



# CO<sub>2</sub> Capture at High Temperature and Low Concentration on Li<sub>4</sub>SiO<sub>4</sub> Based Sorbents

Monica Puccini\*, Maurizia Seggiani, Sandra Vitolo

Department of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino 1, 56122 Pisa, Italy  
 m.puccini@diccism.unipi.it

Solid sorbents based on lithium orthosilicate (Li<sub>4</sub>SiO<sub>4</sub>) have shown promise for CO<sub>2</sub> capture at high temperature. Improved sorption properties can be obtained by appropriate doping. In this study, different promoted Li<sub>4</sub>SiO<sub>4</sub>-based sorbents were prepared by addition of potassium carbonate and binary/ternary alkali (Li, K and Na) carbonate eutectic mixtures. The CO<sub>2</sub> sorption properties of the sorbents were investigated by thermal gravimetric analysis (TGA) at different temperatures in the range between 500 and 600 °C and at low CO<sub>2</sub> partial pressure (0.04 atm). The results showed that all the promoters used noticeably improved the CO<sub>2</sub> sorption capacity in comparison to no-promoted Li<sub>4</sub>SiO<sub>4</sub>. At the optimum sorption temperature of 580 °C, Li<sub>4</sub>SiO<sub>4</sub> with addition of 30 wt% of K<sub>2</sub>CO<sub>3</sub> showed the best CO<sub>2</sub> adsorption properties with sorption capacities of 230 mg CO<sub>2</sub>/g sorbent corresponding to a conversion of about 80 %. Besides this sample maintained its original capacity during multiple CO<sub>2</sub> sorption/desorption cycles.

## 1. Introduction

Carbon dioxide (CO<sub>2</sub>) is considered one of the most important greenhouse gases (GHG) among the anthropogenic emissions into the atmosphere due to the dependence of world economies on fossil fuels as energy source. Approximately 85 % of world energy demand is supplied by fossil fuels (Yang et al., 2008), which results in the emission of about 23·10<sup>9</sup> tonnes CO<sub>2</sub>/year (Pires et al., 2011). One approach that holds great promise for reducing GHG emissions is carbon capture and sequestration (CCS). Under this concept, CO<sub>2</sub> would be captured from large point source, such as power plants and refineries, and injected into geological formations (depleted oil and gas fields, saline formations, unmineable coal seams) (Soundararajan and Gundersen, 2012).

Among the technologies for CO<sub>2</sub> capture from flue gases, the absorption process using aqueous solution of monoethanolamine (MEA) is the most common and available for industrial applications (Chavez and Guadarrama, 2011). But, the significant energy penalty due to the low operating temperatures (40-150 °C) and the high regeneration energy requirements represent important limitations for its application (White et al. 2003). The flue gases produced after the combustion of fossil fuels in a turbine are usually in the temperature range from 700 to 900 K (Ochoa-Fernández et al., 2006). Consequently, they need to be cooled to the temperature levels required for the absorption process in case a wet-absorption method is chosen for separation. Thus, in recent years emerging technologies operating at high temperature (450-750 °C) are being investigated as alternatives to low-temperature CO<sub>2</sub> capture systems.

A promising approach consists in using suitable metal-oxide based inorganic sorbents that reversibly react with CO<sub>2</sub> at elevated temperature (Wang et al., 2010). Materials containing lithium zirconate (Li<sub>2</sub>ZrO<sub>3</sub>) and lithium orthosilicate (Li<sub>4</sub>SiO<sub>4</sub>) seem to be promising CO<sub>2</sub> acceptors in the range of 500-700 °C (Pannocchia et al., 2007). Main advantages of these materials are their high CO<sub>2</sub> capture capacity, lower regeneration temperatures (< 750 °C) compared to other high-temperature sorbents, such as CaO, and their excellent stability that allow operation over a significant number of cycles without losing their sorption capacity. Kato et al. (2005) investigating the CO<sub>2</sub> adsorption properties of Li<sub>2</sub>ZrO<sub>3</sub> and Li<sub>4</sub>SiO<sub>4</sub> pellets at low CO<sub>2</sub> concentration (500 ppv – 20 vol%) concluded that the CO<sub>2</sub> adsorption on Li<sub>4</sub>SiO<sub>4</sub> is more than 30 times faster than that on Li<sub>2</sub>ZrO<sub>3</sub> at the same sorption conditions. Furthermore, Li<sub>4</sub>SiO<sub>4</sub> shows lower costs of the raw materials involved comparing the expensive ZrO<sub>2</sub> with cheaper SiO<sub>2</sub>.

