros and Aspen Plus Dynamics were investigated:

- Direct simulator-to-simulator OPC connection
- OPC- and Excel-based connection
- OPC- and Matlab/Simulink-based connection.

The direct OPC connection was realized with the Aspen Plus Dynamics's OPC tools and the OPC Server of Apros. It was noticed that connecting the simulators with this technique seemed to be infeasible. The main reason for this was that both Apros and Aspen Plus Dynamics will simulate (i.e. perform numerical integration of their model equations) independently of each other. In other words, there is no guarantee that Apros' simulation clock will run at the same pace as Aspen Plus Dynamics' clock. This will pose problems especially when the two simulators run at a considerable speed difference, since the faster simulator's clock will run ahead of the slower one's. Thus the values transferred from simulator to another will not have any timely relevance to each other. In other words, they are not synchronized. After this was noticed, this alternative was abandoned.

The second connection alternative was to use Excel as a mediator between Apros and Aspen Plus Dynamics. The basic idea was to have Excel commanding both simulators to simulate for a certain period, say 1s, and then wait until both simulators have done their job. Next data would be transferred from simulator to another and the process repeated. This way the two simulators' clocks would remain synchronized. Aspen Plus Dynamics offered readymade connection to Excel and example Visual Basic codes to achieve this. On the other hand, there was no direct way to connect Apros to Excel. Thus, it was investigated whether we could utilize OPC to connect Excel and Apros. Three free Excel OPC toolkits were tested, namely the OPC Office Link by Rensen Information Services Ltd. (<http://www.ris.co.nz/>), Resolvica's OPCEX (<http://www.resolvica.com/>) and Cogent's OPC DataHub (http://www.opcdatahub.com/Features/OPC_to_Excel.html). All three products offer easy ways to get data from an OPC server to Excel sheets, but controlling a simulator through the link proved to be difficult or even impossible. Such a control action, which was found to be missing, was for example loading of simulation models. For this reason the Excel-based connection was abandoned too.

The third connection alternative was to use Matlab Simulink as a mediator between Apros and Aspen Plus Dynamics. The connection from Simulink to Aspen Plus Dynamics was realized with Aspentech's own interface and the connection from Simulink to Apros with OPC (using the "OPC for Matlab" - product by Ipcos (http://www.ipcos.com/en/opc_for_matlab)). The entire linking system is depicted in the following Figure 4.

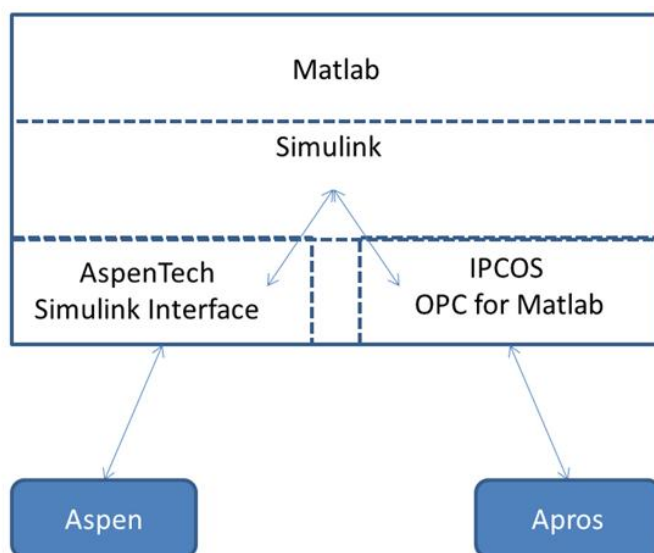


Figure 4. Matlab Simulink-based communication.

This system was tested with "toy models" and with the ASU+Boiler model (ASU in Aspen Plus Dynamics and boiler in Apros). Although some performance issues were raised, this way of linking proved to be the most promising. A view of the connection in Simulink is shown in the Figure 5.

