

Optimizing the start-up process of post-combustion capture plants by varying the solvent flow rate

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Abstract

This paper presents an optimization of the start-up process of a post-combustion carbon capture plant (PCC-plant) by varying the solvent flow rate. In a first optimization run the start-up time is minimized. In a second optimization run the overall carbon capture rate during the start-up process is maximized. The results show the great potential of the optimization, as the start-up time can be reduced from $\Delta t = 4650$ s in the reference case to $\Delta t = 2840$ s in the optimized scenario.

Keywords: optimization, start-up, absorption process, carbon capture, process engineering

1 Introduction

To stop global warming, ambitious goals have to be set. At the United Nations Climate Change Conference in Paris in 2015 a limit for the global temperature increase was set to 1.5 °C above pre-industrial levels (United Nations, Framework Convention on Climate Change, 2016). To achieve this goal the carbon dioxide emissions have to be reduced significantly. One possibility is the usage of the Carbon Capture and Storage (CCS) technology, which means that the carbon dioxide is removed from the flue gas and can be stored in underground formations. As reported by the International Energy Agency (IEA) it is estimated that CCS can have a 17 % share on the CO₂ reduction in the year 2035 (IEA (International Energy Agency), 2013).

Furthermore, the increasing amount of renewable energies will lead to more fluctuations of net load in the power grid (Montañés et al., 2016). This will impose new challenges and operational requirements on the flexibility of thermal power plants as start-up and shutdown sequences and the operation at partial load will become still more important in the future.

The start-up process of a power plant is a time consuming and complex operation. When a carbon capture plant is coupled to a power plant the start-up procedure becomes even more complex. As power plants will start up and shutdown even more frequently in the future, the minimization of the start-up time is desirable. Hence, there is a requirement of reducing the start-up time. This can be achieved by optimizing the start-up time using dynamic models. As a first step an approach for the optimization

of a post-combustion carbon capture plant is given in this paper. At the moment the common start-up procedure of carbon capture plants is only based on experience.

Many different studies focus on the dynamic simulation of post-combustion carbon capture plants (Bui et al., 2014). Some studies present the optimization of a capture plant but most of them focus only on the steady state and full time operation. Since the full time operation of carbon capture plants might not be economically feasible, also the optimization of dynamic operation periods will become important in the future (Bui et al., 2014). There are also studies available dealing with the optimal control of the process, e.g. (Panahi and Skogestad, 2011), (Åkesson et al., 2012), (Lin et al., 2011), (Luu et al., 2015) and (Mechleri et al., 2017). However, to the authors knowledge the studies do not concentrate on modelling start-up and shut down procedures of the whole plant. In order to close this gap, a model which can describe the start-up process is developed and a first approach for an optimization of the process is presented.

2 Process description

Several processes are available for the post-combustion capture (PCC) of CO₂ from power plant flue gases such as membrane processes, adsorption and absorption processes. One possibility is to remove the CO₂ in a gas scrubbing unit using aqueous solutions of different alkylamines as a solvent, also known as the amine gas treating process. A process flow diagram of this process is shown in figure 1. The flue gas first enters a flue gas cooler and is compressed in a blower. The cooled flue gas enters the absorption unit at the bottom of the column. The solvent flows counter-current to the flue gas down to the column sump. 90 % of the CO₂ is chemically absorbed by the solvent. Afterwards the rich solvent is preheated in a heat exchanger and pumped to the stripper. The solvent is evaporated in a reboiler using steam from the power plant to provide the required energy for solvent regeneration. Desorption takes place in the stripper and the almost pure CO₂ (up to 99.9 %) leaves the plant through a condenser. The regenerated solvent is pumped back to the absorption unit. Many different solvent additives, primary, secondary and tertiary amines, can be used. In this case the used solvent is a 30 wt.-% monoethanolamine (MEA) aqueous solution.

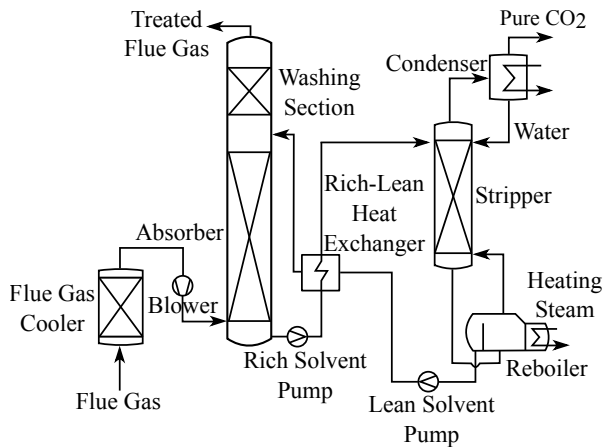


Figure 1. Process flow diagram of a post-combustion capture plant (Wellner et al., 2016).

