

Development of Superior Sorbents for Separation of CO₂ from Flue Gas at a Wide Temperature range during Coal Combustion

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No patentable subject matter is disclosed in this report.

Abstract

For this part of the project the studies focused on the development of novel sorbents for reducing the carbon dioxide emissions at high temperatures. Our studies focused on cesium doped CaO sorbents with respect to other major flue gas compounds in a wide temperature range. The thermo-gravimetric analysis of sorbents with loadings of CaO doped on 20 wt% cesium demonstrated high CO₂ sorption uptakes (up to 66 wt% CO₂/sorbent). It is remarkable to note that zero adsorption affinity for N₂, O₂, H₂O and NO at temperatures as high as 600 °C was observed. For water vapor and nitrogen oxide we observed a positive effect for CO₂ adsorption. In the presence of steam, the CO₂ adsorption increased to the highest adsorption capacity of 77 wt% CO₂/sorbent. In the presence of nitrogen oxide, the final CO₂ uptake remained same, but the rate of adsorption was higher at the initial stages (10%) than the case where no nitrogen oxide was fed.

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List of Acronyms and Abbreviations

KJS:	Kruk-Jaroniec-Sayari
SCR:	Selective Catalytic Reduction
TGA:	Thermo Gravimetric Analyzer
TAGS:	Thermal Analysis Gas Station
TPO:	Temperature Programmed Oxidation
TPD:	Temperature Programmed Desorption
TCD:	Thermal Conductivity Detector
WGS:	Water Gas Shift reaction
XPS:	X-ray Photoelectron Spectroscopy

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A1. Multiple adsorption-desorption cycles of 20%Cs/CaO. Adsorption:60 minutes at 600°C; Desorption: 30minutes at 725°C

A2. Sample chart of TGA

Executive Summary

Cs/CaO based sorbents were synthesized, characterized with modern techniques and tested for sorption of CO₂ and selected gas mixtures simulating flue gas from coal fired boilers. Our studies resulted in highly promising sorbents since they demonstrated zero affinity for N₂, O₂, and NO, very low affinity for water (CO₂/H₂O ratios >100), high CO₂ sorption capacities at high temperatures, rapid sorption characteristics, CO₂ sorption at a very wide temperature range (50 to 650 °C), durability, and low synthesis cost. One of the “key” characteristics of the proposed materials is the fact that we can control very accurately their basicity (optimum number of basic sites of the appropriate strength) which allows for the selective chemisorption of CO₂ at a wide range of temperatures (50 to 650 °C). The unique characteristics of this family of sorbents offer high promise for development of advanced industrial sorbents for the effective CO₂ removal as well as other types of applications such as fuel cells, inorganic membranes, water gas shift reaction (WGS), and syngas applications.

The performed work constitutes about 20% of the proposed work and offers a screening for effectiveness in conjunction with the most important operating parameters. Our efforts fall within the budget.

Since we observed that our CaO sorbents behave satisfactorily with the most important gases of flue gas, our immediate efforts will concentrate on studying numerous types of composite sorbents based on CaO (SiC was considered, various sol-gel made, ceramic foams, and aerosol made materials) in order to come up with sorbents with superior durability. As part of our studies we will study the performance of CaO-based sorbents for CO₂ sorption cycles, regeneration efficiency.

Our long term plans for this project will be to test the best and most durable sorbents in the presence of SO₂. Moreover, we will test our sorbents at conditions used for WGS and syngas applications, gasification.

1. Introduction

The carbonation of CaO sorbents has been recently studied for the separation of carbon dioxide at high temperatures using industrial or natural limestone [1, 2, 3, 4]. The present paper continues our earlier work [4], in which we investigated CaO sorbents supported with alkali metals. It was found that for that family of sorbents which involved low BET surface area supports, the CO₂ sorption increases in the following order Li<Na<K<Rb<Cs. The optimum adsorption temperature for CO₂ in that work was 600°C since this temperature offered the highest sorption rate and high sorption uptake. The reason for the enhanced CO₂ adsorption affinity observed was the increase of the basic nature of CaO sorbent with the addition of the alkali metal, particularly with cesium. Moreover, it was found [4], that CaO support doped with 20wt% cesium synthesized by CsOH precursors reached the highest CO₂ adsorption with respect the other precursors used.