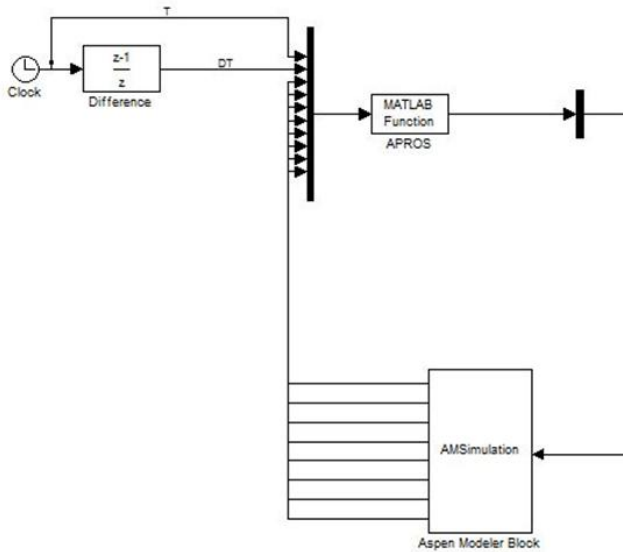


Figure 5. An Example of the Apros-Aspen link in Matlab Simulink.

Details of the connection

In Figure 5 we have one variable transferred from Apros to Aspen and eight variables transferred from Aspen to Apros. The number of variables is configured to both Apros and Aspen Modeller blocks as describe later. In addition to these, the Apros block takes in the current Simulink simulation time (T) and the time step (DT). For the Aspen Modeller Block one first defines which model (.dynf) is to be used. Next from the Input and Output tabs one defines which values are written to Aspen (Input) and which are read from it (Output). For the Apros block configuration of the block is done in a Matlab function `simApros`, which is in the m-file `simApros.m`. This code is called at every Simulink time step; it performs the needed simulation operations. In the configuration phase the two variables `readTag` and `writeTag` need to be edited by the user in order to accommodate the case at hand. Both of these are vectors, each element of the vector containing a string. Each string defines one tag for the Apros OPC connection.

Simulation of the system is done from Simulink. In Simulink the user defines the simulation time, in seconds. Also, the user has a choice of numerical integration method, used by Simulink. As there is no numerical integration to be done in Simulink, it is advisable to follow the recommendations of AspenTech: "Within Simulink, the variable step `ode45` (Dormand-Prince) integrator is recommended". Having defined these the running of the simulation is started by pressing the Play button of Simulink. When the simulation is started the Aspen model is reset to time zero. For the Apros model this is done already in the connection phase by `connectToApros`. Next the simulation cycle proceeds block-by-block in Simulink. For example, if the cycle starts from the Aspen Modeller block the following steps are taken:

1. Data is written to Aspen Plus Dynamics
2. Aspen Plus Dynamics is ordered to simulate for DT seconds
3. Data is read from Aspen Plus Dynamics
4. Data is written to Apros
5. Apros is ordered to simulate for DT seconds
6. Data is read from Apros

The time to simulate during one cycle, DT , is given by Simulink's solver. This six-step cycle is repeated until the defined final time of simulations, T , is reached. During the simulation data can be logged to files or to the screen from Aspen Plus Dynamics, Simulink or Apros. After the simulation is finished the OPC connections are closed.

Conclusions on the connection

Above we presented results from the evaluation of techniques to connect the Apros and Aspen Plus Dynamics simulators. The conclusion was that using Matlab/Simulink as the intermediary is recommended. The tests showed that

- data can be transferred from a simulator to another
- simulator clocks can be kept in synch
- models can be (re)loaded and the simulation experiment controlled.

The evaluation raised some future research issues. Firstly, it was noticed that when Aspen Plus Dynamics is ordered to simulate for DT every simulation cycle, it takes a while to do some preparation actions, before the simulation actually starts to run. This slows the system down. Thus it is recommended that the computer in which the system is used, should be as powerful as possible. This issue can also be alleviated by increasing the communication cycle (i.e. Simulink time step), as much as the Apros and Aspen models and the dynamics of the system allow. Secondly, it was noticed that the simulation models should be individually tested for the targeted simulation transients before connecting them.