The columns are usually filled with structured or random packings of different types.

The start up process of the plant is described in the following. At the beginning, the columns are in a cold and empty state. The process is started with the activation of the solvent pumps. Simultaneously, the other pumps for the washing sections, flue gas cooler and condenser are switched on. When the packing units inside the columns are wetted the heating steam can be supplied in the reboiler and the flue gas compressor can be switched on. The start up process is completed when the capture rate in the absorber reaches its nominal value of 90 %. To achieve this goal, the thermal and chemical equilibrium in the absorption unit has to be reached and the stripper has to attain his operation temperature of approximately 120 °C to ensure a sufficient regeneration of the solvent. The heat up process of the stripper takes the most time and is therefore the limiting factor for the start up time. The stripper heats up in two different ways.

1. The solvent is evaporated in the reboiler and the vapour enters the stripper at the lower part of the column.
2. The solvent which remains in the stripper sump is pumped through a counter flow heat exchanger and heats up the rich solvent that enters the stripper at the top.

A reduction of the start-up time can be performed by selecting the right solvent flow trajectory, which is not trivial, since the variation of the solvent flow rate has counteracting effects on the heat up rate. When the solvent flow rate is increased the temperature in the reboiler is reduced and it takes more time for the solvent to reach the boiling point. On the downside, the residence time of the solvent in the stripper sump decreases leading to a faster increase of the solvent temperature in the stripper sump. Decreasing the solvent flow rate leads to the opposite result. Therefore, the optimal trajectory of the solvent flow rate has to be

found numerically using a model of the post combustion carbon capture plant.

3 Model description

In this section the developed model and the used model libraries are described briefly. A detailed model for the dynamic simulation of the described process is developed within the *ThermalSeparation* library in Modelica (Dietl, 2012; Joos et al., 2009). The Optimization is performed with the commercial *Optimization Library* developed by DLR (A. Pfeiffer, 2012).

3.1 Model libraries

The *ThermalSeparation* library is a free Modelica library intended to describe separation processes such as absorption and rectification processes in Modelica. It can be used for the dynamic simulation of tray and packed columns with different levels of detail. More information about the library can be found in (Dietl, 2012; Joos et al., 2009).

The *Optimization* library is a commercial library for many different optimization tasks such as Trajectory Optimization, Realtime Optimization and Model Optimization. The library is released with Dymola and works only in this simulation environment. In this article the Trajectory Optimization is used. Further information about the library is given in (A. Pfeiffer, 2012).

3.2 Start-up model

A model of a post-combustion CO₂ capture plant, that can describe the start-up process, is developed at the Institute of Engineering Thermodynamics in Modelica using the *ThermalSeparation* library and validated with data of a pilot plant.

The pilot plant is located in Heilbronn, Germany and can handle a nominal flue gas stream of 1500 m³/h. The absorber has a height of 40 m and the stripper of 30 m. Both columns have a diameter of 0.6 m and are filled with the random packing type VSP-25 (VFF GmbH, 2016). The most relevant parameters of the nominal operation point are listed in table 1. More information about the pilot plant can be found in (Rieder and Unterberger, 2013).

The pilot plant is modelled using a first principle approach where the columns are axially divided into stages. The vapour and liquid mass and energy balances are solved separately in each stage. For the heat- and mass transfer across the phase boundary a equilibrium approach is used. The chemical reaction of carbon dioxide with the solvent is considered. It is assumed that the reaction takes place only in the liquid phase. More information about the model and the underlying assumptions can be found in (Wellner et al., 2016).

The most important input variables of the pilot plant are the solvent flow rate \dot{V}_{liq} , the molar flue gas flow rate \dot{N}_{fg}

Table 1. Main parameters of pilot plant.

Parameter	Value
Flue gas volume flow rate	1500 m ³ /h
CO ₂ concentration flue gas	12.3 mol-%
Flue gas temp. absorber inlet	40 °C
Solvent flow rate	5.3 m ³ /h
Solvent temp. absorber inlet	35 °C
MEA concentration	30 wt.-%
Stripper pressure	2 bar
CO ₂ product temperature	23 °C
CO ₂ target capture rate	90 %

and the heat flow rate to the reboiler \dot{Q}_{reb} .

