CO2 and H2O chemisorption mechanism on different potassium-promoted sorbents for SEWGS processes

Citation for published version (APA):
Coenen, K. T., Gallucci, F., Hensen, E. J. M., & van Sint Annaland, M. (2018). CO2 and H2O chemisorption mechanism on different potassium-promoted sorbents for SEWGS processes. Journal of CO2 Utilization, 25, 180-193. https://doi.org/10.1016/j.jcou.2018.04.002

Document license:
CC BY

DOI:
10.1016/j.jcou.2018.04.002

Document status and date:
Published: 01/05/2018

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
CO₂ and H₂O chemisorption mechanism on different potassium-promoted sorbents for SEWGS processes

Kai Coenen, Fausto Gallucci*, Emiel Hensen, Martin van Sint Annaland

Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, Eindhoven, The Netherlands

ARTICLE INFO

Keywords:
SEWGS
Material composition
CO₂ adsorption
H₂O adsorption

ABSTRACT

The sorption kinetics and capacities of CO₂ and H₂O were investigated for two different potassium-promoted hydrotalcite sorbents and potassium-promoted alumina. Thermogravimetric analysis (TGA) and packed-bed reactor (PBR) breakthrough experiments were performed using sequences of adsorption and desorption steps in different gas mixtures containing CO₂ and H₂O. Experiments were carried out at an operating temperature of 400 °C with different partial pressures ranging from 0.025 bar to 0.3 bar for CO₂ and 0.1 to 0.3 bar for H₂O respectively. It was found that a sorption mechanism with different adsorption sites, developed for one of the sorbents, also applies for the other sorbents where capacities are different and depending on the sorbent. From experimental results it was deduced that K₂CO₃ promotion is mainly responsible for a reactive CO₂ adsorption site, which can only be regenerated with steam. The adsorption capacity for this site is enhanced for K₂CO₃ promoted alumina compared to K₂CO₃ promoted hydrotalcite. A second adsorption site for CO₂, which can be regenerated with N₂ is dominant on the K₂CO₃ promoted hydrotalcite with a high MgO content. This indicates that MgO is probably responsible for the formation of basic sites on the surface of the sorbent, which are relatively easily regenerated at the investigated experimental conditions. The results also show that the sorbent with the highest MgO loading has the highest cyclic working capacity under dry adsorption conditions, whereas the hydrotalcite-based adsorbent with a lower MgO content has the highest cyclic working capacity for CO₂ at wet conditions and is therefore the preferred sorbent for sorption-enhanced water-gas shift applications.

1. Introduction

In the sorption-enhanced water-gashift (SEWGS) process, the water-gashift reaction is combined with in-situ CO₂ capture on a solid adsorbent. This process has been widely investigated due to its large potential for pre-combustion CO₂ capture. A relatively low energy penalty for CO₂ capture in comparison to alternative processes (e.g. Selexol) makes this technology very promising [1]. Therefore, over the past years much research on various aspects of SEWGS processes has been carried out [1–3]. Modeling of the CO₂ and H₂O adsorption kinetics and determination of the cyclic working capacity of the adsorbent is a very important aspect for the process design (e.g. the number of adsorption columns, cycle design and process integration) and further process optimization [4–6]. Different adsorbents have been investigated in the past for their use in SEWGS [7–10]. Hydrotalcite (HTC) based adsorbents are very promising candidates because of their low cost, sufficiently high CO₂ cyclic working capacity, fast adsorption kinetics and good mechanical stability over many adsorption/desorption cycles and long time periods [11,12]. Potassium-promoted hydrotalcites with different Mg/Al ratios were investigated in the past and their cyclic working capacity was determined [13]. Usually a potassium carbonate promotion of around 20% is used (optimum loading in terms of cyclic working capacity), where the Mg/Al ratio was varied between 0.54 (30 wt% MgO compared to Al₂O₃) and 2.9 (70 wt% MgO compared to Al₂O₃). In a previous work the adsorption capacity and kinetics for CO₂ and H₂O was studied for two potassium-promoted HTCs with a different Mg/Al ratio and a potassium-promoted alumina. It was found that a higher Mg content can improve the cyclic working capacity for CO₂. A slower continuous adsorption rate after the first initial fast adsorption rate was observed for all adsorbents and this becomes more prominent for a material with a higher Mg content. At a higher operating temperature the desorption rate of CO₂ increases, which increases the cyclic working capacity of HTC-based adsorbents, however, not for a potassium-promoted alumina adsorbent [13]. Various authors have reported that the presence of steam significantly affects the cyclic working capacity for CO₂ [8,9]. Different adsorption sites on a HTC-based adsorbent are most likely responsible for the strong influence of steam on the cyclic working capacity of CO₂ [14].

* Corresponding author.
E-mail address: F.Gallucci@tue.nl (F. Gallucci).

https://doi.org/10.1016/j.jcou.2018.04.002
Received 16 February 2018; Received in revised form 17 March 2018; Accepted 4 April 2018
The existence of one adsorption site for each sorbate species CO₂ (B) and H₂O (A) was elaborated recently with the help of thermogravimetric analysis (TGA) and packed bed reactor (PBR) breakthrough experiments for a potassium-promoted HTC with a Mg/Al ratio of 0.54. Part of the adsorbed CO₂ can only be regenerated with H₂O from the adsorbent which was attributed to an exchange site (C). Therefore, regeneration with steam significantly increases the cyclic working capacity for CO₂. A schematic overview of the different sorption sites can be found in Fig. 1. It was concluded from TGA experiments that the cyclic working capacity for CO₂ increased for all subsequent experiments after the adsorbent was exposed to a stream containing both CO₂ and H₂O. This increase in adsorption capacity was attributed to another site D. In this paper we will investigate whether the observed behavior needs to be described with an additional adsorption site, or whether it can also be attributed to an increase in the capacity of the three other sites.

The influence of the material composition of the adsorbent on the capacity of the different adsorption sites is important for sorbent selection and depends on the selected process conditions. The investigation of different sorption sites and their behavior as function of material composition is crucial in order to design a good adsorbent or select the sorbent for SEWGS.

In this paper, it is investigated whether the developed adsorption mechanism for HTCs is generally applicable, even for different sorbents such as potassium-promoted alumina to further improve our understanding about the nature of the different adsorption sites. These results can significantly improve future sorbent development for different sorption processes where adsorption of CO₂ can enhance the performance of the process. Experiments with both TGA and PBR were carried out for a potassium-promoted HTC with a Mg/Al ratio of 2.95 and a potassium-promoted alumina.

