Modelling of Pulverized Coal Power Plants in Carbon Capture and Storage (CCS) Networks

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Abstract

Carbon dioxide emissions to the atmosphere are getting the worldwide attention. Carbon Capture and Storage technologies promise to take an important role in climate change mitigation. However, nowadays no software can do a full chain analysis of the Carbon Capture and Storage for power plant systems. For that purpose Process System Enterprise with the support of Energy Technologies Institute (ETI) and other associates is developing a new tool-kit, which should have the models for entire chain addressing different types of power plants, injection and storage.

In the scope of this work pseudo steady state component models of a supercritical power plant were developed as well as the composite model that fully represents a supercritical power plant. Two modes, design and operational were developed for the composite model to be able to simulate part load in addition with turbine following control. A daily cycle simulation was analysed and sensitivity studies were made on the boiler efficiency and on the reheat vapour temperature. The mathematical modelling was implemented in the commercial software gPROMS.

This is a highly complex system where all the interactions and all the recirculation of information that appears in the steam cycle were studied and successfully captured by the model. The sensitivity analysis shows that an increase in the reheat vapour temperature improves the power production and the gross efficiency. Pointing out that an improvement of the equipment manufacture material will lead to more efficient power plants.

Keywords: Supercritical Pulverized Coal Power Plant, Turbine following control, Modelling, Simulation, gPROMS

1. Introduction

Mitigating global warming is the major challenge of the next century, global conscience about the problem has been rising along with CO₂ emissions. Measures need to be taken to accomplish a significant reduction in carbon dioxide emissions and Carbon Capture Storage (CCS) technology promises to be an important technology for climate change mitigation.

Coal power plants emitted in 2011 almost 14 billion metric tons of carbon dioxide representing the most significant share in global emission with 45% of the total carbon dioxide emissions. Applying CCS system to this kind of power plant will reduce significantly CO₂ emissions.[1][2]

In September of 2011, UK government by the Energy Technology Institute (ETI) delivered Process Systems Enterprise (PSE) and others stakeholders like EDF, E.ON, Rolls - Royce, CO₂DeepStore and e4Tech a project to build a carbon capture and storage modelling tool-kit. The completion time for this project is scheduled to spring of 2014.

The tool-kit allows the users to study the differences and the effects on the system at part load, start up and shutdown, being able to identify the key issues.

This project will help to support future design of integrated CCS in power plants, analysing economical effects on the entire cluster, help the owners and developers of power plants to understand the all concept from power generation to storage and its trade-offs.

The main objective of this work is the development of (pseudo) steady-state models of relevant unit operations in pulverized coal power plants as feedwater heaters, condenser, gas/gas heater, electrostatic precipitators and flue gas desulphurization unit, as well as modelling the pulverized power plant as a component model using the existing gCCS power plant library and implement turbine following control and other relevant power plant control for part load operation.
1.1. State of the art
A literature review was conducted to see what have already been done in this area. The research showed that there is little information regarding supercritical steam cycles.

Supercritical power plant studies were made by Sergio Espatolero [3], where an optimization of the boiler cold-end was analyzed as well as its integration with the supercritical steam cycle. From the same author and Romeo [4], a supercritical power plant was designed to aim the optimal integration with the capture plant, especially the energy requirements of CO\textsubscript{2} amine scrubbing which require specific steam drawn off from the turbine cycle. Both studies took place in the ASPEN software.

Falah [5], presents a static and dynamic simulation model of a supercritical once-through heat recovery steam generator (SC HRSG). The work was developed in the commercial simulation software named Advanced Process Simulation Software (APROS).

Miroslav Variny [6], presents a part load operation study for a combined cycle to improve the efficiency provisioning the auxiliaries services.

Performance studies were made by Chia-Chin Chuang [7], for a combined cycle power plant with variable condenser pressure and variable load.

Changliang Liu [8], presents an updated, from 2011, overview of the modelling and simulation of thermal power plants. The thermal process control is review as well as the thermal process modelling which the author categorizes in three main areas: simplified boiler-turbine models for CCS research, dynamic models of subsystem and thermal performance calculation and optimization model. He identifies as one of the main challenges in the future the improvement of the accuracy of the models with actual power plant data.