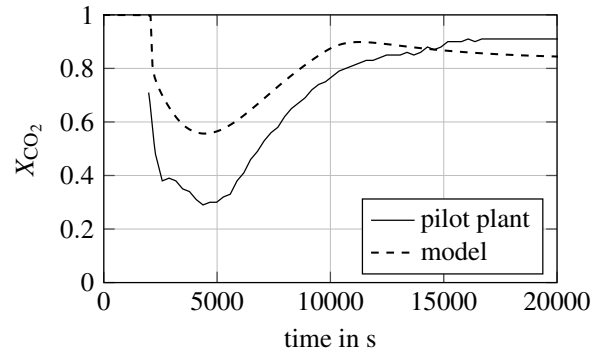
While the solvent flow rate and the heat flow rate are controllable within their limits, the flue gas flow rate depends on the firing output of the power plant. The flue gas flow rate is only controllable when a part of the flue gas is bypassed. In an usual start up scenario the solvent flow rate and the heat flow in the reboiler are set to their steady state values during the whole start-up process. However, this results in a very high start-up time. Hence, there is a high potential for optimization.

Simulation and validation results of the validation start-up scenario are shown in the following. At the beginning of the start-up procedure, the solvent pumps are switched on until the CO₂ concentration in the solvent is homogenized in the whole plant and until the columns are wetted. This step was not included in the optimization, since the solvent pumps should be operated at maximum flow rate to wet the columns as fast as possible. Hence, the focus of the optimization lies on the second part of the process when the flue gas flow enters the absorber.

In Figure 2 the carbon capture rate during the second part of the start-up process in the model and in the pilot plant is illustrated. The CO₂ capture rate is defined in the following way, where $\dot{N}_{CO_2, Abs, out}$ is the molar flow rate of CO₂ after the absorption unit and $\dot{N}_{CO_2, Abs, in}$ the molar flow rate of CO₂ before the absorption unit.

$$X_{CO_2} = 1 - \frac{\dot{N}_{CO_2, Abs, out}}{\dot{N}_{CO_2, Abs, in}} \quad (1)$$

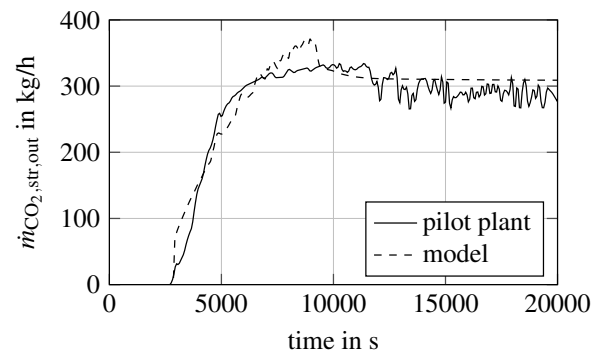
At $t = 0$ s the flue gas flow to the absorber is started. The steam supply in the reboiler starts later at $t = 240$ s due to the time delay in the steam generator and the steam cycle of the power plant. All incoming CO₂ is absorbed until the solution is saturated. Therefore, the CO₂ capture rate is nearly 100 % at the beginning and drops quickly after approximately 2000s since the solvent in the absorption unit is saturated with CO₂ and is not regenerated in the stripper yet. The capture rate in the pilot plant can only be calculated from this point on because the CO₂ concentration at the absorber outlet has not been measured correctly before. Due to the increasing temperature in the stripper, the CO₂ loading of the solvent in the stripper decreases

**Figure 2.** Validation start-up strategy - CO₂ capture rate

and the capture rate rises slowly to its steady state value.

After $t = 2000$ s the results of the model show a significant deviation from the measurements of the pilot plant. One reason is that the columns are modelled based on an equilibrium approach which means that the heat and material transport equations in each stage are neglected. Another reason is the deviation of the measuring instruments, since some measured values, e.g. the CO₂-concentration at the absorber outlet, are far from their nominal values. However, the agreement of the dynamic behaviour between the model and the pilot plant is very good except for the small overshoot after $t = 10000$ s. The start-up process is completed when the plant is capable of keeping a capture rate of 90 %.

Figure 3 shows the transient behaviour of the stripped CO₂ mass flow rate downstream the condenser for the same time period. The measured values are also compared with the simulated ones.