Results

The simulation study presented below conducts a dynamic load change from 100% to 70% and back to 100% load. The simulation was carried out 15 seconds at the time after which Simulink applied the main parameters for the other simulation tool and gave a permission to start simulation. First the boiler load was kept steady for 18 minutes. After that fuel was ramped down 30% of the maximum load in 10 minutes. Then the load was kept steady for 54 minutes and after that ramped back to maximum in 13 minutes. In Figure 6 the main flows of the boiler are illustrated.

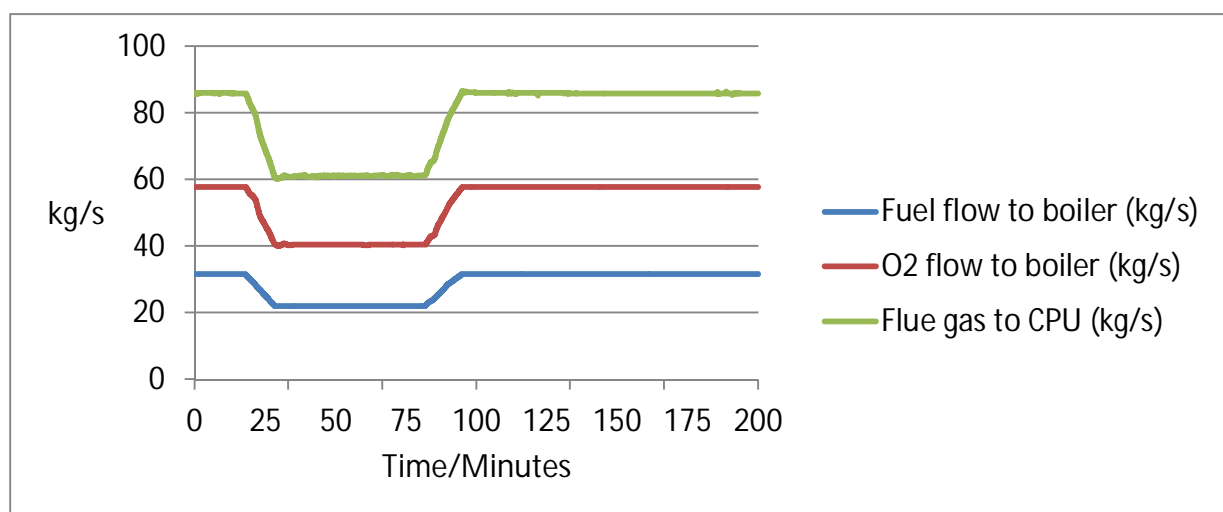


Figure 6. The main flows of the boiler.

In Figure 7 the main steam parameters are illustrated during the load change. There was little oscillation after reaching the minimum load which was a result of the boiler furnace solid material profile.

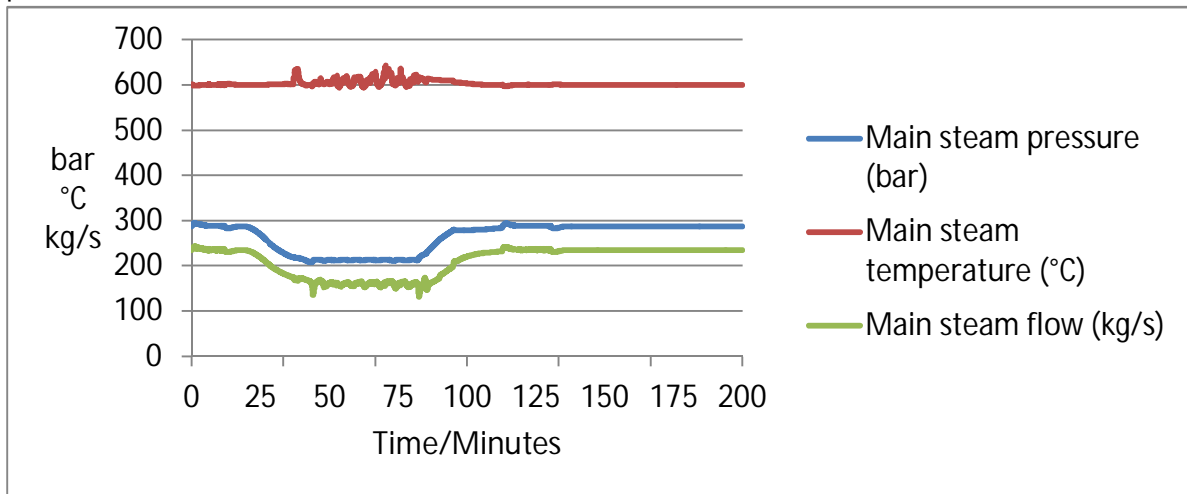


Figure 7. The main steam values.