Modelling and simulation is the base of optimal operation and control and plays an important role in energy saving in thermal power plants.[8] More work can still be done on the improvement of the models and on the analysis of the supercritical power plant steam cycle. Some more studies such as the ones made by Espatolero [3] would be welcome, however accuracy of the models need to be analyzed to perform part load operations studies. Part load operation, control and the integration with the capture plant are the main areas that can be further developed.

2. Pulverized Coal Power Plant
Coal is the most abundant fossil fuel in the world, being a relatively inexpensive energy source which produces relatively high levels of pollution. In 2009, almost 40% of the total electrical power produce in the world was from coal source. [9]

The options for coal electrical power generation are: Circulating Fluidized Bed Combustion (CFBD), Pressurized Fluidized Bed Combustion (PFBC), Integrated Gasification Combined Cycle (IGCC) and Pulverized Coal Power Plant (PCPP).

However pulverized coal (PC) -fired power plant has the highest reliability and commercial readiness for high electricity production capacity. In 2004, PC-fired power plant represented 99% of coal total electrical production.[10]

Different types of PCPP can be found according to the steam conditions in the boiler. Subcritical and supercritical are the most common types. The supercritical power plants are characterize for steam pressure and temperature above supercritical conditions of water, typically above 22.1 Pa and 560 °C.[10]

The components of a PCPP can be found in figure 1. The system can be characterized in two sides, the steam cycle and the steam generation. The steam cycle is where the power is generated with the steam passing through the turbines. The steam generator is as the name implies where the steam is produced.

2.1. Steam Generation
A scheme of a pulverized power plant can be found in figure 1. The key equipment for steam generation is the boiler, where the coal is burned with air, to heat up and vaporize the water to generate electricity in the steam cycle.

Inside the boiler there is a control of nitrogen oxides (NO\textsubscript{x}) like nitrogen dioxide that is produce in the combustion, this control is done in a Selective Catalyst Reduction (SCR). An air heater can be found in the boiler scheme as well, in the air heater the air is integrated with the hot flue gas to take advantage of the available heat.

Particulate removal of ash or particulate matter is done in a fabric filter or Electrostatic Precipitator (ESP). Ash removal is followed by the sulphur removal that is done in the Flue Gas Desulphurization unit (FGD), this uses limestone to react with the sulphur content of the flue gas and gets a sub product which is gypsum. One missing unit in the fig. 1 is the Gas/Gas Heater (GGH) which is locate between the ESP and the FGD and has the function of cooling the flue gas before going into the FGD.

After these purifications steps to control pollutants emissions, flue gas goes to the stack where is dispersed into the atmosphere.

2.2. Steam Cycle
Power plant steam cycle try to produce energy as much efficiently as possible, using thermodynamics. A thermodynamic cycle is a series of thermodynamic processes at the end of which the system returns to its initial state.[12]
Modern power plants use reheat regenerative cycles which have two turbines due to the reheat strategy. The regenerative strategy reduces the energy requirement to heat the high pressure water in the boiler and the condenser duty since less steam is needed to condensate. Nowadays, power plants have complex systems getting up to 8 feedwater heaters (FWH).

The main equipments for the steam cycle are: condenser, deaerator, feedwater heater, turbines, governor valve, boiler and pumps.

2.3. Control mode
2.3.1. Boiler/turbine control

The control of the boiler-turbine system is essential for a proper response to power demands. Three main control options can be presented to a boiler/turbine system: Boiler following control, Turbine following control and Coordinated boiler turbine control.

Boiler following control system implies that the boiler response follows the turbine response. In this control mode a change in power demand will implicate a response to the throttle pressure, and a change in the boiler pressure produces a change of the firing rate.

The turbine following control is the opposite since the turbine response follows the boiler response. A change in power demand set point will produce a change of the firing rate, therefore the boiler pressure will change and to main the throttle pressure constant, the turbine control valves change position.

Coordinated boiler turbine control combines both previous control modes to exploits their advantages and minimize the disadvantages. In simple terms power demand changes and throttle pressure changes are responsibility of both boiler and turbine systems.

2.3.2. Condenser control

In the condenser it is crucial to control the pressure, since as low as this pressure can be the higher is the thermal efficiency of the power. Thus the pressure in this unit is always measured and controlled by the cooling water inlet flowrate.[13]

3. Step change in power plant load

The step change in load is well describe in literature and the responses are typically difference depending on the type of control strategy implemented in the power plant. Figure 2 presents the expected responses for a positive step change in the power plant load. Even though the step is not quantified by the reference. The trend in the fig.2 helps to infer if the response of the power plant model is correct.