The carbonation reaction on calcinated limestone is well investigated, but most of the studies have been performed under non-practical conditions such as absent of poisons or low temperature. Species such as H₂O, NO and particularly SO₂, can influence the CO₂ sorption on CaO-based sorbents. Borgwardt [5] investigated the influence of water on CaO sorbent and he reported that of increasing sorbent sintering effects. Although several studies have been carried out to investigate the effect of flue gas on pure CaO, to the best of our knowledge no investigation was performed for the direct influence of flue gas for CO₂ adsorption on alkali metal doped CaO sorbents.

We will study in this project the sorption performance of Cs/CaO sorbent for the major components of exhaust gases from coal fired power plants such as CO₂, N₂, O₂, NO, SO₂ and H₂O. We investigated the effects of both the individual compounds and selected gas mixtures simulating flue gas at various conditions (Table 1) as a preliminary effort to screen for effectiveness this family of sorbents. At this point it is essential that we note that this family of sorbents demonstrates significant sorption uptakes and very rapid kinetic characteristics at temperatures above about 400 °C (reaching as high as 700 °C). This characteristic is unique and offers the potential for these sorbents to be used at significantly higher temperatures for capture of CO₂ in the energy industries in general beyond the traditional way (removal of CO₂ after the FGD). With these sorbents, one can capture CO₂ before the air heater or the particle collector (Figure 1). Due to the ability of our sorbents to operate at high temperatures, we can use them right after the boiler to capture CO₂ from the hot stream of flue gas. A potential advantage of the latter proposal is that these sorbents might be able to capture Hg and other trace metals in addition to CO₂; something with obvious advantages for the remaining processes/reactors of the “purification train”.

At this stage it should be noted that the increased effectiveness of these sorbents to capture selectively CO₂ at elevated temperatures (>550 °C) can be beneficial to other types of applications such as fuel cells, inorganic membranes, water gas shift reaction (WGS), and syngas applications.

2. Experimental

The test plan involves the evaluation of the Cs/CaO sorbent as a function of the key operating parameters. This study constitutes a screening for effectiveness of this sorbent

and provides invaluable information for understanding the potential for the industrial realization of CO₂ capture.

2.1 Synthesis procedure

The alkali metal doped sorbents were prepared by the wet impregnation method using commercial CaO (Aldrich) support. The precursor used for the loading of cesium was CsOH (Aldrich, 50 wt% solution in water) since we found earlier [4] that this precursor leads in better sorbents. The sorbent was prepared by mixing the appropriate amount of alkali metal precursor and calcium oxide (in the order of grams) in order to reach cesium of 20wt% (based on cesium metal and CaO only). Distilled water was added for the formation of the slurry in the proportion of 1 gram of CaO to 100 g of aqueous solution of the alkali metal precursor. The slurry was heated and stirred until the water was evaporated. The powder was ground to fine powder and dried in an oven at 120 °C overnight. The calcination of sorbent was carried out under an oxygen atmosphere at 750 °C for 5 hours in order to reach a full oxidation of the cesium precursor. After the step of calcination, the sorbent were stored under inert atmosphere.

2.2 Particle Size Analysis

The particles-size distribution of the sorbent material was obtained (Figure 2) with a laser scattering particle distribution analyzer (Malvern Mastersizer S series). The instrument is accurate to within 5 % of the median value, as claimed by the manufacturer. Prior to the measurements, the sorbent was dispersed using ultrasound.

2.3. BET surface area and pore size measurements

BET surface area and pore size distribution measurements were performed using nitrogen adsorption and desorption isotherms at –196 °C on a Micromeritics ASAP 2010 volumetric adsorption analyzer. The sorbent samples were degassed at 300 °C for at least 5 hours in the degassing port of the apparatus. The pore size distribution was obtained from the branch of the isotherm using the KJS (Kruk-Jaroniec-Sayari) method [7]. An additional BET measurement was carried out in an AutoChem 2910 analyzer to determine the BET surface area before and after the water vapor injection by avoiding exposing the sorbents to the ambient atmosphere. The sorbent was pretreated at 750 °C for 5 hours in order to get a complete outgassed sorbent. In this manner, the sorbent is free of all pre-adsorbed atmospheric water or carbon dioxide. The results are presented in Table 3 .

2.4. Sorption Experiments

The adsorption and desorption experiments were carried out in a Perkin Elmer PYRIS-1 thermo gravimetric analyzer (TGA) equipped with thermal analysis gas station (TAGS). For the sorption experiments the samples were placed in a platinum sample holder. The sample-pan holder was batch operated with a single charge of about 5 mg.