In Figure 8 turbine power is illustrated during the load change.

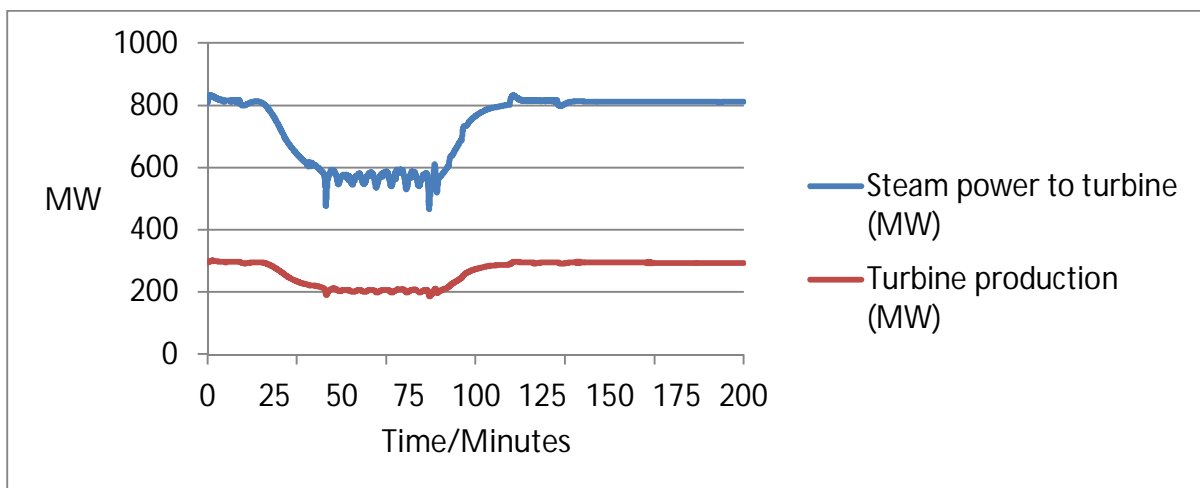


Figure 8. Turbine production.

In Figure 9 O₂ concentration in flue gas, and primary and secondary oxidants are illustrated during the load change. In this first generation concept of oxy firing, the O₂-concentration in oxidants is close to air firing values, typically between 21-28 mass-%. Flue gas oxygen was quite steady during the change.