2. Materials and methods

A potassium-promoted hydrotalcite-based adsorbent, with a Mg/Al ratio of 2.95 (KMG70) and a potassium-promoted alumina (KSORB) were used in this work and compared to a potassium-promoted hydrotalcite-based adsorbent with a Mg/Al ratio of 0.54 (KMG30). The compositions are summarized in Table 1. The commercial materials were pre-calcined by the manufacturer at 250 °C and 450 °C for 24 h [8].

KMG30 and KMG70 adsorbent pellets (4.7 × 4.7 mm) and KSORB (spheres with a diameter of 2 mm) were crushed to powders with the same particle size, which have been used in TGA-measurements. Sorption experiments were carried out in an in-house developed TGA setup which was already described elsewhere [14,15]. Prior to the adsorption experiments all materials were pretreated in the same way (heating the samples to 600 °C in N₂ with a dwelling at 600 °C for 120 min). For TGA measurements the cyclic working capacity (cwc) is defined according to Eq. (1), where the average between adsorption and desorption capacity with respect to the pretreated sample mass is calculated for each experiment.

\[
cwc_{\text{cyclic}} = \frac{abs(\Delta m)_{\text{ads}} + abs(\Delta m)_{\text{des}}}{2m_{\text{sample(pretreated)}}}
\]  

(1)

This cwc was determined for each adsorption/desorption step using the mass change averaged over the last three consecutive experiments. Note that we use the mass-based cyclic working capacity, as the TGA does not provide additional information on the species absorbed/desorbed. For all experiments the measured weight change was corrected with a blank experiment carried out at the same condition without the sorbent sample. Experiments were carried out twice starting one time with H₂O as a first adsorption step after the pretreatment and a second time starting with CO₂. Details on the experimental setups and the procedures used in this work can be found in an earlier published work [14].

Packed bed reactor experiments were carried out using a small packed bed reactor with an inner diameter of 27 mm and 350 mm length (AISI 316 L). A detailed description on the experimental Setup was described elsewhere previously [15,16]. The reactor was filled with different sorbent particles with characteristics reported in Table 2.

A multipoint thermocouple (10 measuring points with a distance to each other of 20 mm) was installed to measure the axial temperature profile in the bed and to monitor the temperature fronts due to sorption.

Different molar fractions were used during the PBR and TGA experiments as summarized in Table 3. Changing the gas composition was performed by bypassing the reactor for 5 min and measuring the concentration (to check the feed gas composition). After this stabilization time, the feed was sent to the reactor from bottom to top while monitoring the outlet composition of the reactor for 30 min. Experiments were conducted at atmospheric pressure and different operating temperatures between 300 and 500 °C. The mixing in the empty volume of the reactor and the tubing was determined using an inert (CH₄ in this case). The breakthrough of the Intert was used to determine the contribution of gaseous species to the breakthrough time for each material independently because different porosity and bed height will have an impact on the inert breakthrough time. The determined adsorption capacity during each adsorption/desorption step was corrected with the determined contribution of gas phase. An overview of all experiments including different partial pressures of sorbate species is listed in the Table 4.

For each experiment listed in Table 4 a sequence of adsorption and desorption steps have been performed as reported in Table 5. Cycles have been repeated 5 times for the TGA experiments. The cyclic working capacity for the TGA experiments was calculated based on the last three adsorption/desorption cycles. Every cycle for the PBR experiments was carried out twice. We will refer to the different experiments performed with ‘n,m’, where the first number refers to the

---

**Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| CWC          | cyclic working capacity |
| HTC          | hydrotalcite |
| FTIR         | Fourier transform infrared spectroscopy |
| KSORB        | potassium-promoted alumina (sorbent material) |
| KMG30        | potassium-promoted hydrotalcite with 30 wt% MgO |
| KMG70        | potassium-promoted hydrotalcite with 70 wt% MgO compared to Al₂O₃ (sorbent material) |
| PBR          | packed bed reactor |
| PCO₂         | partial pressure of CO₂ [bar] |
| PH₂O         | partial pressure of H₂O [bar] |
| TGA          | thermo-gravimetric analysis |

---

![Fig. 1. Schematic overview of the different adsorption sites on a hydrotalcite-based adsorbent. Site A (H₂O), Site B (CO₂), Site C for both CO₂ and H₂O and site D which was assigned to the higher adsorption capacity of the material after exposure to CO₂ and H₂O.](image)
In the results and discussion section, we will show the presence of the earlier introduced different sorption sites based on TGA and PBR experiments. The different adsorption sites will be introduced consecutively, and their cyclic working capacity will be determined for the different sorbent materials. The importance of the different sorption sites for the different materials will be discussed with a simple model to predict the weight change observed in the TGA experiments. The total CO\(_2\) and H\(_2\)O cyclic working capacities will be determined for all sorbents at different operating conditions to find the best operating conditions.

### 3.1. TGA data

Arrows are used in the figures that show the normalized weight change as a function of time to indicate which sites are involved in the adsorption/desorption steps, where the mass at the start and end of each step is indicated by a dotted line. Red arrows represent the mass of CO\(_2\) exchanged in one experimental step, whereas blue arrows represent the mass of H\(_2\)O exchange. The length of the arrow represents the total mass change obtained in the experimental step and the contributions for the different sites are indicated by their letter. An increase in the adsorbate content is represented by a solid arrow, a decrease by a shaded arrow. An example for a representation of three different sites involved in an adsorption step can be found in Fig. 2.

### 3.2. PBR data

The areas in the figures (integration of analyzer signal over the time with respect to the baseline) are colored in the same way as for the TGA results (see Fig. 2). The signal for CO\(_2\) and the corresponding areas are plotted in red, whereas the signal and areas for H\(_2\)O are plotted in blue. Again, we distinguish between adsorption (solid area above the signal) and desorption (shaded area below the analyzer signal). Note that the integrated areas were corrected afterwards for gas phase contribution during the experiments. The graphs show the uncorrected analyzer signals.