For these reasons,  $\text{Li}_4\text{SiO}_4$  is considered one of the most promising candidates for the post-combustion  $\text{CO}_2$  capture at high temperature and low  $\text{CO}_2$  concentrations (following the reaction:  $\text{Li}_4\text{SiO}_4 + \text{CO}_2 \leftrightarrow \text{Li}_2\text{CO}_3 + \text{Li}_2\text{SiO}_3$ ). Lithium orthosilicate can theoretically adsorb  $\text{CO}_2$  in amounts up to 0.36 g  $\text{CO}_2$ /g sorbent. In practice,  $\text{CO}_2$  capacities up to 35 wt% have been reported at a temperature of 700 °C in pure  $\text{CO}_2$  (Kato et al., 2005). Considering the potential applications of these sorbents for carbon dioxide capture from exhaust gas in thermal power plants (low  $\text{CO}_2$  concentrations) or for the in situ removal of  $\text{CO}_2$  produced in some reactions such as water gas shift (WGS) reaction and steam-methane reforming (SMR), the requested temperature range is between 450 and 600 °C. At these temperatures, kinetic limitations during  $\text{CO}_2$  adsorption are still the main obstacle for application of  $\text{Li}_4\text{SiO}_4$ .

For this reason, various doping methods have been proposed to improve the  $\text{Li}_4\text{SiO}_4$  reactivity (Seggiani et al., 2011). Different alkali carbonates dispersed in  $\text{Li}_4\text{SiO}_4$  have been proposed as promoters since such carbonates forms eutectic mixtures with product  $\text{Li}_2\text{CO}_3$  that melt at high temperatures (> 500 °C) (Seggiani et al., 2013). According to the double shell model proposed for the  $\text{CO}_2$  adsorption mechanism on  $\text{Li}_4\text{SiO}_4$  (Kato et al., 2002), the resultant molten carbonate shell greatly facilitates  $\text{CO}_2$  diffusion throughout the product layer compared to the solid  $\text{Li}_2\text{CO}_3$  shell in pure  $\text{Li}_4\text{SiO}_4$  case. The objective of this work was the development of novel promoted  $\text{Li}_4\text{SiO}_4$  based sorbents for  $\text{CO}_2$  capture at high temperature and low  $\text{CO}_2$  concentration by addition of alkali carbonate mixtures. Different promoted  $\text{Li}_4\text{SiO}_4$ -based sorbents were prepared by addition of potassium carbonate and binary/ternary alkali (Li, K and Na) carbonate eutectic mixtures. The promoters were added in several amounts (10, 20 and 30 wt%) to pure  $\text{Li}_4\text{SiO}_4$  powders synthesized by solid state reaction using crystalline silica. Their  $\text{CO}_2$  sorption properties were investigated by thermal gravimetric analysis (TGA) at different temperatures in the range between 500 and 600 °C and at low  $\text{CO}_2$  partial pressure (0.04 atm). In addition, the cyclic stability of the selected samples were investigated by carrying out 25 cycles of  $\text{CO}_2$  sorption/desorption.