**Figure 3.** Validation start-up strategy - CO₂ mass flow downstream the stripper

The simulation data shows a very good agreement with the measurement data except for the overshoot in the simulation data at the end of the start-up process. The overshoot can be explained by the model assumption that the steam in the stripper condenses in every stage where the boiling temperature is not reached yet. In reality the CO₂ leaving the stripper is loaded with steam especially at high temperatures close to the boiling point. This energy loss leads to a smaller amount of stripped CO₂ in the pilot plant at

Table 2. General criteria in optimization runs

Variable name	Constraint	Type
Reboiler temperature	$T_{Reb} \leq 125^\circ\text{C}$	at any time
Liquid hold-up	$V_{liq,Reb} \geq 0.35\text{ m}^3$	at any time
Solvent flow rate	$0.0002\text{ m}^3/\text{s} \leq \dot{V}_{liq} \leq 0.002\text{ m}^3/\text{s}$	at any time

the end of the start-up process. It can be seen that the amount of stripped CO_2 in the stripper is nearly the same in the model as in the pilot plant in the timespan between approximately $t = 2000\text{ s}$ and $t = 8000\text{ s}$. However, the amount of captured CO_2 is much higher in the model in the same timespan. Therefore, if one assumes a correct initial amount and loading of the solvent, the overall CO_2 mass balance in the pilot plant is not fulfilled, which leads to the assumption of a certain measuring error. Furthermore, the time limiting component during the start-up process is the stripper. The model can therefore be used for optimization purposes.

According to the simulation, the start-up time in the validation case is $\Delta t = 9440\text{ s}$, which is very high.

4 Optimization setup

In this section the simplification of the model and the implementation of the optimization run is presented.

The model used for validation is simplified in a first step in order to reduce the computation time and improve the robustness of the model. The following simplifications of the model were made:

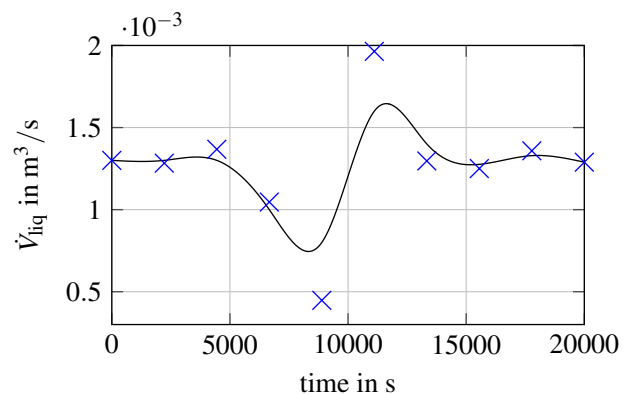
- The intermediate cooling unit in the absorber was neglected.
- The flue gas scrubbing units before and after the absorber were removed

Furthermore, the total amount of solvent in the pilot plant is specifically high compared to other post-combustion capture plants (Wellner et al., 2016). Therefore, the total amount of solvent in the pilot plant is reduced by 50% to get more commonly results. Thermal stresses were neglected in the reboiler as the start-up process is most of all limited due to the high amount of solvent in the stripper sump. Nevertheless, thermal stresses should be taken into account in the future to prove this assumption. An overview of the model used for the optimization is shown in Figure 5. The gas streams are marked orange, the solvent streams are marked blue. The flue gas stream entering the absorber and the heat flow rate are implemented using a ramp from the Modelica Standard library as source signal. The solvent flow rate can be set by using an input connector which is connected to the lean

solvent pump. The input connector is used for the optimization. The rich solvent pump is controlled keeping the filling level of the absorber sump at a setpoint of 2 metres.

As optimization method a *Single Shooting Technique* approach is used. The trajectories are approximated with B-splines of order 3. For the construction of the splines 10 equidistant knots, so called de Boor points, are used in the optimization runs. They can be used as tuner variables in the optimization method. Using more knots would lead to a more accurate solution but the optimization would take more time. Optimizations with different amounts of knots were carried out. The result is that 10 knots are a good compromise between accuracy and simulation time. An example of the construction of the trajectory using B-splines is shown in figure 4. The optimization problem is solved by using the gradient based Sequential Quadratic Programming (SQP) algorithm. The algorithm is effective for solving nonlinear optimization problems with linear constraints. The constraints are essential for the optimization problem. Therefore an algorithm which is capable of solving optimization problems with constraints has to be used.

Generally, different optimization algorithms for nonlinear optimization with constraints can be used, such as Random search, interior-point method. A overview of possible optimization algorithms can be found in (Rao, 2009). In this paper a gradient based method was used as these algorithms converge faster in general. The SQP algorithm is sufficient for solving the optimization problem. A disadvantage is that the algorithm can only find local optima.