### 3.3. Sorption of H\(_2\)O (site A)

The three different sorbents were exposed in the TGA to a H\(_2\)O/N\(_2\) mixture with a partial pressure of 0.34 bar H\(_2\)O (during the first part of experiment 6). The cyclic working capacity for H\(_2\)O (site A) follows the order: KMG30 > KMG70 > KSORB (see Fig. 3). The same trend was already reported in an earlier publication using a different experimental setup [13]. The absolute value of the cwc of site A for KMG30 is somewhat lower than reported before [16], most probably due to some aging of the material during these tests.

The packed bed reactor experiments confirm the higher cyclic working capacity of H\(_2\)O for KMG70 compared to KSORB. Both the surface basicity and surface area affect the adsorption capacity of the sorbents, explaining the obtained results since a direct correlation between surface area and adsorption capacity of the materials for steam could not be found. Surface area of the different sorbents has already been published earlier [13]. The breakthrough curves for KSORB can be found in the Appendix. Note that the longer breakthrough times for KSORB are a result of the higher sorbent mass used in the experiments.

### 3.4. Sorption of CO\(_2\) (site B)

The cyclic working capacity for CO\(_2\) of site B has been determined based on results obtained by TGA during experiment 2 (see Fig. 4a), the sub-experiment as listed in Table 5 (1–8).

### 3. Results and discussion

### 3.1. TGA data

Arrows are used in the figures that show the normalized weight change as a function of time to indicate which sites are involved in the adsorption/desorption steps, where the mass at the start and end of each step is indicated by a dotted line. Red arrows represent the mass of CO\(_2\) exchanged in one experimental step, whereas blue arrows represent the mass of H\(_2\)O exchange. The length of the arrow represents the total mass change obtained in the experimental step and the contributions for the different sites are indicated by their letter. An increase in the adsorbate content is represented by a solid arrow, a decrease by a shaded arrow. An example for a representation of three different sites involved in an adsorption step can be found in Fig. 2.

### 3.2. PBR data

The areas in the figures (integration of analyzer signal over the time with respect to the baseline) are colored in the same way as for the TGA results (see Fig. 2). The signal for CO\(_2\) and the corresponding areas are plotted in red, whereas the signal and areas for H\(_2\)O are plotted in blue. Again, we distinguish between adsorption (solid area above the signal) and desorption (shaded area below the analyzer signal). Note that the integrated areas were corrected afterwards for gas phase contribution during the experiments. The graphs show the uncorrected analyzer signals.

### 3.3. Sorption of H\(_2\)O (site A)

The three different sorbents were exposed in the TGA to a H\(_2\)O/N\(_2\) mixture with a partial pressure of 0.34 bar H\(_2\)O (during the first part of experiment 6). The cyclic working capacity for H\(_2\)O (site A) follows the order: KMG30 > KMG70 > KSORB (see Fig. 3). The same trend was already reported in an earlier publication using a different experimental setup [13]. The absolute value of the cwc of site A for KMG30 is somewhat lower than reported before [16], most probably due to some aging of the material during these tests.

The packed bed reactor experiments confirm the higher cyclic working capacity of H\(_2\)O for KMG70 compared to KSORB. Both the surface basicity and surface area affect the adsorption capacity of the sorbents, explaining the obtained results since a direct correlation between surface area and adsorption capacity of the materials for steam could not be found. Surface area of the different sorbents has already been published earlier [13]. The breakthrough curves for KSORB can be found in the Appendix. Note that the longer breakthrough times for KSORB are a result of the higher sorbent mass used in the experiments.

Since it was the first time that the adsorbent was exposed to a sorbate not only adsorption site A is filled with H\(_2\)O, but also site C (Fig. 3b, first adsorption), explaining the larger amount of H\(_2\)O adsorbed in the first cycle (larger blue area in Fig. 3b). This was also observed in the TGA experiments, but in Fig. 3a only the last cycle is plotted to focus on the cyclic behavior of the different materials.

### 3.4. Sorption of CO\(_2\) (site B)

The cyclic working capacity for CO\(_2\) of site B has been determined based on results obtained by TGA during experiment 2 (see Fig. 4a), the sub-experiment as listed in Table 5 (1–8).
which are also confirmed with the results from the breakthrough curves in the packed bed reactor experiments (Fig. 4b). The results show that the order in the cyclic working capacity for CO₂ is changed compared to H₂O. The sorbent with the highest Mg content (KMG70) has the highest cyclic working capacity for site B. This trend was also found in a previous study and was explained with the higher surface basicity of the sorbent when a larger amount of MgO is present in the sorbent structure. It seems that MgO induces a second reaction, which could be explained e.g. by diffusion of carbonate species into the bulk of the material which is enhanced for a more basic sorbent. This explanation is supported by the observed difference in adsorption profile for KSORB (without MgO), where an adsorption equilibrium is established after 30 min half-cycle time, while this is not the case for KGM30 and KMG70. The findings reported here confirm earlier measurements [13].

3.5. Replacement of CO₂ by H₂O (site C)

To determine the cyclic working capacity of the adsorption site which can be either occupied by H₂O or CO₂ (site C) experiment 3 was carried out (feeding CO₂ and H₂O consecutively). Fig. 5a (TGA) and b (PBR) show the results obtained for KSORB and Fig. 5c and d show the results for KMG70. A significant difference in the cyclic working capacity between the different sorbents was observed. The cyclic working capacity for KSORB (11.3 mg/g) is slightly smaller than for KMG30 (12.6 mg/g) but still comparable, whereas KMG70 shows a very low cyclic working capacity of 5.9 mg/g. When comparing the results obtained during the breakthrough experiments the ratio between the area of site B and site C should be compared rather than the breakthrough time or the total area due to the difference in sorbent mass in the experiments. Based on the PBR breakthrough results we can conclude that MgO cannot be responsible for this adsorption site, because the sorbent with the highest MgO content shows the lowest capacity for site C. The impregnation of the sorbents with K₂CO₃ could be the reason for the higher capacity of this adsorption site. It has been proposed in the literature that indeed the interaction of K₂CO₃ with Al is a crucial for the availability of adsorption sites on a potassium-promoted hydrotalcite [17]. These findings explain the rather high adsorption capacity of this site for KSORB compared to KGM70. Since KGM30 has the highest surface area [13] K₂CO₃ can interact to a larger extent with the available Al on the surface resulting in the highest cyclic working capacity of site C for KMG30.