## 2. Experimental

### 2.1 Sorbents preparation and characterization

$\text{Li}_4\text{SiO}_4$  powders were prepared by the solid state method. Starting materials were reagent-grade  $\text{Li}_2\text{CO}_3$  and  $\text{ZrO}_2$  (from Sigma-Aldrich) in a 2:1 molar ratio. The materials were weighed, mixed, and ground in an agate mortar with a suitable amount of water. Then, the mixtures were dried and calcined in air at 900 °C for 4 h. Both temperature increase and decrease ramping rates were set to 60 °C/h. The resulting powders were ground by agate mortar to break down any agglomeration and then sieved to produce  $\text{Li}_4\text{SiO}_4$  particles with size below 10  $\mu\text{m}$ .  $\text{Li}_4\text{SiO}_4$ -based sorbents were prepared mixing 10, 20, 30 wt% of potassium carbonate ( $\text{K}_2\text{CO}_3$ ), binary ( $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$ ) and ternary ( $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3/\text{Na}_2\text{CO}_3$ ) eutectic carbonate mixtures with the previously synthesized pure  $\text{Li}_4\text{SiO}_4$  powder. Table 1 shows the composition and melting points of the binary and ternary eutectic mixtures used in this study.

Powder X-ray diffraction (XRD) characterization of pure and promoted  $\text{Li}_4\text{SiO}_4$  samples prior to and after  $\text{CO}_2$  sorption was conducted using a Philips PW 1050/25 X-ray diffractometer with  $\text{Cu-K}\alpha$  radiation. The accelerating voltage and the applied current were 40 kV and 40 mA, respectively. The XRD patterns were recorded over a  $2\theta$  range between 10° and 70°. Phase identification was verified by comparison against the corresponding Joint Committee Powder Diffraction Standards (JCPDS).

A JEOL 5600 LV scanning electron microscope (SEM) was used to observe the morphology and the promoter distribution in the samples.

### 2.2 Experimental procedure

Carbon dioxide adsorption on prepared powders was studied using a thermogravimetric analyser (TGA Q500 TA Instrument). About 20 mg of sample were placed in a sample pan and, prior to  $\text{CO}_2$  sorption testing, the sample was pre-conditioned and dried in a nitrogen flow (100 mL/min) elevating the temperature (at 10 °C/min) to the operating temperature, till sample weight became stable. Then, the  $\text{N}_2$  flow was switched to a mixture  $\text{CO}_2/\text{N}_2$  containing 4 vol% of  $\text{CO}_2$ . The total feed gas flow rate was maintained at 100 mL/min at atmospheric pressure. The weight increase due to  $\text{CO}_2$  sorption was recorded as a function of time during the adsorption process lasted 120 min. Besides, to assess the stability of the optimized sorbent twenty-five adsorption/desorption cycles were carried out. The adsorption of  $\text{CO}_2$  was carried for 60 min at the desired temperature in 4 vol%  $\text{CO}_2$  flow. Afterwards, the feed gas stream was switched to a pure  $\text{N}_2$  flow (100 mL/min) and the temperature was raised to 700°C with heating rate of 20°C/min. The sample was kept to the regeneration temperature until it was completely regenerated. The regeneration process lasted about 15 min. After that, a new cycle was carried out.

Table 1. Composition and melting point of binary and ternary eutectic mixtures used as promoters.

Eutectic composition (mol %) <sup>a</sup>	Melting point (°C) <sup>a</sup>
Li <sub>2</sub> CO <sub>3</sub> (42.7 %) / K <sub>2</sub> CO <sub>3</sub> (57.3 %)	498
Li <sub>2</sub> CO <sub>3</sub> (42.5 %) / K <sub>2</sub> CO <sub>3</sub> (26.8 %) / Na <sub>2</sub> CO <sub>3</sub> (30.6 %)	393

<sup>a</sup> Data extracted from NSRDS (1978).