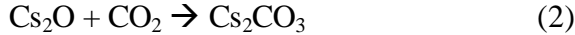
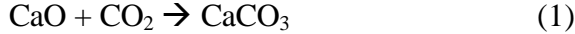
Each experiment started with a pretreatment step, in order to degass the sorbent from pre-adsorb gases and water. The temperature profile of these experiments was consisted of a heating up step with a ramp of 10 °C/min to 750 °C, holding of the sample for 3 hours at 750 °C, and a cooling down step with a rate of 15 °C /min to the adsorption temperature. The pretreatment was carried under helium atmosphere. The adsorption

experiments were carried out at the adsorption temperature of interest for 5 hours. The same characteristics were followed for a limited number of experiments we performed to investigate the cyclic operation of the sorbents (see Appendix A1). Prior to the adsorption experiments, the samples were held for 30 min at the adsorption temperature in helium flow in order to get a stable flow profile and baseline (see a typical experiment in appendix A2).

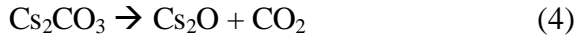
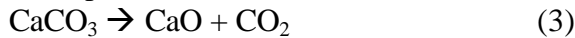
3. Results and Discussion

Characteristic TGA curves of isothermal CO₂ adsorption over 20 wt% Cs/CaO sorbent are depicted in Figure 3 within a temperature range of 225 °C to 675 °C. A monotonic increase of CO₂ sorption was observed by increasing the temperatures. At relatively low temperatures the CO₂ chemisorption is low but the uptake increased significantly for temperatures above 450 °C. The maximum adsorption uptake was reached at 600 °C and was equal to 66 wt% CO₂/sorbent. Surprisingly, at 675 °C the CO₂ sorption is about 10 wt% lower in comparison with that at 600 °C. The reason is that the thermal stability of formed Cs₂CO₃ is limited for the bulk face to ~610°C [8]. Hence, when the adsorption and/or the desorption steps take place at temperature higher than 610 °C, the state of the sorbent significantly changes. Evidently, the ideal temperature for high temperature CO₂ adsorption using cesium-doped sorbents is around 600°C. XPS investigations performed by our group confirm the reactions of carbonation and desorption in the corresponding range, which are presented in equations (1-4).

Chemisorption



Desorption

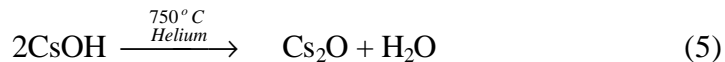


The advantage of cesium doped CaO sorbent is clearly demonstrated in comparison to the CO₂ uptake on the pure CaO sorbent at 600 °C (dashed curves in Figure 3). This is due to the fact that cesium oxide leads to higher surface basicity, which favors the chemisorption of a weak acid such as CO₂.

A monotonic increase of the sorption uptakes is observed in the entire range of temperatures investigated. However, the uptake is very low at ambient temperature or temperatures slightly higher than ambient (Table 4). Our data demonstrate that the great potential of this family of sorbents occurs at elevated temperatures.

It is worth noting that the uptake of the sorbent reaches as high as 30 wt% CO₂/mass of sorbent within the first two minutes, a property of unique importance from kinetic point of view since it can result in rapid sorption/desorption cycles. This behavior is different, in comparison with our previous experimental observations [4] where a lower adsorption rate was observed. However, it can be justified by the use of different gas atmospheres during the calcinations. In our previous work [4] the sorbent was calcined under helium atmosphere and the CsOH precursor used was dehydrated but not fully

oxidized. In the present set of experiments the calcinations were carried out under oxygen and resulted in the complete oxidation of the cesium precursor thus leading to the fully oxidized form of sorbent. Consequently, the surface characteristics of the present sorbents are completely different in comparison to those in our earlier work. Equations (5) and (6) present what is happening during the calcinations under the different atmospheres.