Based on the packed bed reactor experiments, the replacement ratio between CO₂ and H₂O was determined. Note that this information cannot be obtained from the TGA experiments. The average cyclic working capacity for CO₂ of site C was determined based on the desorbed amount of CO₂ during step d of an experiment n.3 (were n represents the experiment number from Tables 4 and 3 refers to step 3 as listed in Table 5) and the adsorbed amount of CO₂ during step a of experiment n.3 minus the cyclic working capacity of site B determined based on step c of each experiment according to Eq. (2):

\[
C(CO_2) = \frac{\text{average}(CO_2^{des}(d) - CO_2^{ads}(a) - CO_2^{des}(c))}{\text{C}}
\]  

Analogously, the average cyclic working capacity of site C for H₂O was determined based on the desorbed amount of H₂O during the step d of an experiment n.3 and the adsorbed amount of H₂O during the step a minus the cyclic working capacity of site A, determined based on the amount of H₂O desorbed during step e of each experiment, as given by Eq. (3):

\[
C(H_2O) = \frac{\text{average}(H_2O^{des}(a) - H_2O^{ads}(d) - H_2O^{des}(e))}{\text{C}}
\]

Table 6 shows a summary of the determined CO₂/H₂O ratios based on all the experiments. For all the sorbents and for all the different

| Cycle Number | 1 | 2* | 3* | 4* | 5* | 6 | 7 | 8 |
|--------------|---|----|----|----|----|---|---|---|
| a. ADS       | H₂O | CO₂ | CO₂ | CO₂/H₂O | CO₂ | CO₂/H₂O | CO₂/H₂O | CO₂/H₂O |
| b. ADS       | CO₂ | CO₂ | CO₂ | CO₂/H₂O | CO₂ | CO₂/H₂O | CO₂/H₂O | CO₂/H₂O |
| c. DES       | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ |
| d. ADS       | H₂O | H₂O | H₂O | H₂O | H₂O | H₂O | H₂O | H₂O |
| e. DES       | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ | N₂ |

**Table 5**

Adsorption/desorption steps during the experiments (Note that depending on the experiment adsorption of one species can lead to the desorption of an adsorbed species).

![Table 5](image)

![TGA and PBR Visualizations](image)

Fig. 2. Visualizations used in the figures to explain the different sites involved in CO₂ and H₂O adsorption on different sorbent materials [15,16].
conditions, a CO₂/H₂O ratio close to 1 was found, except for KMG70 that showed for some experiments a much higher value. Inspecting the breakthrough curves of KMG70, it can be seen (e.g. Fig. 5) that the amount of H₂O desorbed during CO₂ adsorption is within the detection limit (noise) of the FTIR. Combined with the low capacity of site C on KMG70 the determination of the replacement ratio for KMG70 is rather inaccurate. Because of the transient behavior and the slow desorption kinetics of CO₂ and H₂O on this type of sorbents, the determination of the cyclic working capacities is unfortunately subjected to rather large experimental inaccuracies. Nevertheless, it seems that for the higher cyclic working capacities of site C for KMG30 and KSORB the replacement ratio could be determined more accurately. Generally, the determined values of the replacement ratio correspond to 1:1 replacement of H₂O by CO₂ for site C, which was postulated earlier [16].

3.6. Simultaneous feed of CO₂ and H₂O

Experiment 4 was used to determine the cyclic working capacity of site C at equilibrium conditions when feeding both CO₂ and H₂O simultaneously, indicated with Ceq. The TGA and PBR results are shown in Fig. 6. Fig. 6a and c show that a higher cyclic working capacity for the site Ceq is found for KSORB compared to KMG70. This is expected because the cyclic working capacity of site Ceq should be directly correlated to the cyclic working capacity of site C. For KMG30 the highest cyclic working capacity for site C and Ceq was found.

3.7. Adsorption capacity change for CO₂ and H₂O (site D)

In an earlier work [16] a site D was introduced to describe the higher adsorption capacity of all sorbents when CO₂ and H₂O are fed together during the first step of experiment 4. The increase in cyclic working capacity is more pronounced for KMG70 (6.3 mg/g) compared to KSORB (3.3 mg/g). However, it could also be considered that the increase in working capacity is mainly related to an increase in the cyclic working capacity of site B, which would also explain the higher capacity of this adsorption site for KMG70.

The results from experiment 5 can be described with the 4 sites mechanism introduced until this point. Fig. 7a and b show the results of KSORB for both TGA and PBR experiments, and similarly Fig. 7c and d show the results for KMG70. When comparing the ratios of the areas of site B and C in the PBR breakthrough experiments, it can be concluded that indeed the replacement effect (cyclic working capacity of site C) is

---

**Fig. 3.** a) TGA Experiment 6.1: Adsorption/desorption of H₂O at 400 °C and PH₂O = 0.34 bar (we only consider KMG70(2) & KSORB(1)); b) PBR Experiment 21.1 at 400 °C and PH₂O = 0.1 bar for KMG70.

**Fig. 4.** a) TGA experiment 6.2: adsorption/desorption of CO₂ at 400 °C and PCO₂ = 0.66 bar (we only consider KMG70(2) and KSORB(1)) b) PBR experiment 21.2 for KMG70 at 400 °C and PCO₂ = 0.05 bar.
much smaller for KMG70 compared to KSORB. During step 2, the replacement of CO₂ is only barely visible for KMG70. Moreover, it was found that the sorbent was still adsorbing CO₂, which can be explained with the slower adsorption kinetics of KMG70, which were shown before (Experiment 2).

For KSORB it was observed during experiment 5 that not all CO₂ can be desorbed from site B. This observation was obtained from both TGA and PBR experiments. If CO₂ would desorb completely from site B and H₂O from site A during step three one would expect a weight decrease of about 16.5 mg/g. However, the obtained weight decrease is much lower (about 10 mg/g). PBR experiments confirm that indeed the amount of CO₂ desorbed during this step is smaller than during experiment 4. In the following step (step 4) some additional CO₂ is desorbed compared to the previous experiments. In Fig. 8 the area of the breakthrough curve for CO₂ is plotted for experiments 4, 5 and 6. It is evident, that the amount of CO₂ desorbed in experiments 5 and 6 is significantly lower compared to experiments 3 and 4, confirming the introduced hypothesis.