### 3. Results and discussion

In order to establish the optimum CO<sub>2</sub> sorption temperature, preliminary sorption runs were performed on the pure and some doped Li<sub>4</sub>SiO<sub>4</sub> samples at temperatures between 500 and 600 °C. As an example, Figure 1 shows the weight increase of the Li<sub>4</sub>SiO<sub>4</sub> with addition of 20 wt% K<sub>2</sub>CO<sub>3</sub> as a result of CO<sub>2</sub> sorption from a 4 vol% CO<sub>2</sub> stream at temperatures between 500-590 °C. As can be seen, the CO<sub>2</sub> sorption capacity increases with the temperature between 500 and 580 °C and then decreases at higher temperatures. The same behaviour was observed for the other samples showing that the maximum adsorption of CO<sub>2</sub> after 2 h was reached at 580 °C. This is attributed to the equilibrium temperature of Li<sub>4</sub>SiO<sub>4</sub> that was calculated to be about 590 °C at the CO<sub>2</sub> partial pressure of 4.04 kPa (4 vol% CO<sub>2</sub> at a total pressure of 101 kPa).

Since the promoters showed no affinity for the CO<sub>2</sub> capture but contributed to the sorbent weight, the conversion of Li<sub>4</sub>SiO<sub>4</sub>,  $X_{\text{Li}_4\text{SiO}_4}$ , was used to assess and compare the effect of the different promoters used on the CO<sub>2</sub> sorption reaction. The percentage conversion  $X_{\text{Li}_4\text{SiO}_4}$  was calculated by using the equation (1):

$$X_{\text{Li}_4\text{SiO}_4} (\%) = \frac{\Delta W}{F_{\text{Li}_4\text{SiO}_4} \cdot r_s} \quad (1)$$

where  $\Delta W$  is the percentage weight change of the sorbent during the adsorption,  $F_{\text{Li}_4\text{SiO}_4}$  is the weight fraction of Li<sub>4</sub>SiO<sub>4</sub> in the sorbent and  $r_s$  is the stoichiometric uptake of CO<sub>2</sub> by Li<sub>4</sub>SiO<sub>4</sub>, which is about 0.36 g of CO<sub>2</sub>/g of Li<sub>4</sub>SiO<sub>4</sub>. For each series of promoted samples, the CO<sub>2</sub> sorption rate generally increases as a function of the promoter amount added (see Table 2). This can be attributed to a more efficient distribution of promoter over the surface of the Li<sub>4</sub>SiO<sub>4</sub> particles. As shown, the addition of 30 wt% K<sub>2</sub>CO<sub>3</sub> to pure Li<sub>4</sub>SiO<sub>4</sub> powders produced a sorbent which exhibited the best CO<sub>2</sub> adsorption performance in terms of sorption capacity: the adsorbed amount of CO<sub>2</sub> after 2 hours was nearly 23 wt% of the starting material corresponding to a 80% conversion of Li<sub>4</sub>SiO<sub>4</sub>. Besides, the sorption capacity of the samples prepared by addition of potassium carbonate are higher than those of sorbents prepared with the relative binary/ternary eutectic carbonate mixtures. These results can be related to the formation of a liquid phase of Li-K carbonates occurred on the surface of Li<sub>4</sub>SiO<sub>4</sub> particles during the carbonation reaction that reduces CO<sub>2</sub> diffusion resistance to the solid product Li<sub>2</sub>CO<sub>3</sub> shell in pure Li<sub>4</sub>SiO<sub>4</sub> (Ida and Lin, 2003). While, for the Li-K and Li-K-Na samples a eutectic liquid phase is already present at the start of CO<sub>2</sub> sorption.

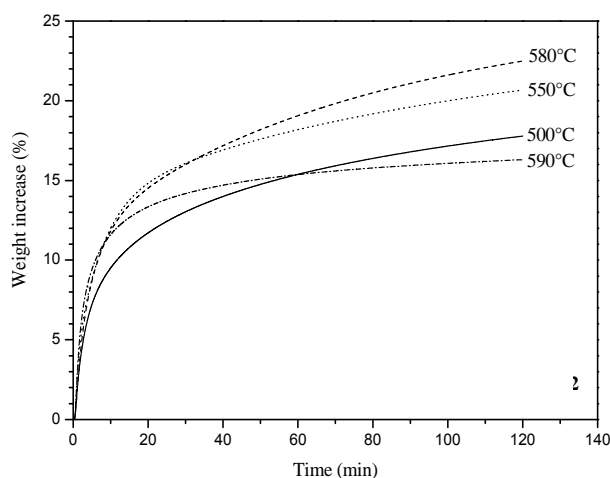


Figure 1: CO<sub>2</sub> sorption profiles on the sorbent with 20 wt% K<sub>2</sub>CO<sub>3</sub> added, in 4 vol% CO<sub>2</sub> stream at different temperatures.