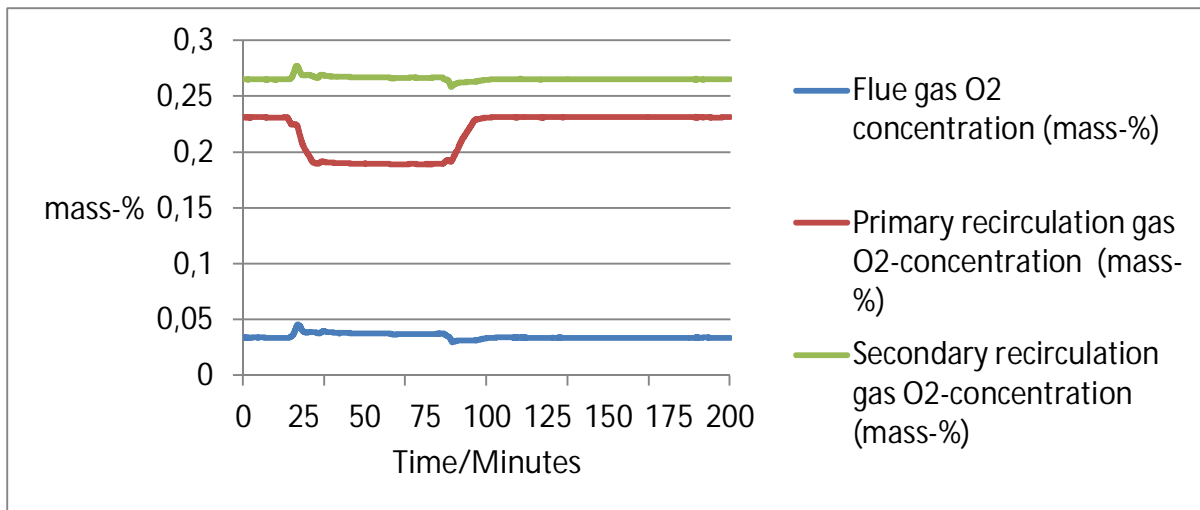


Figure 9. O₂-concentration in flue gas and primary and secondary oxidants.

In the following Figure 10 the main flows of the ASU are illustrated.

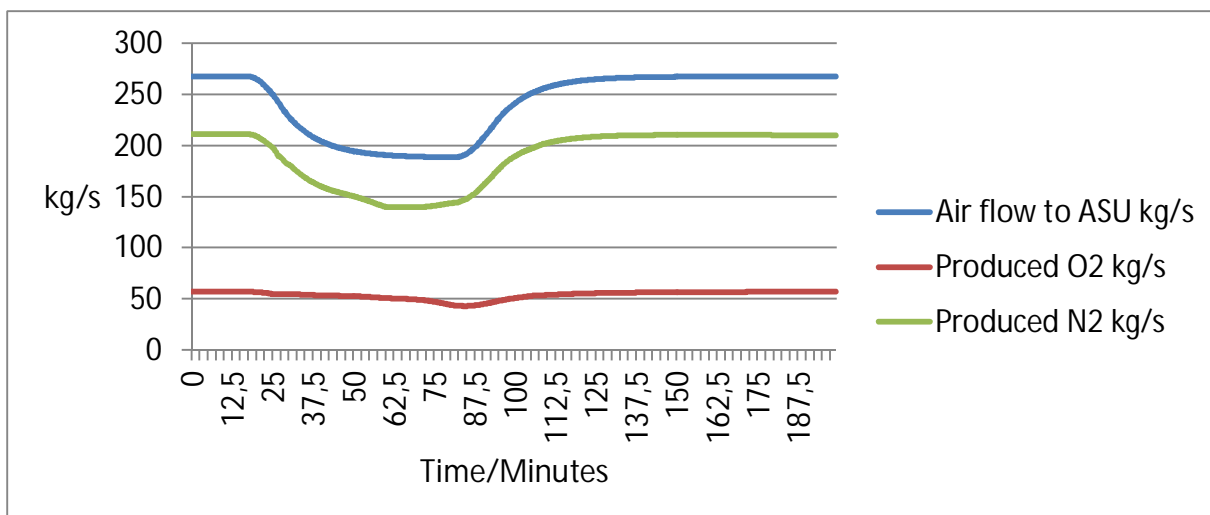


Figure 10. The main flows of the ASU.

Figure 11 shows oxygen and nitrogen concentration changes in ASU production during the load change. At lower load level the produced oxygen concentration was decreasing and as a result of this the efficiency of the whole system was decreasing.