Also, the results obtained from experiment 6 confirm our proposed mechanism. The results from both the TGA and PBR experiments for both KGM70 and KSORB can be described. An important observation from the TGA experiments is the observed capacity change of adsorption site D. When comparing the total observed weight change during step 1 of experiment 5 (Fig. 8) and experiment 6 (Fig. 9), we observed a lower weight change during experiment 6. This observation seems to be valid for all sorbents, but it is most apparent for KSORB. Deactivation of this adsorption site can be explained with the fact that the measured adsorption capacity is always dependent on the prior desorption step [14]. Therefore, if the desorption time is not sufficient to desorb the amount of CO₂ on site D, the capacity of this site will decrease. This would imply that the pseudo steady state between adsorption and desorption on site D was not yet reached or is not occurring at these operating conditions. To describe the cyclic working capacity during all experiments this adsorption site should deactivate with experimental time if the capacity of the other adsorption site is assumed constant.

During the experiment 7 (Fig. 10), the capacity of site D for KSORB is reduced to already 20% of its original value, indicating that this site

![Fig. 5. TGA experiments: Adsorption of CO₂ with dry (N₂) and wet regeneration (H₂O) at 400 °C and PH₂O = 0.34 bar PCO₂ = 0.66 bar: a) KSORB (experiment 6.3); c) KMG70 (experiment 27.3) and PBR experiments at 400 °C and PH₂O = 0.1 bar PCO₂ = 0.05 bar b) KSORB (experiment 1.3); d) KMG70 (experiment 21.3).](image)

Table 6

| Sorbent | CO₂/H₂O | PCO₂ | PH₂O | T | PCO₂ | PH₂O | T |
|---------|--------|------|------|---|------|------|---|
| KSORB  | 1.04-1.12 | 0.05 | 0.1  | 300 | 0.3  | 0.1  | 400 |
| KMG30  | 0.62-1.33 | 0.3  | 0.1  | 400 | 0.025| 0.1  | 500 |
| KMG70  | 0.98-3.05 | 0.3  | 0.1  | 400 | 0.05 | 0.15 | 400 |

much smaller for KMG70 compared to KSORB. During step 2, the replacement of CO₂ is only barely visible for KMG70. Moreover, it was found that the sorbent was still adsorbing CO₂, which can be explained with the slower adsorption kinetics of KMG70, which were shown before (Experiment 2).

For KSORB it was observed during experiment 5 that not all CO₂ can be desorbed from site B. This observation was obtained from both TGA and PBR experiments. If CO₂ would desorb completely from site B and H₂O from site A during step three one would expect a weight decrease of about 16.5 mg/g. However, the obtained weight decrease is much lower (about 10 mg/g). PBR experiments confirm that indeed the amount of CO₂ desorbed during this step is smaller than during experiment 4. In the following step (step 4) some additional CO₂ is desorbed compared to the previous experiments. In Fig. 8 the area of the breakthrough curve for CO₂ is plotted for experiments 4, 5 and 6. It is evident, that the amount of CO₂ desorbed in experiments 5 and 6 is significantly lower compared to experiments 3 and 4, confirming the introduced hypothesis.

Also, the results obtained from experiment 6 confirm our proposed mechanism. The results from both the TGA and PBR experiments for both KGM70 and KSORB can be described. An important observation from the TGA experiments is the observed capacity change of adsorption site D. When comparing the total observed weight change during step 1 of experiment 5 (Fig. 8) and experiment 6 (Fig. 9), we observed a lower weight change during experiment 6. This observation seems to be valid for all sorbents, but it is most apparent for KSORB. Deactivation of this adsorption site can be explained with the fact that the measured adsorption capacity is always dependent on the prior desorption step [14]. Therefore, if the desorption time is not sufficient to desorb the amount of CO₂ on site D, the capacity of this site will decrease. This would imply that the pseudo steady state between adsorption and desorption on site D was not yet reached or is not occurring at these operating conditions. To describe the cyclic working capacity during all experiments this adsorption site should deactivate with experimental time if the capacity of the other adsorption site is assumed constant.

During the experiment 7 (Fig. 10), the capacity of site D for KSORB is reduced to already 20% of its original value, indicating that this site
probably will not be needed to describe the steady state operation of a SEWGS process. For KMG70, the TGA experiments can be described more accurately using 70% of site D still participating in the adsorption and desorption steps. It appears that the deactivation of site D depends on the type of sorbent. It was found that the reported mechanism of KMG30 could also be improved by a slow deactivation of site D. Table 7 shows the model used for the different sorbents during the different experiments and the different adsorption/desorption steps. It can be seen, that indeed the strongest deactivation of site D seems to be present for the potassium-promoted alumina (KSORB), where a higher MgO content results in a slower deactivation rate of this adsorption site. Most probably the slow continuous adsorption of CO₂ which was reported earlier for HTC based sorbents with a higher MgO content, can balance the effect of the deactivation of site D for KSORB. Therefore, the deactivation of site D is less important for sorbents with a higher MgO content. Still one can expect for experiments with more than 1000 cycles that probably for all sorbent materials this site will be completely deactivated and is therefore not needed to describe the cyclic working capacity of the sorbent. The experimentally determined cyclic weight change in the TGA experiments together with the difference with the predicted weight change by the developed mechanistic model can be found in Table 8 in the Appendix.

The determined cyclic working capacities using the model according to Table 7 are plotted in Fig. 11a. The error bars represent the standard deviation between two different experimental sets which were carried out for all sorbents independently. The determination of the adsorption sites using the proposed model is quite accurate. Although a direct comparison between TGA and PBR results is not possible due to the difference in experimental conditions (partial pressure of the sorbate species, transient behavior of the PBR) the trend in adsorption capacities of the different adsorption sites can be compared. Error bars in the PBR experiment plot represent the standard deviation for determination of cyclic working capacities based on the adsorbed and desorbed amount within one cycle. Because adsorption and desorption of site C and site Ceq goes along with adsorption and desorption of site A and B it’s determination is more difficult. The adsorption capacities of the adsorption sites A, B and C for the different materials show indeed the same trend in terms of cyclic working capacity. These results support the identification of different adsorption sites on weight bases measured with TGA experiments. To our best knowledge this is the first time that different adsorption sites on various HTC based sorbents has been identified using a direct combination of both measurement techniques. Site D has not been determined using packed bed reactor experiments since it is expected that the determination of this site cannot be done in an accurate way due to the axial concentration profiles associated with the transient behavior of the packed bed.
Fig. 7. TGA experiments: Adsorption of CO₂ followed by CO₂/H₂O and desorption with dry (N₂) and wet regeneration (H₂O) at 400 °C and P(H₂O) = 0.34 bar, P(CO₂) = 0.66 bar, a) KSORB (experiment 6.5); c) KMG70 (experiment 27.5) and PBR experiments at 400 °C and P(H₂O) = 0.1 bar and P(CO₂) = 0.05 bar: b) KSORB (experiment 1.5); d) KMG70 (experiment 21.5).