Table 2. Percentage conversion of  $\text{Li}_4\text{SiO}_4$ .

Promoter	10%	20%	30%
$\text{K}_2\text{CO}_3$	57.5	75.0	81.4
$\text{Li}_2\text{CO}_3 / \text{K}_2\text{CO}_3$	44.6	72.0	75.3
$\text{Li}_2\text{CO}_3 / \text{K}_2\text{CO}_3 / \text{Na}_2\text{CO}_3$	57.0	67.4	69.6

As example, the SEM images of the  $\text{Li}_4\text{SiO}_4$  sorbent doped with 30 wt% of  $\text{K}_2\text{CO}_3$  and 30 wt% of  $\text{K}_2\text{CO}_3/\text{Li}_2\text{CO}_3$  eutectic mixture quenched at  $580^\circ\text{C}$  in  $\text{N}_2$  before  $\text{CO}_2$  sorption are reported in Figure 2. As can be seen, the sample with 30 wt% of  $\text{K}_2\text{CO}_3$  shows the same morphology (Figure 2b) of the starting  $\text{Li}_4\text{SiO}_4$  powder (Figure 2a), i.e. porous agglomerates of dense particles with submicron particles of  $\text{K}_2\text{CO}_3$  dispersed on the particle surfaces. Whereas, dense particle agglomerates with average size of  $50\ \mu\text{m}$  were observed in the sample with 30 wt% of  $\text{K}_2\text{CO}_3/\text{Li}_2\text{CO}_3$  (Figure 2d). This is attributed to the fusion of the eutectic mixture on  $\text{Li}_4\text{SiO}_4$  particles during the heating in  $\text{N}_2$  to the adsorption temperature ( $580^\circ\text{C}$ ) greater than the reported melting point ( $498^\circ\text{C}$ ). The presence of these large agglomerates with dense morphology allowed to reduce the interface surface for the reaction between gaseous  $\text{CO}_2$  and sorbent particles with consequent reduction in  $\text{CO}_2$  uptake. In addition, the diffusion of  $\text{CO}_2$  through the molten layer of eutectic mixture before reaching the  $\text{Li}_4\text{SiO}_4$  particle surface may represent an additional diffusional resistance. Figure 3 shows, by means of X-ray analysis, the microstructure changes of the 30 wt%  $\text{K}_2\text{CO}_3$  doped  $\text{Li}_4\text{SiO}_4$  before and during  $\text{CO}_2$  sorption and after  $\text{CO}_2$  desorption. Compared to XRD pattern of the original sorbent (top of Figure 3), XRD pattern of the sorption product (middle of Figure 3) shows that the peaks assigned to  $\text{Li}_4\text{SiO}_4$  disappeared and that the peaks associated with  $\text{Li}_2\text{CO}_3$  and  $\text{Li}_2\text{SiO}_3$  are present instead. This result indicates that during the  $\text{CO}_2$  sorption process  $\text{Li}_4\text{SiO}_4$  reacts with  $\text{CO}_2$  to become  $\text{Li}_2\text{CO}_3$  and  $\text{Li}_2\text{SiO}_3$ . XRD pattern of the regenerated sorbent (bottom of Figure 3) only shows peaks assigned to  $\text{Li}_4\text{SiO}_4$ : this means that, after  $\text{CO}_2$  desorption,  $\text{Li}_2\text{CO}_3$  and  $\text{Li}_2\text{SiO}_3$  react to produce again  $\text{Li}_4\text{SiO}_4$  by releasing  $\text{CO}_2$ .