3.1. Daily Cycle

In a country power demand there are 3 types of energy load requirements: the base load, the interme-
diate load and the peak load. The base load is the minimum level of demand on an electrical supply system over 24 hours. Base load power sources are those plants which can generate dependable power to consistently meet demand, typically nuclear and coal power plants are used.

Base load power plants produce continuous, reliable, efficient power at low cost and often are relatively inefficient at less than full output.

Peak load generators, such as natural gas, have low fixed costs, low plant load factor and high marginal costs. Also coal can be used as intermediate and peak load power plants, but natural gas is much more flexible and faster than coal power plants.[15]

4. Mathematical Modelling of PCPP Components
The mathematical modelling of the components developed for the project will be explain briefly in this section. The models developed for the steam generation side where the electrostatic precipitator, flue gas desulphurization unit and the gas/gas heater. For the steam cycle the feedwater heater model and the condenser where modelled. To be able to implement control strategies a simple valve model was also developed.

4.1. Electrostatic Precipitator
The Electrostatic Precipitator (ESP) model removes the required particulate matter from the inlet stream, the outlet ash concentration or the unit efficiency can be specified. The model estimates the amount of power required to perform this operation with empirical equations. The pressure drop across the equipment is not estimated, must be an input from the user.

This is a steady-state and lumped model. No explicit modelling of the particulates themselves or the equipment is done and no temperature change is considered. The outlet flue gas is in gas phase nothing condenses and only ash is removed.

4.1.1. Equations
The power consumption of the ESP is quite variable, however there is a clear relationship between capture efficiency and the power, to achieve greater efficiencies more power will be required. A two branch equation was obtained for the power (W):

\[
P = \begin{cases} 
\frac{1100}{\rho_{in}} F_{in} & \text{if } \eta > 99.9 \\
\frac{21.94 + 0.22 \eta}{1 - 0.02 \eta + 9.0410^{-5}\eta^2} F_{in} & \text{otherwise}
\end{cases}
\]

4.2. Flue Gas Desulphurisation
The flue gas desulphurisation (FGD) unit removes sulphur dioxide of the flue gas to a certain specifica-

tion level. Either the sulphur content in the outlet flue gas stream is specified or the unit efficiency (of sulphur removal).

The model estimates the power and material requirements based on the outlet sulphur dioxide content specification. The outlet temperature and composition are also estimated by the model.

The wet flue gas desulphurisation system is modelled, specifically the limestone forced oxidation (LSFO). The following reaction will take place in the FGD unit:

\[
CaCO_3 + \frac{1}{2}O_2 + 2H_2O + SO_2 \rightarrow CaSO_4 \cdot 2H_2O + CO_2
\]

(2)

This is a steady-state and lumped model. Desulphurisation operation is not detailed modelled, ratio and stoichiometric data used for estimation of the material requirements. The outlet water content in the flue gas is determined assuming saturation and in the enthalpy balance the model only takes into account the liquid and vapour components, the solids are ignored. Another assumption is that the outlet liquid content is only water and dissolved carbon dioxide.

4.2.1. Equations
In this equipment there is a reaction to take in account, therefore the mass and energy balance are presented.

Mass balance :

\[
F_{in} + \frac{F_{lime}}{wt_{lime}} + F_{water} + F_{air} = F_{out} + \frac{F_{gyp}}{wt_{gyp}}
\]

Energy balance:

\[
F_{in}.h_{in} + \left(1 - \frac{wt_{lime}}{wt_{lime}}\right) F_{lime}.h_{lime} + F_{air}.h_{air} = F_{out}.h_{out} + \left(w_{gyp} + \frac{1 - wt_{gyp}}{wt_{gyp}}\right) F_{gyp}.h_{gyp} + \Delta r. H^\theta \cdot \frac{F_{removed}^{SO_2}}{M_{SO_2}}
\]

4.3. Gas/Gas Heater
The gas/gas heater model is a simple heat exchanger, exchanging heat from two gas streams. The user needs to assign the hot outlet temperature or the heat duty. The pressure drop and the heat transfer efficiency should be specified by the user as well. This is a steady state and lumped model.

