Modelling and simulation of the start-up process of coal fired power plants with post-combustion CO₂ capture

Thomas Marx-Schubach¹ and Gerhard Schmitz¹

¹Institute of Engineering Thermodynamics, Hamburg University of Technology, Denickestrasse 17, 21073 Hamburg, Germany

Abstract

The reduction of CO₂ emissions is essential to stop global warming and mitigate its effects. Besides electricity generation from renewable energies an important possibility to reduce CO₂ emissions is CO₂-capturing from flue gases of coal fired power plants. Electricity generation from renewable energies leads to an increase of fluctuations in the power grid [1]. Power plants have to be operated in a more flexible way to compensate these fluctuations. Therefore, the amount of start-up and shutdown sequences will also increase [2]. To examine and optimize these dynamic periods and thus allow an efficient plant operation, the development of dynamic models is crucial. Many studies focus on the dynamic operation of power plants and post-combustion capture plants even in joined operation, but only a few studies deal with the modelling of start-up and shutdown procedures.

To close this gap, a detailed model of a post-combustion CO₂ capture plant (pcc-plant) is developed in the Modelica®-Language [3], which allows the simulation of start-up and shutdown processes. The model is validated with measured data from an amine gas treatment pilot plant located in Heilbronn, Germany. The solvent used in this plant is monoethanolamine (MEA). Figure 1 shows the results of the start-up process validation for two important comparative quantities.

Figure 1: Two validation results of the post-combustion carbon capture plant model
A supercritical coal fired power plant located in Heyden, Germany is used as reference power plant. It has a net power output of 875 MW. For the amine gas treatment pilot plant a scale-up process is performed with Aspen Plus®, resulting in three parallel capture plants, handling the entire flue gas flow of the reference power plant.

The model of the pcc-plant is coupled to a simplified model of a coal fired power plant. The resulting model consists of 90840 equations and 1173 continuous time states. It allows the combined simulation of start-up and shutdown processes of both models.

To guarantee a stable and automatic operation, a sequential control for start-up and shutdown procedures is implemented in both plants. The sequential control of the power plant is implemented according to the power plant in Heyden, but in a simplified form. The sequential control for the carbon capture plant is developed in a way that stable operation is achieved. Only PID controllers are used.

First of all, the model development is described in detail. Two case studies, focusing on the pcc-plant, are subsequently performed in this contribution. In the first case study, the influence of different parameters and input variables on the start-up time is investigated in order to analyse the start-up process of the pcc-plant. The varied variables are the steam flow rate to the reboiler, the solvent flow rate and the total amount of solvent in the pcc-plant. The model of one carbon capture plant consists of 34539 equations and 279 continuous time states.

In figure 2 simulation results for a shutdown process, followed by a hot start, are shown. In this simulation an exemplary relative load profile is used. The downtime of both plants is approx. 10 hours. During the downtime of the plant, the ambient heat loss is calculated for all components. The assessment of different downtimes confirms the assumption that the start-up time increases with downtime.

In the second case study the performance of different start-up control structures for the carbon capture plant are compared. When taking into account safety-relevant control structures, such as level controllers etc., only two degrees of freedom remain [4]. A state-machine for such a control structure is illustrated schematically in figure 3 as an example. In this case, the solvent flow rate is used to control the carbon capture rate, whereas the steam flow to the reboiler is used to control the reboiler temperature. This control structure was also used to generate the simulation results shown in figure 2. The most important benchmark for controller performances comparison is start-up time. The start-up is completed, when the generator output and the carbon capture rate reach their targeted steady state value. Further important values for comparison are the total energy input and the emitted or captured CO₂ during start-up.

References:


Figure 2: Exemplary relative load profile of a shutdown and start-up scenario and selected results
<table>
<thead>
<tr>
<th>Switching Condition</th>
<th>Steps</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin start-up</td>
<td>Step 1</td>
<td>Solvent pumps are switched on to wet the columns and mix the solvent</td>
</tr>
<tr>
<td>Firing in power plant starts</td>
<td>Step 2</td>
<td>Solvent flow rate is set to constant L/G ratio (solvent flow rate/flue gas flow rate)</td>
</tr>
<tr>
<td>Steam Pressure between IP and LP turbine reaches 4 bar</td>
<td>Step 3</td>
<td>Steam flow to reboiler is determined by a constant split ratio ($\frac{m_{flow to LP turbine}}{m_{flow to reboiler}}=1$)</td>
</tr>
<tr>
<td>Reboilertemperature $T_{\text{Reb}} &gt; 120 ^\circ \text{C}$</td>
<td>Step 4</td>
<td>Reboiler temperature is controlled using the steam flow rate to the reboiler</td>
</tr>
<tr>
<td>CO$<em>2$ carbon capture rate $X</em>{\text{CO}_2} \geq 0.9$</td>
<td>Step 5</td>
<td>Carbon capture rate is controlled using the solvent flow rate</td>
</tr>
</tbody>
</table>

*Figure 3: Schematic overview of a state-machine of one possible sequential control*