The cyclic stability of the  $\text{Li}_4\text{SiO}_4$  sorbent doped with 30 wt % of  $\text{K}_2\text{CO}_3$  was investigated by carrying out 25 cycles of  $\text{CO}_2$  sorption/desorption (Figure 4). At the end of the first regeneration, a mass loss of about 4% compared to the initial weight of the sample (after preconditioning) was observed. This behaviour can be attributed to the completion of release of bound water from the sorbent. This weight loss justifies the apparent  $\text{CO}_2$  sorption capacity loss registered in the second adsorption run. After the first cycle, the  $\text{CO}_2$  absorption capacity and capture-regeneration rate remained essentially constant during the subsequent cycles, implying excellent stability. SEM images of one-cycle and twenty-five cycles used sample (Figure 5) shows that the morphology of the sorbent did not change after 25  $\text{CO}_2$  capture-regeneration cycles, supporting the good regenerability properties evidenced by the  $\text{CO}_2$  capture/regeneration cycles.

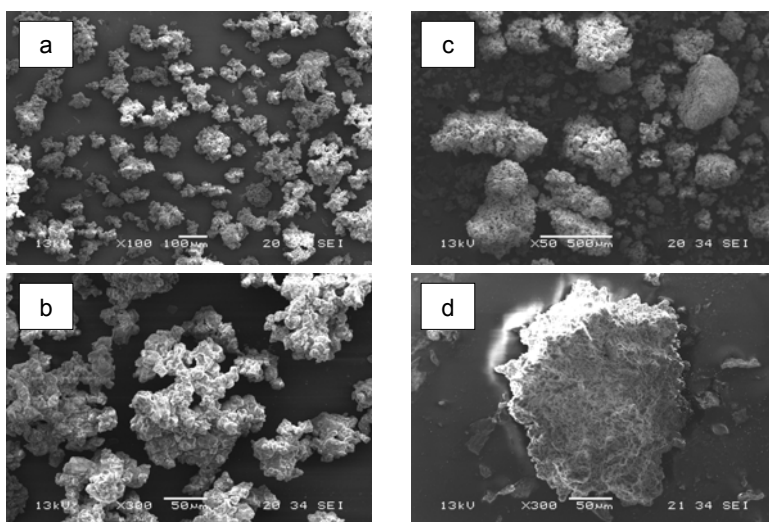


Figure 2: SEM images of the  $\text{Li}_4\text{SiO}_4$  sorbent doped with 30 wt% of  $\text{K}_2\text{CO}_3$  (a) and 30 wt% of  $\text{K}_2\text{CO}_3/\text{Li}_2\text{CO}_3$  (c) before  $\text{CO}_2$  sorption and the same samples (b and d, respectively) heated to  $580^\circ\text{C}$  in  $\text{N}_2$  and quenched in  $\text{N}_2$  to room temperature.