4.3.1. Equations
Energy balance to the hot and cold side are presented:

\[
\eta = \frac{Q}{F_{hot} \cdot (h_{in}^{hot} - h_{out}^{hot})} \cdot 100
\]

\[
\eta = \frac{Q}{F_{cold} \cdot (h_{out}^{cold} - h_{in}^{cold})} \cdot 100
\]
4.4. Feedwater Heater

The Feedwater Heater (FWH) model is used to preheat boiler feedwater using condensing steam from the turbines and is usually used to determine the steam flowrate drawn off from the turbine. This is a lumped and steady-state model. There can be two or more inlet streams, these streams are first mixed and the properties of the mixture are estimated by mass and energy balances. The only exception is the inlet pressure which is assumed to be the minimum of all the inlet steam pressures. It is assumed that the inlet and outlet cooling water is in liquid phase and the outlet steam condensate is saturated.

For the design of the equipment is assumed the same as the for the FWH.

4.4.1. Equations

Energy balance for the heat exchange:

\[ Q = F_{in} \cdot (h_{in} - h_{out}) \]  \hspace{1cm} (7)

\[ Q = F_{FW} \cdot (h_{FW_{out}} - h_{FW_{in}}) \] \hspace{1cm} (8)

Design calculation:

\[ Q = U.A.\Delta_{in}T \] \hspace{1cm} (9)

Some of the temperature differences are also presented. Terminal temperature difference:

\[ TTD = T_{hot_{out},sat} - T_{FW_{out}} \]  \hspace{1cm} (10)

Drain effectiveness:

\[ Deff = \frac{T_{hot_{out},sat} - T_{out}}{T_{hot_{out},sat} - T_{FW_{in}}} \] \hspace{1cm} (11)

4.5. Boiler Steam Condenser

The BoilerSteamCondenser model is used for condensation of low-pressure steam, using cooling water. This is a lumped and steady state model that is usually used to calculate the value of the cooling water flowrate. There can be two or more inlet streams, these streams are first mixed and the properties of the mixture are estimated by mass and energy balances. The only exception is the inlet pressure which is assumed to be the minimum of all the inlet steam pressures.

The model includes temperature relationships such as terminal temperature difference and drain effectiveness, these type of temperatures relationships are more or less constant in the feedwater heaters relating the temperatures with the pressure of the system. They are very important in part load operations because the pressures of the system start to decrease but these relations are kept constant.

4.5.1. Equations

The equations for the heat exchange are similar to the ones in the FWH. For this reason are not presented.

4.6. Control Valve

This model describes a valve, determining the flow as a function of the pressure difference and the valve stem position. The model is characterized in terms of the valve flow coefficient \( (C_v, \text{gpm/psi}^{0.5}) \), the inherent flow characteristic (linear, equal-percentage, quick-opening), the rangeability factor and the leakage fraction. The flow-characteristic options for the valve can be linear, quick-opening or equal-percentage.

The dynamics of the valve are modelled via a time delay equation on the stem position of the valve. This model can have both liquid or gas inlet streams and no phase change occurs in the system. It is assumed isenthalpic expansion and irreversible flow. Since this is a control valve, the stem position setting is an input from the controller connected in the control port.

4.6.1. Equations

The flow across the valve will be a function of the maximum allowable flow for the valve, depending on the stem position opening and the inherent flow characteristics:

\[ F = C_v f. F_{max} \] \hspace{1cm} (12)

\[ F = C_v C_v f. |\Delta p|^{\frac{1}{4}} \] \hspace{1cm} (13)

The valve dynamics can be described by the following equation:

\[ \tau \frac{dV_{act}}{dt} = V_{sp} - V_{act} \] \hspace{1cm} (14)

5. Supercritical Pulverized Coal Power Plant Modelling

Using the models developed and the models available in the gCCS library a Supercritical PCPP composite model was created. The objective was to confirm the accuracy of the models and be able to simulate part load operation with turbine following control and condenser control implemented.

A supercritical pulverized coal power plant was simulated producing 471.25 MW of gross power with an efficiency of 46.25% and a specific carbon dioxide emission of 718.65 g/kWh of gross
power. The coal consumption is 38.50 kg/s producing 438.65 kg/s of flue gas. The power plant has 350 kg/s of feedwater circulating the system.