Figure 4. Example of the construction of B-splines

A general optimization problem with equality and in-

start-up time. As presented in section 4 the model structure was changed slightly and the total amount of solvent was reduced. Therefore, the validation scenario shown in section 3.2 can not be used as a reference for the optimization. The start-up time decreases significantly due to the reduction of the total amount of solvent. For this reason a new reference scenario has to be defined by simulating the reduced model. The carbon capture rate in the reference scenario is shown in figure 6.

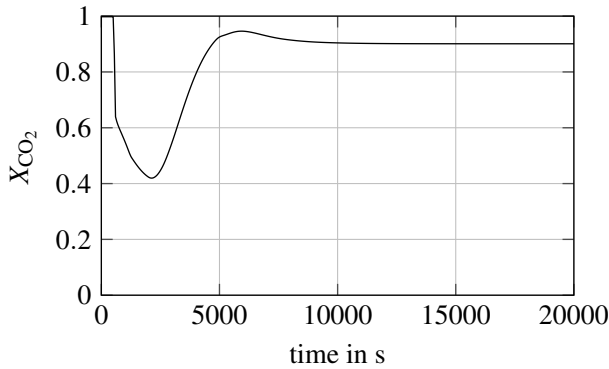


Figure 6. Reference start-up scenario - capture rate

All manipulated variables are kept at their steady state values during the whole start-up process in the reference case. The start-up time in the reference scenario is $\Delta t = 4650$ s, which is reduced in the following optimization scenario.

6 Minimizing the start-up time

In this section the minimization of the start-up time should be achieved by finding the optimal solvent flow trajectory (optimization 1). For the optimization run additional constraints and criteria have to be set.

First, the end of the start-up process has to be specified by using constraints. Therefore, it is defined that the carbon capture rate has to be at least 90 % at the end of the optimization. However, this constraint does not guarantee that the plant can keep a stable capture rate of 90 %. To make sure that the solvent is sufficiently regenerated at the end of the start-up process, a constraint for the solvent loading in the stripper sump is added. The solvent loading is defined in equation 4 and is the ratio of the amount of CO_2 and MEA in the solvent.

$$\alpha = \frac{N_{\text{CO}_2}}{N_{\text{MEA}}} \quad (4)$$

The solvent loading in the stripper sump has to reach the steady-state value of $\alpha = 0.184 \text{ mol}_{\text{CO}_2} / \text{mol}_{\text{MEA}}$ to ensure a stable carbon capture rate of 90 %. As the library only handles criteria in the form presented in equation 3 the capture rate was also inverted in the model. The additional criteria are shown in table 3.

Table 3. Additional criteria in optimization run 1

Variable name	Criteria	Type
Capture rate	$X_{\text{CO}_2} \geq 0.9$	end point
Solvent loading	$\alpha_{\text{str, sump}} = 0.184 \frac{\text{mol}_{\text{CO}_2}}{\text{mol}_{\text{MEA}}}$	end point
Start-Up time	t	minimize

The resulting solvent flow rate trajectory of the first optimization run is shown in Figure 7.

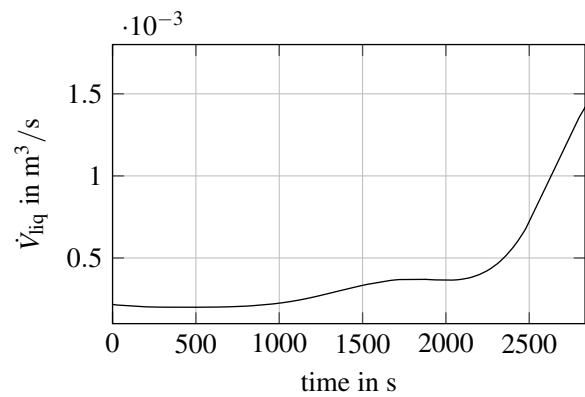


Figure 7. Minimized start-up time - solvent flow rate

As in the reference start-up scenario presented in chapter 3.2 the flue gas flow to the absorber starts at $t = 0$ s. The steam supply in the reboiler starts also later at $t = 240$ s due to the time delay in the steam generator and the steam cycle of the power plant. The solvent flow trajectory during the start-up process can be split up into three phases. At the beginning of the optimal start-up process the solvent flow rate is at the minimum flow rate of $0.0002 \text{ m}^3/\text{s}$. The minimum solvent flow rate leads to a maximum of the reboiler heat up rate. The reboiler temperature is shown in figure 8.