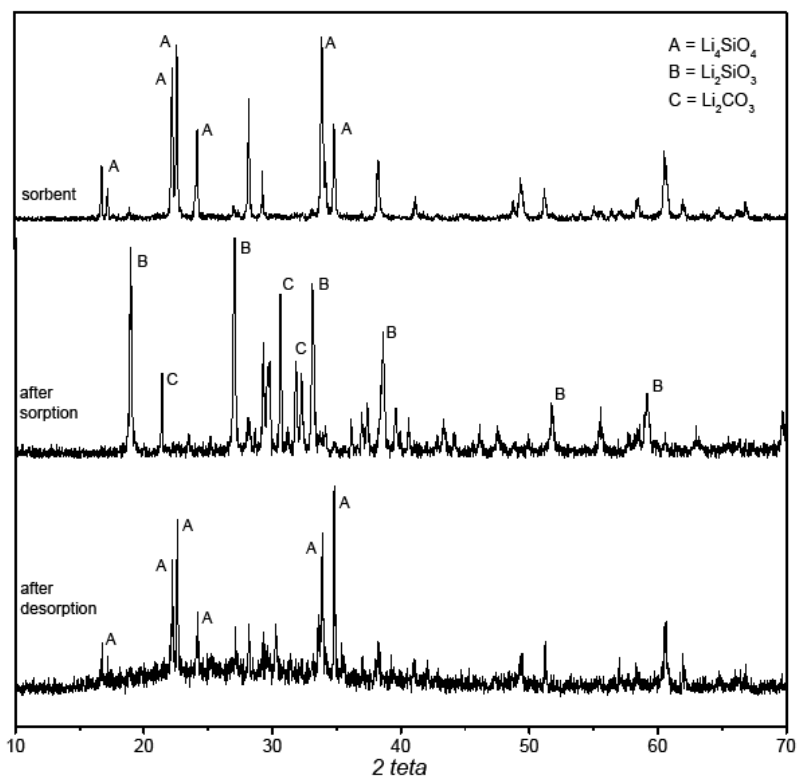


Figure 3: XRD patterns of  $\text{Li}_4\text{SiO}_4$  sorbent with addition of 30 wt% of  $\text{K}_2\text{CO}_3$  before (top) and during (middle)  $\text{CO}_2$  sorption and after  $\text{CO}_2$  desorption (bottom).

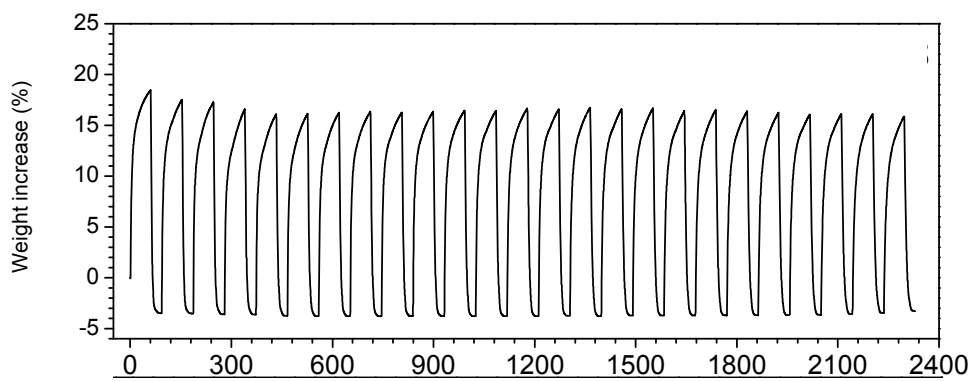


Figure 4: Multiple cycles of  $\text{CO}_2$  sorption (60 min at  $580^\circ\text{C}$  in 4 vol%  $\text{CO}_2$ ) and desorption on the  $\text{Li}_4\text{SiO}_4$  sorbent doped with 30 wt% of  $\text{K}_2\text{CO}_3$ .

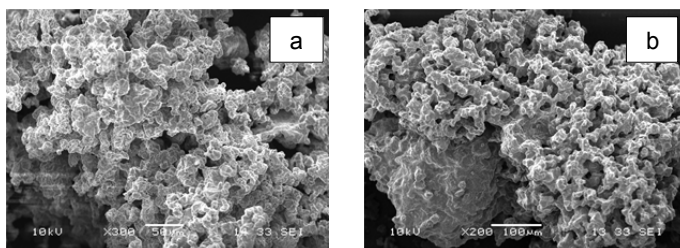


Figure 5: SEM images of the  $\text{Li}_4\text{SiO}_4$  sorbent doped with 30 wt% of  $\text{K}_2\text{CO}_3$  regenerated after the first cycle (a) and the sorbent regenerated after 25 sorption/desorption cycles (b).