<table>
<thead>
<tr>
<th>Model</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>Superheat T and P Reheat T and pressure drop</td>
</tr>
<tr>
<td>Turbine</td>
<td>Inlet pressure Outlet T or vapour fraction</td>
</tr>
<tr>
<td>Governor Valve</td>
<td>Stem position</td>
</tr>
<tr>
<td>Condenser</td>
<td>Operating pressure Minimum T difference</td>
</tr>
<tr>
<td>FeedWaterHeater</td>
<td>Outlet temperatures</td>
</tr>
<tr>
<td>Deaerator</td>
<td>Operating pressure</td>
</tr>
<tr>
<td>Drum</td>
<td>Residence time Volume occupation</td>
</tr>
<tr>
<td>PumpUtility</td>
<td>Discharge pressure</td>
</tr>
<tr>
<td>ESP</td>
<td>Efficiency</td>
</tr>
<tr>
<td>Blower</td>
<td>Discharge pressure</td>
</tr>
<tr>
<td>GGH</td>
<td>Outlet hot temperature</td>
</tr>
<tr>
<td>FGD</td>
<td>Outlet limit concentration</td>
</tr>
<tr>
<td>Coal</td>
<td>Coal ultimate analysis</td>
</tr>
<tr>
<td>Air</td>
<td>Air conditions</td>
</tr>
</tbody>
</table>

Two modes were implemented to be able to simulate part load operations: Design mode and Operational mode.

In design mode the main operating conditions (flowrates, temperatures and pressures of the streams) are specified in order to obtain the equipments design parameters (size, area, efficiency, TTD, etc). Table 1 has the main system specifications.

In operational mode equipment parameters determined in the design mode are now specified. The objective of this mode is to ensure that changing the specifications the same stream conditions are achieved. This will allow in a further step to address part load operations with no fixed temperatures or pressures in the steam cycle but only fixed equipment performance parameters. In table 2 are presented the trade-offs from design to operational mode. Stodola’s constant is a parameter used to relate through an empirical equation the pressure ratios and the flowrate of vapour being expanded in the turbine.

After the operational specification is done the turbine following control and the condenser control was implemented, and with it a step change and a daily cycle were simulated to confirm the responses of the system. The controllers were tuned manually however the first guess for the parameters were based on the values obtained from Paranjape [16].

In order to verify the accuracy of the models the results were compared with the Romeo et al. [4]

<table>
<thead>
<tr>
<th>Model</th>
<th>Design</th>
<th>Operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td>P, CW outlet T</td>
<td>P, TTD</td>
</tr>
<tr>
<td>FWH</td>
<td>Drain T, Feedwater outlet T</td>
<td>TTD, Area</td>
</tr>
<tr>
<td>Deaerator</td>
<td>Operational P, Pressure drop</td>
<td></td>
</tr>
<tr>
<td>Drum</td>
<td>Residence time, Volume of liquid</td>
<td>Design volume, Level</td>
</tr>
<tr>
<td>Turbine</td>
<td>Inlet P, Outlet T or vapour fraction, Efficiency</td>
<td></td>
</tr>
</tbody>
</table>

which studied the same flowsheet. The gCCS flowsheet is presented in the figure 3. A sensitivity study was also conducted on the reheating vapour temperature. The key performance indicators, gross power, efficiency, etc were analyzed.

6. Results
Some of the results obtained in this work were compared with the values found in Romeo et al. [4]

6.1. Design Mode
The main assignments of the design mode can be found in the Table 1. Table 3, presents the stream average and maximum deviation of the gCCS design mode results from the Romeo et al. [4].

Table 3: Average and maximum difference from gCCS design results and Romeo et al. [4]. Pressure and flowrate is in deviation and temperature in Celsius absolute difference.

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>P(%)</th>
<th>F(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.42</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Table 3, shows that the temperatures, pressures and flowrates are close to the expected which gives confidence on the results that could be obtained from the PCPP composite model.

The examples of the calculated parameters in design mode can be seen in the Tables 4 and 5.

Table 4: Calculated turbines design parameters.