Fig. 8. Comparison of the desorption signal of CO₂ for the regeneration step with N₂ with KSORB for different experiments a) Experiment 4 (Step 3) and Experiment 5 (Step 3) b) Experiment 4 (Step 3) and Experiment 6 (Step 2). Amount of CO₂ desorbed is significantly reduced in Experiments 5 and 6 compared to Experiment 4.
3.8. Importance of adsorption site D

To investigate the behavior of the adsorption site D compared to the other adsorption sites a TGA experiment with identical conditions (CO$_2$ and H$_2$O partial pressure at 400°C) was performed with a longer step duration of 60 min instead of 30 min. It can be seen from the results shown in Fig. 12 that the adsorption capacity is increasing for all adsorption sites except for site D if the step time is increased compared to the experiment with a shorter step duration. It is known that a longer experimental time would lead to a lower loading of CO$_2$ and H$_2$O on the sorbent, leading to an increase in measured cyclic working capacity. In a previous work it was reported that slower desorption kinetics are the reason for this change in capacity [14]. The fact, that the determined cyclic working capacity for site D is decreasing support our hypothesis that site D is a combination of a capacity increase of the adsorption sites B and C and mainly caused by the slow desorption rate. By using a longer step time, more CO$_2$ and H$_2$O can be desorbed from the site A – C making the correction with site D less important. This observation, together with the deactivation of this site D needed to accurately describe the TGA experiments, illustrates that indeed site D is not required to describe long term experiments and steady state behavior of the different adsorbents.

3.9. Cyclic working capacities of different sorbents

For the application of the different adsorbents in a SEWGS process, the total cyclic working capacities of gaseous sorbate species at operating conditions play a key role in the selection of the best sorbent. In Fig. 13 one can find a summary of the cyclic working capacity of CO$_2$ and H$_2$O for the all sorbents determined by TGA (Fig. 13a) and PBR (Fig. 13b) experiments. Depending on the process conditions, the total cyclic working capacity of CO$_2$ and H$_2$O will change mainly because of the adsorption site C which is dependent on feed partial pressures of the sorbates in the gas phase. KMG30 has the highest cyclic working capacity for both CO$_2$ and H$_2$O for a dry gas feed of CO$_2$ (Total CO$_2$) and for a wet gas feed (Total CO$_2$ capacity at a feed of P$_{CO_2}$ = 0.66 bar and P$_{H2O}$ = 0.34 bar). The high cyclic working capacity of the adsorption site C has also a major influence on the total cyclic working capacity for H$_2$O on KMG30. Depending on the process conditions a lower adsorption capacity for steam can be beneficial in terms of energy efficiency. Reducing the required amount of steam is usually a crucial factor in order to reduce energy costs of a chemical process [18]. KMG70 has a high cyclic working capacity for CO$_2$ with a much lower adsorption capacity for H$_2$O. PBR reactor experiments confirm the trend observed in the TGA experiments. However, because of the lower partial pressures of the feed gas the reported cyclic working capacities are much lower.
lower compared to the ones determined from the TGA experiments. Also the transient behavior of the packed bed reactor reveals an incomplete regeneration of the sorbent compared to the experiments performed in the TGA. Sorbate species desorbing from the sorbent material can re-adsorb on the other sorbent particles along the reactor during the regeneration step hindering a complete desorption. It can be seen in Fig. 13b that, under certain process conditions, for KMG70 (see Total CO₂ at EQ), the cyclic working capacity for CO₂ can be even higher than for the other sorbent materials. Considering the generally higher cyclic working capacity of this sorbent at dry regeneration conditions (only site B active), KGM70 can be an interesting material if the process conditions do not allow regeneration with steam. However, it has to be proven that this sorbent is mechanically stable throughout cyclic operation in long term tests under dry adsorption conditions, since it was found that high partial pressures of steam and CO₂ result in the formation of MgCO₃ leading to a loss in mechanical stability [11].

3.10. Influence of operating conditions on cyclic working capacity

To achieve a high cyclic working capacity, the influence of operating conditions (variations in operating temperature and operating partial pressure) were investigated with PBR experiments. An operating temperature higher than 400 °C was not considered for KSORB because it was found that the presence of steam at high operating temperature leads to an irreversible decrease in the CO₂ cyclic working capacity due to decomposition of carbonate species[13]. It can be discerned from Fig. 14a and b that a decrease in operating temperature leads to an increase in the cyclic working capacity for H₂O on site A and a decrease for CO₂ on site B. This is in agreement with earlier studies for KMG30, where the same trend was observed [16]. Indeed, it seems that this behavior is in general valid for potassium-promoted HTC's and potassium-promoted Al₂O₃. For KMG70, site C (for CO₂) shows the highest cyclic working capacity at 300 °C, which is probably due to the higher amount of CO₂ being replaced by H₂O. H₂O in general shows a higher affinity to adsorb at lower operating temperatures. KSORB exhibited an opposite behavior. This can be explained by the increased desorption kinetics at higher operating temperatures. Since the cyclic working capacity of site C is much higher for KSORB compared to KMG70 and the total mass of sorbent was higher during the experiments the desorption rate becomes more important for this site than the replacement.