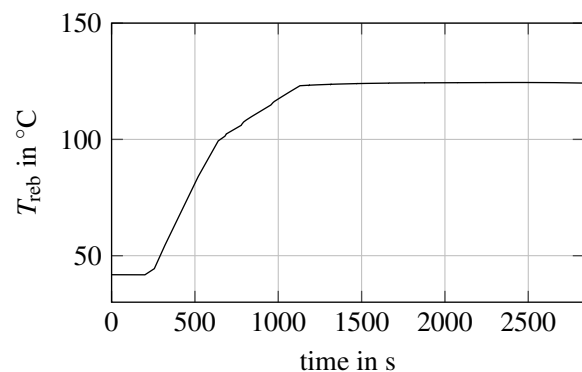


Figure 8. Minimized start-up time - Reboiler temperature

When the reboiler reaches its operation temperature of approximately 120°C the solvent flow rate rises to $0.00037 \text{ m}^3/\text{s}$. This happens for two reasons. On the one

hand the solvent flow rate has to be increased to prevent that the temperature in the reboiler exceeds the limit of 125 °C. On the other hand the increasing solvent flow rate leads to a smaller residence time in the stripper sump in order to achieve a higher heat up rate of the solvent in the stripper sump. As soon as the stripper reaches the operation temperature the solvent flow rate increases continuously to increase the capture rate. At a capture rate of 90 % a PID controller is switched on. The controller uses the capture rate of 90 % as a setpoint and the solvent flow rate as the manipulated variable. This results in a small oscillation of the solvent flow rate after the controller is switched on. The start-up process is finished at this point.

Figure 9 shows the carbon capture rate during and after the start-up process.

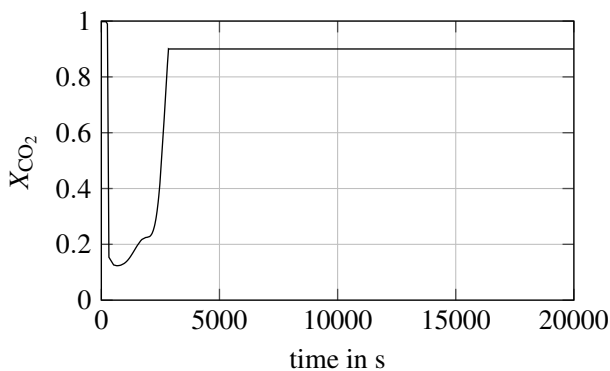


Figure 9. Minimized start-up time - capture rate

The capture rate drops quickly to a very small value of 12 % and increases with increasing solvent flow rate and stripper temperature until a capture rate of 90 % is reached. The start-up time is significantly reduced from $\Delta t = 4650$ s to $\Delta t = 2840$ s. As illustrated in figure 9, the plant can keep the capture rate of 90 % after the start-up process.

The result of the optimization is a specific optimal solvent flow trajectory for the pilot plant. As the trajectory cannot be applied directly to other plants a more generalized approach for the solvent flow trajectory should be given. Furthermore, the optimal solvent flow trajectory is quite complex since many control actions are required.

To solve this problem a simplified approach based on the optimal solvent flow trajectory is developed. As already mentioned, the solvent flow trajectory can be divided into three phases. Based on this segmentation the recommendations for an optimal start-up scenario are:

1. Set the solvent flow rate to its steady state or maximum possible value to wet the columns.
2. When the columns are wetted and the steam can be supplied from the power plant reduce the solvent flow rate to the lowest possible value.
3. As soon as the reboiler temperature reaches the operation temperature of 120 °C, increase the solvent flow rate to a certain value (in the case of the pilot plant:

$\dot{V}_{liq} = 0.00037 \text{ m}^3/\text{s}$). The value has to be found by optimizing a model of the certain plant. If this is not feasible another possibility is to control the reboiler temperature with the solvent flow rate by using a PID controller.

4. When the top of the stripper is heated up to 100 °C set the solvent flow rate to the optimal steady state value (in the pilot plant: $\dot{V}_{liq} = 0.001289 \text{ m}^3/\text{s}$).
5. Just as the capture rate reaches 90 % switch on the PID controller to keep a constant capture rate.

When applying the simplified start-up strategy to the model, the start-up time increases slightly. However, the implementation of the start-up strategy is a lot simpler. The simplified solvent flow rate derived from the optimization case is presented in figure 10.