<table>
<thead>
<tr>
<th>Turbines</th>
<th>Efficiency</th>
<th>Stodola’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP 1</td>
<td>89.3 %</td>
<td>20235.2</td>
</tr>
<tr>
<td>IP 2</td>
<td>89.3 %</td>
<td>270.7</td>
</tr>
<tr>
<td>LP4</td>
<td>62.1 %</td>
<td>2.8</td>
</tr>
</tbody>
</table>

6.2. Operational mode
The operational mode simulation presented the expected results which are equal to the design ones that can be verified in the Table 6.
Figure 3: gCCS diagram of a Supercritical Pulverized Coal Power Plant. Legend: A - Source coal; B - Source air; C - Boiler; D - Governor Valve; E - Turbine; F - Generator; G - Condenser; H - Drum; I - Pump; J - Feedwater heater; K - Deaerator; L - Electrostatic Precipitator; M - Blower; N - Gas/Gas Heater; Flue gas desulphurization unit; P - Stack; Q - Recycle breaker.

Table 5: Calculated FWH design parameters.

<table>
<thead>
<tr>
<th>FWH</th>
<th>TTD (K)</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1</td>
<td>509.6</td>
</tr>
<tr>
<td>3</td>
<td>3.3</td>
<td>270.7</td>
</tr>
<tr>
<td>7</td>
<td>13.5</td>
<td>259.4</td>
</tr>
</tbody>
</table>

Table 6: Key Performance Indicators deviation from this work and Romeo et al.[4] in design and operational modes.

<table>
<thead>
<tr>
<th>KPI</th>
<th>Romeo</th>
<th>Design</th>
<th>Oper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross power (MW)</td>
<td>471.25</td>
<td>-1.7 %</td>
<td>-1.7 %</td>
</tr>
<tr>
<td>Gross efficiency (%)</td>
<td>46.37</td>
<td>-1.8 %</td>
<td>-1.8 %</td>
</tr>
<tr>
<td>Specific CO₂ emissions (g/kWh)</td>
<td>718.65</td>
<td>2.4 %</td>
<td>2.4 %</td>
</tr>
<tr>
<td>Coal flowrate (kg/s)</td>
<td>38.50</td>
<td>0.1 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Flue gas (kg/s)</td>
<td>438.67</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>

In the gCCS model less power is generated which is due to limitations on the steam cycle. The turbines models used from Aspen used by Romeo et al.[4] probably have different assumptions which make the gCCS turbines generate less power. The gross efficiency is defined as the power generated divided by the ideal power produced which is equal to the lower heating value of the coal times the coal flowrate.

Flue gas composition was also analyzed and the only significant deviation is on the carbon dioxide emitted which was 0.6% higher than the reference.

6.3. Step change in power plant load
A positive step change was simulated and the results are presented in the figure 4. Since no relative deviation was defined in the reference, a step of 4% was defined for the simulation from 90% to 94% of load change.

Figure 4: Load change and throttle pressure deviation results for 4% step change in load.

The step change was done within the typical rate change allowed in a power plant. Physical restrictions in supercritical power plants usually set the limit rate of load change to 8% per minute. [17]
In the figure 4 are presented the responses of the several controllers.

The controller 2 with the power gain of 0.15 is the quickest to get to the set point only taking 1.1 minutes to reach it and 1.7 minutes to stabilize the pressure which does not represent correctly the expected behavior. The controller that shows the closer behavior to the expected is the controller 2, taking more time to reach the set point (2.4 minutes) than to stabilize the disturbance in the pressure (1.8 minutes). The set of parameters used in the controller 2 will be used to simulate the daily cycle in the following section, the parameters can be found in the following table.

Table 7: Controllers parameters and stabilization time for every controller of the turbine following.

<table>
<thead>
<tr>
<th>Controller 2 parameters</th>
<th>Power</th>
<th>Gain</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller Reset time (s)</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilization time (s)</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Gain</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controller Reset time (s)</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilization time (s)</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The parameters of the pressure controller in the condenser and the level controller in the drum were also tuned manually. The pressure controller has a gain of 2 and reset time of 3 s. The level controller in the deaerators drum has a gain of 8.

Figure 5: Deaerator drum level control loop. Legend: A - Drum; B - Deaerator; C - Feedwater heater; D - Pump; E - Recycle breaker; F - Governor valve; G - Controller

One issue that was not discussed so far was the importance of the drums in the power plant simulation. The drums provide stability during part load operations and were specially added in the gCCS flowsheet. When the load decreases the steam flowrate to the condenser will decrease as well, therefore the pressure will drop instantaneously and since the condenser model sets the temperature to the saturation this will decrease with the pressure, which produces a perturbation in the FWH causing problems due to temperature crossovers. To clarify, this is only needed because the pressure in the condenser is being controlled and the controller can’t avoid the pressure to change.