Experiments at different partial pressures for CO₂ and H₂O confirm the opposite behavior of the two sorbents. In Fig. 14(c and d) the cyclic working capacities of the different adsorption sites are plotted for different partial pressures. A higher CO₂ partial pressure consistently leads to an increase in the cyclic working capacity for site B, whereas for site C the cyclic working capacity is decreased for KMG70, but increased for
KSORB. Note that for KMG70 the small amount of CO₂ and H₂O being exchanged by site C result in a small area for integration which makes the determination of the cyclic working capacity of this adsorption site less accurate (Fig. 15).

| Table 7 |

Model description for the two sorbent materials used for the weight changes in Table 3.

| EXP | CO₂ | CO₂/H₂O | N₂ | N₂/H₂O | N₂ |
|-----|-----|---------|----|---------|----|
| Model KSORB |
| 1 | +B | +A | -A |
| 2 | +B +C | -B | +A − C | -A |
| 3 | +B +C | -B | +A − C | -A |
| 4 | +C − Ceq | +A + B + Ceq + D | -B | +A − C − D | -A |
| 5 | +B +C | +A − C + Ceq + 0.6D | -0.5B − A | -0.5B − C | -A |
| 6 | +A + B + Ceq + 0.4D | -0.5B − A | -0.6D | -0.4D |
| 7 | +B + Ceq + 0.2D | -B − Ceq | -0.2D |
| 8 | +A + B + Ceq | -B − Ceq | -A |
| Model KMG70 |
| 1 | +B | +A | -A |
| 2 | +B +C | -B | +A − C | -A |
| 3 | +B +C | -B | +A − C | -A |
| 4 | +C − Ceq | +A + B + Ceq + D | -A − B | +A − C − D | -A |
| 5 | +B +C | +A − C + Ceq + D | -A − B | +A − C − D | -A |
| 6 | +A + B + Ceq + 0.8D | -A − B | +A − C | -A |
| 7 | +B + Ceq + 0.6D | -B − Ceq | -0.6D |
| 8 | +A + B + Ceq + 0.6D | -B − Ceq | -0.6D |
| Model KMG30 |
| 1 | +B | +A | -A |
| 2 | +B +C | -B | +A − C | -A |
| 3 | +B +C | -B | +A − C | -A |
| 4 | +C − Ceq | +A + B + Ceq + D | -A − B | +A − C − D | -A |
| 5 | +B +C | +A − C + Ceq + 0.8D | -A − B | +A − C | -A |
| 6 | +A + B + Ceq + 0.6D | -A − B | +A − C | -A |
| 7 | +B + Ceq + 0.4D | -B − Ceq | -0.4D |
| 8 | +A + B + Ceq + 0.4D | -B − Ceq | -0.4D |

4. Conclusions

A detailed experimental study using TGA and PBR experiments with three different adsorbents for the application in a SEWGS process, showed that the mechanism for CO₂ and H₂O adsorption on a potassium-promoted hydrotalcite reported in our earlier publication, is also valid for similar sorbents with a different material composition. Depending on the material composition, the cyclic working capacity of certain adsorption sites for CO₂ and H₂O are changing. It was found that an increase in MgO content in the sorbent leads to an increase in the cyclic working capacity for CO₂ (called site B) for an adsorption site, which can be relatively easily regenerated with e.g. N₂ due to the increase of basic adsorption sites on the surface of the sorbent materials. The cyclic working capacity for CO₂ on a reactive adsorption site (called site C), which can only be regenerated using H₂O is highest for potassium-promoted alumina and a HTC-based adsorbent with a low MgO content. This indicates that mainly K₂CO₃ interactions with Al centers would be responsible for this reactive adsorption site. The cyclic working capacity on an adsorption site for H₂O (called site A) is slightly higher for potassium-promoted HTC compared to the potassium-promoted alumina. The activation of an additional adsorption site for CO₂
Fig. 13. a) CO$_2$ and H$_2$O working capacities for different sorbent materials at PCO$_2$ = 0.66 bar and PH$_2$O = 0.34 bar determined during TGA experiments with a time used for each experimental step being 30 min b) CO$_2$ and H$_2$O working capacities for different sorbent materials at PCO$_2$ = 0.025 bar and PH$_2$O = 0.1 bar determined during PBR experiments with a time used for each experimental step being 30 min.

Fig. 14. Cyclic working capacities of different adsorption sites at different operating conditions. The legend shows 1st the operating temperature, 2nd H$_2$O partial pressure and 3rd CO$_2$ partial pressure a) KMG70 at different operating temperature b) KSORB at different operating temperature c) KMG70 at different CO$_2$ and H$_2$O partial pressures d) KSORB at different CO$_2$ and H$_2$O partial pressures.
if the sorbent is exposed to CO₂ and H₂O together during one step (called site D) was confirmed for all sorbents. It was found that the additional capacity of this site is decreasing with time on stream. This can be described with a deactivation of this adsorption site. Therefore, in order to describe the steady state adsorption behavior this adsorption site does not need to be included. It was proven with PBR breakthrough experiments comparing the cyclic working capacity of the proposed adsorption sites, that indeed the proposed mechanism can describe the experimental results of both measurement techniques. For SEWGS KGM30 shows the highest cyclic working capacity for CO₂ and is therefore the preferred sorbent for the process. For adsorption process where dry regeneration of the sorbent is used, KGM70 could be a very promising alternative, if its mechanical stability is demonstrated during long-term cyclic experiments.

Acknowledgement

The research leading to these results has received support through the ADEM innovation lab program, project number TUE-P05.

Appendix A

This appendix contains the results from breakthrough experiments for H₂O and CO₂ adsorption performed in a packed bed reactor filled with HTC based materials. Additionally, the weight change during different experiments are given together with the deviation with predictions by a developed model using different adsorption sites. The total deviation in mg/g predicted by the model for each experiment is provided in Table 8.

Figure 15. a) EXP1 KMG70 at 400 °C with PH₂O = 0.1 bar b) EXP2 KMG70 at 400 °C with PCO₂ = 0.05 bar.

Table 8

Summary of the weight change in mg/g observed during TGA experiments compared to predicted weight change by the model for KMG70 and KSORB. The values of the model represent the total deviation between the predicted weight change and weight change measured during the experiments.