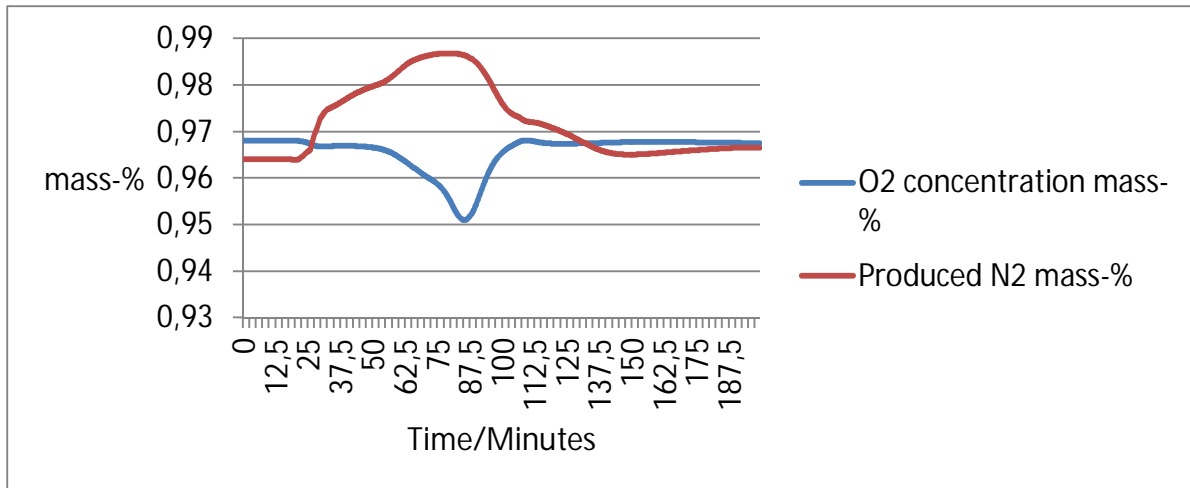


Figure 11. Oxygen and nitrogen concentration of the ASU product streams.

In Figure 12 the CPU main flows are illustrated.

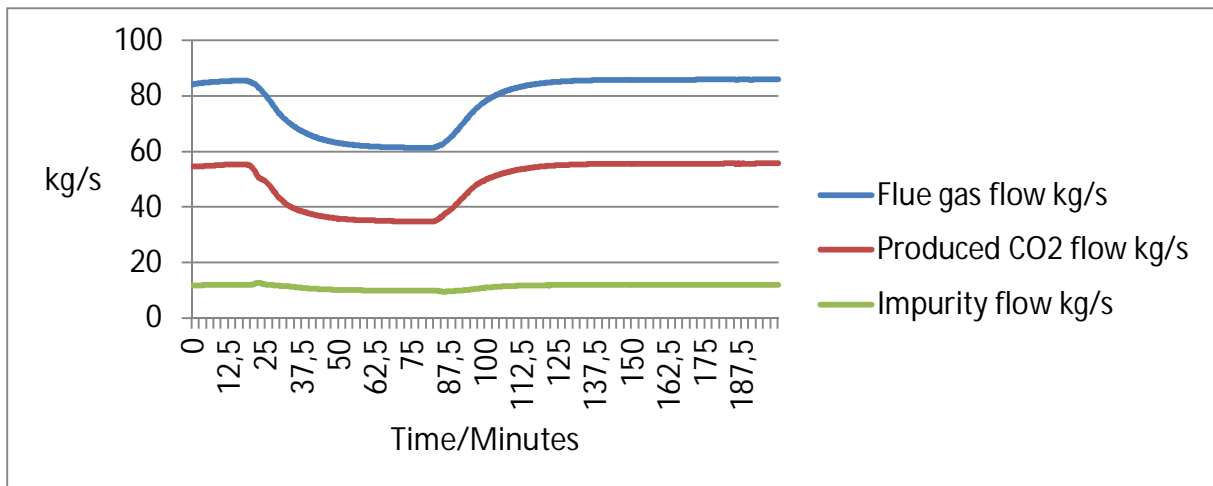


Figure 12. The main flows of the CPU.

Conclusions

This paper presented an overview of the novel CCS capable power plant concept, the modelling of the process areas within two commercial dynamic simulation platforms, the communication principles behind the co-simulation with the simulation tools, and illustrative simulation results of a load change. The Matlab Simulink based method was found workable for co-simulation of the Apros and Aspen Plus Dynamics simulators. The co-simulation approach proved to provide the benefits of both simulation platforms in challenging operational transients. It is obvious that dynamic process simulation offers a cost-effective and time saving way to develop new process concepts, evaluate the operability and controllability with alternative control structures and thus, improve the maturity of the overall system in early phase of the design.

The work with the full chain oxy combustion power plant concept continues. In near future, modelling and simulation of the 2nd generation oxy combustion concept will be presented. The overall system

efficiency will be improved, for example with additional heat integration points between the ASU, boiler and CPU plants, thus giving new challenges for plant operation and control.