With the introduction of this dynamic drum models, even though the pressure still decreases in the condenser that change will be diluted in the tank. In the figure 5 it can be seen the controller and how it is rearranged.

6.4. Daily Cycle

For purpose of this work, coal is considered base load and is analyzed the daily demand for the Portuguese Electrical Grid (provided by REN) for the 3 of September of 2012.[18]

Figure 6: Daily cycle of the Portuguese National Grid from 3 of September 2012.

Taking into account the figure 6, the schedule for the daily cycle of the power is decided. From 1 a.m to 8 a.m less power is required, therefore the power plant could work at 90% load. From 8 a.m to 5 p.m the power plant is working at full capacity, then drops to 95% until 10 p.m when it goes back to the 90% load.

The simulation results of the daily cycle can be seen in the following figures 7, 8, 9 and 10.

Figure 7: Simulation of the daily cycle schedule.

When the coal flowrate is decreased (power demand decreased, less heat required) the pressure in the boiler decreases, then the governor valve will close increasing the pressure drop and letting less vapour to flow across and going into the turbines which will increase the pressure. This physical response can be seen in the figures 8, 9 and 10.

The key performance indicators can also be analyzed for the 95% and 90% load in the table 8.
6.5. Sensitivity analysis on the reheat temperature

The reheat temperature is a condition of the power plant design, typically for supercritical power plants the temperature can be above 600°C which is the case for this power plant. The effect of the reheat temperature in the overall performance of the power plant will be the objective in this section.

The study was done to see if increasing the temperature of the reheated vapour would be valuable for the power plant performance. Table 9, summarizes the results for the key performance indicators (KPI).

Table 9: Reheat temperature sensibility study, relative deviation to the reference case is presented.

<table>
<thead>
<tr>
<th>KPI</th>
<th>Ref Case</th>
<th>Study cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reheat T (°C)</td>
<td>610.0</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Gross power (MW)</td>
<td>471.25</td>
<td>0.7 %</td>
</tr>
<tr>
<td>Gross efficiency (%)</td>
<td>46.37</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Specific CO₂ emissions (g/kWh)</td>
<td>718.65</td>
<td>-0.1 %</td>
</tr>
<tr>
<td>Coal flowrate (kg/s)</td>
<td>38.50</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Flue gas (kg/s)</td>
<td>438.67</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>

The key performance indicator that improved the most with reheat temperature, was the power production, for the 1.4% increase in the reheat (RH) vapour temperature the power increases 0.7%. In terms of numbers it represents an increase of 3 MW for an increase around 9°C in the temperature, which clearly confirms the importance of the reheat temperature in the power generation.

7. Conclusions

The main original contributions of this work were the development from scratch in the gPROMS software of the sub models and the composite power plant model. Also the understanding of the system which allows the simulation of part load operations fixing the equipments design parameters.

The control loops implemented showed the expected response which was proved by the step change done in the load. However, due to the lack of dynamics in the models, the introduction of dynamic drum models was crucial to part load operations.

The daily cycle simulation presents a clear relation between the key performance indicators and the load. The decrease in power production of 5% does not mean that the coal consumed decreases 5%, actually the coal consumption decreases around 4.5% which makes the efficiency of the power plant worse in 0.6%. This is due to the fact that the steam cycle in part load operation does not maintain the heat recovery efficiency.
The daily cycle helped to understand the dynamic in part load operation. To produce less 5% of power, less feedwater is required in the same proportion (5%). With less feedwater the outlet temperatures and pressure in the turbine will be reduced and all the steam cycle will be rearranged. The amount of reduction is different from the steam cycle position but is accentuated with the load decrease.

The reheat temperature clearly affects the steam cycle completely and an optimization of the steam cycle with those conditions could increase up to 50% or more the efficiency of the power plant. Nowadays those temperatures are not possible to achieve but in a close future new materials will allow higher temperatures and pressures.

The objective of this work was fully accomplished with the supercritical pulverized coal power plant being able to successfully simulate the part load operation. However some work can still be done to improve the accuracy of the simulations, namely with the introduction of dynamics in the boiler, feedwater heaters, condenser and deaerator. Some ideas are already in place and this is just the first model library.

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**References**