#### 4. Conclusions

In this study, different promoted  $\text{Li}_4\text{SiO}_4$ -based sorbents were prepared by addition of potassium carbonate and binary/ternary alkali (Li, K and Na) carbonate eutectic mixtures for carbon dioxide capture at high temperature and low  $\text{CO}_2$  concentration. For each series of promoted samples, the  $\text{CO}_2$  sorption uptake and the conversion increased with increasing the promoter amount due to a more efficient distribution of promoter on a larger surface area. The formation of a molten Li-K carbonate shell on the surface of  $\text{Li}_4\text{SiO}_4$  particles during the carbonation reaction improved significantly the  $\text{CO}_2$  sorption rate. These results indicate that  $\text{CO}_2$  sorption process is governed by the diffusion of  $\text{CO}_2$  within the outer layer of the solid product  $\text{Li}_2\text{CO}_3$  shell. The addition of 30 wt% of  $\text{K}_2\text{CO}_3$  produced modified  $\text{Li}_4\text{SiO}_4$ -based sorbents which provided the highest  $\text{CO}_2$  sorption capacities after 2h at 580 °C (about 230 mg of  $\text{CO}_2$ /g sorbent corresponding to a conversion of 80%). Besides, this sorbent maintained its sorption properties after 25 sorption/desorption cycles, displaying a good prospect for application in the separation at high temperatures of  $\text{CO}_2$  from fuel-fired power stations as well as in the in situ removal of  $\text{CO}_2$  produced in some reactions such as SMR and WGS reactions to enhance hydrogen production.

#### References

- Chavez R.H., Guadarrama J.J., 2011, Optimized process from post-combustion  $\text{CO}_2$  capture in thermoelectric power plant using structured packing, *Chemical Engineering Transactions*, 25, 69-74.
- Kato M., Yoshikawa S., Nakagawa K., 2002, Carbon dioxide absorption by lithium orthosilicate in a wide range of temperature and carbon dioxide concentrations, *Journal of Materials Science Letters*, 21(6), 485-487.
- Kato M., Nakagawa K., Essaki K., Maezawa Y., Takeda S., Kogo R., Hagiwara Y., 2005, Novel  $\text{CO}_2$  absorbents using lithium-containing oxide, *International Journal of Applied Ceramic Technology*, 2(6), 467-475.
- Ochoa-Fernández E., Rønning M., Grande T., Chen D., 2006, Synthesis and  $\text{CO}_2$  capture properties of nanocrystalline lithium zirconate, *Chemistry of Materials*, 18, 6037-6046.
- Pannocchia G., Puccini M., Seggiani M., Vitolo S., 2007, Experimental and modelling studies on high temperature capture of  $\text{CO}_2$  using lithium zirconate based sorbents, *Industrial & Engineering Chemistry Research*, 46, 6697-6706.
- Pires J.C.M., Martins F.G., Alvim-Ferraz M.C.M., Simões M., 2011, Recent developments on carbon capture and storage: An overview, *Chemical Engineering Research and Design* 89, 1446-1460.
- Seggiani M., Puccini M., Vitolo S., 2011, High-Temperature and Low Concentration  $\text{CO}_2$  Sorption on  $\text{Li}_4\text{SiO}_4$  based Sorbents: Study of the used silica and doping method effects, *International Journal of Greenhouse Gas Control*, 5, 741-748.
- Seggiani M., Puccini M., Vitolo S., 2013, Alkali promoted lithium orthosilicate for  $\text{CO}_2$  capture at high temperature and low concentration, *International Journal of Greenhouse Gas Control*, in press, DOI: 10.1016/j.ijggc.2013.04.009.
- Soundararajan R., Gundersen T., 2012, Coal based power plants using oxy-combustion for  $\text{CO}_2$  capture: pressurized coal combustion to reduce capture penalty, *Chemical Engineering Transactions*, 29, 187-192.
- Wang J., Manovic V., Wu Y., Anthony J., 2010, CaO-based sorbents for capturing  $\text{CO}_2$  in clean energy processes, *Chemical Engineering Transactions*, 21, 187-192.
- White C.M., Strazisar B.R., Granite E.J., Hoffman J.S., Pennline H.W., 2003, Separation and capture of  $\text{CO}_2$  from large stationary sources and sequestration in geological formations - coal beds and deep saline aquifers, *Journal of Air Waste Management Association* 53, 645-715.
- Yang H., Xu Z., Fan M., Gupta R., Slimane R.B., Bland A.E., Wright I., 2008, Progress in carbon dioxide separation and capture: A review, *Journal of Environmental Sciences* 20, 14-27.