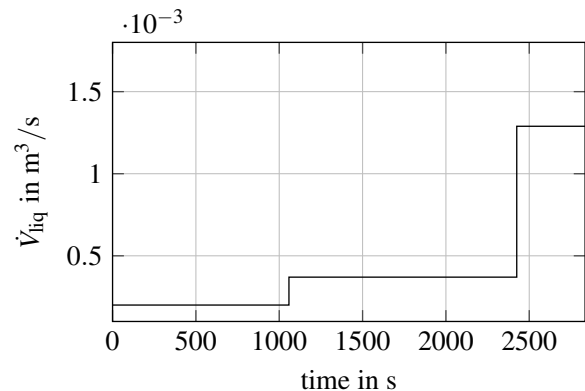


Figure 10. Minimized start-up time - solvent flow rate (simplified)

The result for the carbon capture rate is shown in figure 11. The carbon capture rate increases as expected steeply with increasing solvent flow rate. Between the steps of the solvent flow rate the capture rate increases slightly as the CO₂ loading in the stripper sump decreases slowly over time.

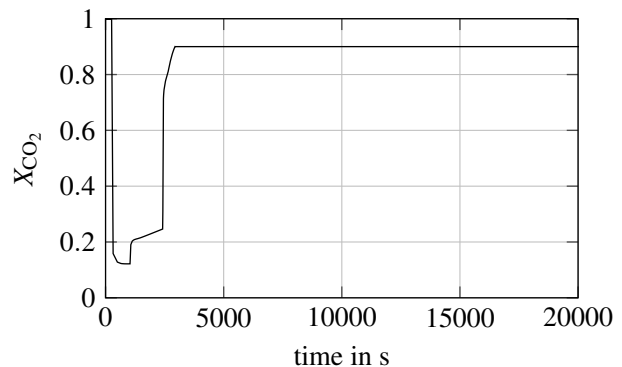


Figure 11. Minimized start-up time - capture rate (simplified)

The start-up time in the simple case increases marginally from $\Delta t = 2840$ s to $\Delta t = 2939$ s. However, the

implementation of the strategy requires only three control actions of the solvent flow rate during the whole start-up process. The simple approach also offers a high reduction of the start-up time while the constraints are still fulfilled. The reboiler temperature and the liquid hold-up in the reboiler do not exceed their limits at any time.

7 Maximizing the capture rate

In a second approach, the main goal is to maximize the mean value of the capture rate during the start-up process (optimization 2). This start-up strategy is useful when low CO₂ emissions are more important than a minimal start-up time.

For this optimization run additional constraints have to be determined. The maximum CO₂ capture rate is limited to $X_{CO_2} = 0.95$ after $t = 1000$ s since the carbon capture efficiency is decreasing steeply at very high capture rates. The reason is the very low CO₂ partial pressure in the gas phase at very high capture rates. The accuracy of the model decreases in this point of operation. The optimal stationary solvent flow rate is $\dot{V}_{liq} = 0.001289 \text{ m}^3/\text{s}$ which is defined as the end point of the trajectory. As the library only handles minimization criteria as presented in equation 3 the mean value of the negative carbon capture rate in a time period of $t = 20000$ s is chosen. The additional constraints are shown in table 4.

The resulting solvent flow rate trajectory of the second optimization run is shown in Figure 12. The trajectory starts at $0.001 \text{ m}^3/\text{s}$ and decreases to a minimum at approximately $0.00064 \text{ m}^3/\text{s}$. Afterwards the solvent flow rate rises till $0.0016 \text{ m}^3/\text{s}$ and drops again until the optimal stationary solvent flow rate of $0.001289 \text{ m}^3/\text{s}$ is reached.

Table 4. Additional constraints in optimization run 2

Variable name	Criteria	Type
Capture rate limit	$X_{CO_2} \leq 0.95$	anytime
Solvent flow rate	$\dot{V}_{liq} = 0.001289 \text{ m}^3/\text{s}$	end point
Mean capture rate	X_{CO_2}	maximize

The CO₂ capture rate in the second optimization run is depicted in figure 13. In comparison with the reference start-up strategy, the capture rate drops quickly to a lower value at the beginning because of the lower solvent flow rate. However, the lower solvent flow rate leads to a faster heat-up in the stripper and regeneration of the solvent. When the solvent flow rate is increased the carbon capture rate increases as well. As a side effect, the start-up time is also in this scenario reduced significantly to $\Delta t = 3520$ s.