| No | CO₂ | CO₂/H₂O | N₂ | N₂/H₂O | N₂ | CO₂ | CO₂/H₂O | N₂ | N₂/H₂O | N₂ | STD DEV |
|----|-----|---------|----|-------|----|-----|---------|----|-------|----|---------|
| KMG70 EXP | | | | | | | | | | |
| 1 | 7.42 | 7.37 | 0.29 | 0.27 |
| 2 | −14.72 | 0.29 | 0.27 |
| 3 | −14.54 | 0.29 | 0.27 |
| 4 | −2.29 | −6.79 | 0.00 | 0.09 |
| 5 | −2.29 | −6.79 | 0.00 | 0.09 |
| 6 | −2.29 | −6.79 | 0.00 | 0.09 |
| 7 | −2.29 | −6.79 | 0.00 | 0.09 |
| 8 | −2.29 | −6.79 | 0.00 | 0.09 |
| Model KMG70 | 0.06 | 0.00 | 0.03 | 0.03 |
| KMG30 EXP | | | | | | | | | | |
| 1 | 7.90 | 8.06 | 0.10 | 0.10 |
| 2 | −10.71 | 0.10 | 0.10 |
| 3 | −12.19 | 0.10 | 0.10 |
| 4 | −11.19 | 0.10 | 0.10 |
| 5 | −2.29 | −6.79 | 0.00 | 0.09 |
| 6 | −2.29 | −6.79 | 0.00 | 0.09 |
| 7 | −2.29 | −6.79 | 0.00 | 0.09 |
| 8 | −2.29 | −6.79 | 0.00 | 0.09 |
| Model KMG70 | 0.17 | 0.01 | 0.09 | 0.09 |
| KSORB EXP | | | | | | | | | | |
| 1 | 5.40 | 6.65 | 0.18 | 0.66 |
| 2 | −8.73 | 0.18 | 0.66 |
| 3 | −9.06 | 0.18 | 0.66 |
| 4 | −9.36 | 0.18 | 0.66 |
| 5 | −9.36 | 0.18 | 0.66 |
| 6 | −9.36 | 0.18 | 0.66 |
| 7 | −9.36 | 0.18 | 0.66 |
| 8 | −9.36 | 0.18 | 0.66 |
| Model KMG70 | 1.30 | 0.06 | 0.68 | 0.42 |
including the standard deviation of the model results compared to the experimental results.

References

[1] G. Manzolini, E. MacChi, M. Gazzani, E. MacChi, G. Manzolini, CO2 capture in integrated gasification combined cycle with SEWGS - part A: thermodynamic performances, Fuel 105 (2013) 206–219.

[2] R. Reijers, E. Van Selow, P. Cobden, J. Boon, R. Van Den Brink, SEWGS process cycle optimization, Energy Procedia 4 (2011) 1155–1161.

[3] E.R. van Selow, P.D. Cobden, R.W. van den Brink, J.R. Hufton, A. Wright, Performance of sorption-enhanced water-gas shift as a pre-combustion CO2 capture technology, Energy Procedia 1 (February 1(1)) (2009) 689–696.

[4] M.H. Halabi, M.H.J.M. de Croon, J. van der Schaaf, P.D. Cobden, J.C. Schouten, Reactor modeling of sorption-enhanced autothermal reforming of methane. Part I: performance study of the selectivity of lithium zirconate-based processes, Chem. Eng. J 168 (April 21) (2011) 872–882.

[5] H. Du, A.D. Ehner, Ja. Ritter, Temperature dependence of the nonequilibrium kinetic model that describes the adsorption and desorption behavior of CO2 in k-promoted HTIC, Ind. Eng. Chem. Res. 49 (April 7) (2010) 3328–3336.

[6] A.D. Ehner, S.P. Reynolds, J.A. Ritter, Nonequilibrium kinetic model that describes the reversible adsorption and desorption behavior of CO2 in a k-promoted hydro-talcite-like compound, Ind. Eng. Chem. Res. 46 (no. 6) (2007) 1737–1744.

[7] M. Maroño, Y. Terreiro, L. Montenegro, J. Sánchez, Lab-scale tests of different materials for the selection of suitable sorbents for CO2 capture with H2 production in IGCC processes, Fuel 116 (2014) 861–870.

[8] M. Maroño, Y. Terreiro, L. Gutierrez, Influence of steam partial pressures in the CO2 capture capacity of k-doped hydroxyl-talcite-based sorbents for their application to SEWGS processes, Int. J. Greenh. Gas Control 14 (2013) 183–192.

[9] E.I.G. Oliveira, Ca. Grande, A.E. Rodrigues, CO2 sorption on hydroxyl-talcite and alkali-modified (K and Cs) hydroxyl-talcites at high temperatures, Sep. Purif. Technol. 62 (2008) 137–147.

[10] L.K.G. Bhatta, S. Subramaniam, M.D. Chengala, S. Olivera, K. Venkatesh, Progress in hydroxyl-talcite like compounds and metal-based oxides for CO2 capture: a review, J. Clean. Prod. 103 (2014) 171–196.

[11] E.R. Van Selow, P.D. Cobden, a.D. Wright, R.W. Van Den Brink, D. Jansen, Improved sorbent for the sorption-enhanced water-gas shift process, Energy Procedia 4 (January 1(1)) (2011) 1090–1095.

[12] D.P. Debecker, E.M. Gaigneaux, G. Busca, Exploring, tuning, and exploiting the basicity of hydroxyl-talcites for applications in heterogeneous catalysis, Chem. Eng. J. 334 (2018).

[13] K. Coenen, F. Gallucci, P. Cobden, E. van Dijk, E. Hensen, M. van Sint Annaland, Influence of material composition on the CO2 and H2O adsorption capacities and kinetics of potassium-promoted sorbents, Chem. Eng. J. 293 (2016) 9–23.

[14] J. Boon, K. Coenen, E. van Dijk, P. Cobden, F. Gallucci, M. van Sint Annaland, On the influence of steam on the CO2 chemisorption capacity of a hydroxyl-talcite-based adsorbent for SEWGS applications, Chem. Eng. J. 307 (2017) 554–569.

[15] J. Boon, V. Spallina, Y. van Delft, M. van Sint Annaland, On the influence of steam on the CO2 and H2O adsorption capacities of hydroxyl-talcite-based adsorbents for sorption-enhanced water-gas-shift applications, Chem. Eng. J. 293 (2016) 9–23.

[16] K. Coenen, F. Gallucci, G. Pio, P. Cobden, E. van Dijk, E. Hensen, M. van Sint Annaland, On the influence of steam on the CO2 chemisorption capacity of a hydroxyl-talcite-based adsorbent for SEWGS applications, Chem. Eng. J. 314 (2017) 1737–1744.

[17] S. Walspurger, L. Boels, P.D. Cobden, G.D. Elzinga, W.G. Haije, R.W. van den Brink, R.W. van den Brink, The crucial role of the K+-aluminium oxide interaction in K+-promoted alumina- and hydroxyl-talcite-based materials for CO2 sorption at high temperatures, ChemSusChem 1 (January 7(1)) (2008) 643–650.

[18] J. Boon, V. Spallina, Y. van Delft, M. van Sint Annaland, Comparison of the efficiency of carbon dioxide capture by sorption-enhanced water-gas shift and palladium-based membranes for power and hydrogen production, Int. J. Greenh. Gas Control 50 (2016) 121–134.