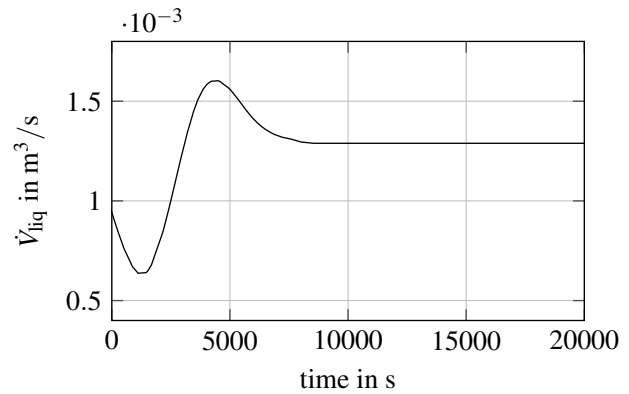


Figure 12. Maximized amount of captured CO₂ - solvent flow rate

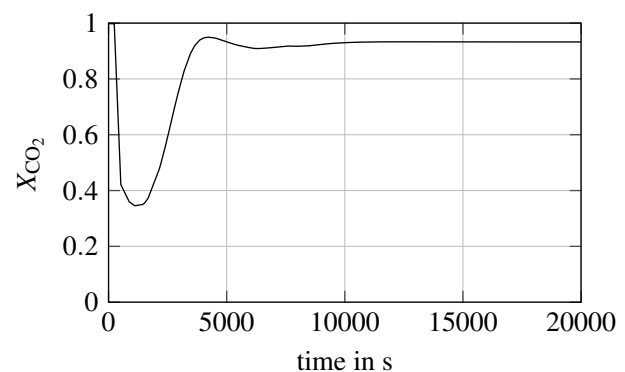


Figure 13. Maximized amount of captured CO₂ - capture rate

In table 5 a comparison of the mean capture rate in the different start-up scenarios over the same time period of $t = 20000$ s is shown. The minimization of the start-up time is labelled as *Optimization 1*, the maximization of the mean capture rate is labelled as *Optimization 2*. The reference strategy is presented in section 5.

Table 5. Mean value of capture rate in different start-up scenarios

Reference	Optimization 1	Optimization 2
0.836	0.805	0.856

As expected the highest mean capture rate is achieved in the second optimization run, but the enhancement of the mean capture rate in comparison with the reference start-up strategy is quite small. However, the second optimization run leads to a very good compromise between a relatively fast start-up process and a high amount of captured carbon dioxide during the start-up process as the mean capture rate is comparatively small in the first optimization run. In the future, also a multicriteria optimization with the combination of both optimization criteria is conceivable.

8 Performance

The optimization model consists of 29833 equations. As the optimization algorithm can only find local optima one can not guarantee that the best solution has been found. Therefore, the optimization is repeated several times and different start values for the solvent flow rate are used. The result is that the solutions actually are different but they vary only slightly when different start values are used. Sometimes the algorithm does not converge. This is mostly due to the fact that the optimization algorithm cannot evaluate a new solution since the integration of the model fails in some cases. One optimization run takes approximately an average of 18 hours.

9 Conclusion and Outlook

The results of this paper show that there is a high optimization potential for the start-up process of a post-combustion capture plant. The start-up time can be significantly reduced by varying the solvent flow rate only.

The results of the model optimization should be applied to the real operation of a carbon capture plant for validation purposes in the future. Unfortunately, the pilot plant used for the validation of the model is no longer in operation.

The optimization does not take thermal stresses in the reboiler into account. Additionally, the reboiler should be discretized in space in order to calculate local temperatures in the reboiler. Both options should be added to the model in the future.

This work focusses on the start-up process at full load. Future work could concentrate on the start-up process at partial load. Furthermore, future optimization should include the variation of other parameters of the plant that influence the start-up process as for example the total amount of solvent. It could be also performed with the used *Optimization Library*.

The technical design of the pilot plant was not changed during the optimization. Future work should also include the improvement of the technical design. A possible option would be for example the implementation of the lean vapour compression (Fernandez et al., 2012).

The SQP solver used in the optimization does not guarantee that the global optimum is found. The optimization should be also performed by using a genetic algorithm to confirm the results of this paper in the future.

Nomenclature

α	solvent loading (mol _{CO₂} /mol _{MEA})
\dot{m}	mass flow rate (kg/s)
\dot{N}	molar flow rate (mol/s)
\dot{Q}	heat flow rate (W)

\dot{V}	volume flow rate(m ³ /s)
N	amount of substances(mol)
T	temperature (°C)
t	time s
X	CO ₂ capture rate (-)

Abbreviations

CO ₂	carbon dioxide
CCS	carbon capture and storage
MEA	monoethanolamine
PCC	post-combustion carbon capture

Subscripts

abs	absorber
fg	flue gas
in	incoming stream
liq	liquid
out	outgoing stream
reb	reboiler
str	stripper
sump	column sump

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