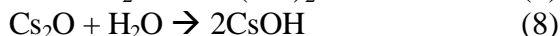
During the wet impregnation method, only the excess water of the slurry was evaporated, the slurry becomes a solid material at ambient temperatures, and acquires the uniform dispersion of cesium on the sorbent. Hence, the uncalcined sorbents possess CsOH. Typical dehydration of CsOH (reaction 5) is only taking place during the calcinations at 750 °C under helium atmosphere. The CsOH is fully oxidized (reaction 6) and forms cesium superoxide, CsO₂ [9] layers on the sorbent surface, when calcined at 750 °C under oxygen atmosphere. Yagi and Hattori [10] investigated the oxygen adsorption on cesium-added zeolite X. They reported that Cs₂O adsorbs oxygen to form Cs₂O₃ and Cs₂O₄. TPO-TPD experiments of un-calcined sorbent under oxygen atmosphere were carried out in order to find out the temperature and phase of the cesium oxides formed in our sorbents. As shown in Figure 4 only one adsorption peak was found at 643 °C, which, corresponds, to CsO₂ as determined by total amount of oxygen consumed after integration of the TCD peaks. The CO₂ adsorption affinity of sorbents calcined under helium and oxygen (figure 5 and 6) was compared. It was observed that the sorbent calcined under oxygen atmosphere demonstrated significantly high adsorption compared to the sorbent calcined under helium. This difference was due to the formation of Cs₂O₃ phase in the sorbent during the calcination under oxygen atmosphere. Whereas, Cs₂O phase of cesium oxide was observed by XPS [4], when the sorbent was calcined under helium atmosphere. From these results it is well demonstrated that the sorbent calcined in oxygen with its full-oxidized cesium oxide (Cs₂O₃) enforce the rapid and significantly high amount of CO₂ adsorption.

Effect of N₂ and O₂

The results of the nitrogen and oxygen adsorption experiments were presented in Figure 3. It is remarkable to note that the sorbent shows zero affinity for both gases. This is the case for the entire range of temperatures we investigated varying from 50 to 600 °C. This demonstrates that the sorbent adsorbs only the gas molecules, which are of acidic nature. Neither of these two gases can react with the surface. More specifically, since the sorbent was calcined at 750 °C under O₂ atmosphere, it cannot further react with oxygen at 600 °C. On the other hand, our sorbents do not react with N₂ in a wide range of temperatures. This property is of unique importance for the development of highly selective CO₂ sorbents from a stream of flue gas utilizing any fossil fuels and air since the nitrogen and the unused O₂ will correspond to at least 70vol.% of the gases.

Effect of temperature on H₂O adsorption

The effect of temperature for water adsorption on our sorbents is presented in Figure 7. A rather “complicated” behavior is observed with respect to temperature due to the various reactions occurring. The reaction of water with calcium oxide, equation (7) is a well-known and keen process at ambient pressures and temperatures. In addition, the cesium oxide also possesses high adsorption affinity towards water since cesium oxide is the strongest known basic oxide, and it readily reacts with water to form CsOH, the reaction is shown in (8).



Hence, at 225 °C Ca(OH)₂ [11] and CsOH layers were formed on the sorbent's surface due to high water adsorption, namely 27 wt% H₂O/mass of sorbent. However, with increasing sorption temperature a considerable decrease of the water adsorption was observed. This behavior continues monotonically up to the point where the sorbent exhibits a zero water adsorption affinity at temperatures equal or higher than 600 °C. The chemical explanation for the monotonic decrease of the adsorbed amount of water with increasing temperature is based on the continuously decreasing extent of reactions 6 and 7 with temperature. Ca(OH)₂ and CsOH completely decompose at temperatures higher than 580 °C [8] Furthermore, the sorbents become more porous and acquire smaller particle sizes, which explains the significantly larger CO₂ adsorption capacity at high temperature in the presence of water. To some extent this phenomenon is somehow similar to the synthesis of activated carbons by water treatment. The influence of water for the surface chemistry on CaO was intensively investigated by Borgwardt [5] and supports our results, since it is reported that water vapor promotes the sorbent sintering and agglomeration. However, in the latter paper the authors only studied the first 10-20 min of the sintering process. Therefore, it was not clear if the final surface area was affected by water.

NO Influence

The results of the performance of adsorption experiments using nitrogen oxide are presented in Figure 8. A monotonic trend of decreasing NO adsorption affinity at rising temperatures was found. At relatively low temperatures (225 °C) a slight NO adsorption of 0.8 wt% NO/sorbent was obtained. The reason for this behavior is that nitrogen oxide is reacting with trace amounts of undispersed cesium oxide on the sorbent surface. This compound is thermally stable up to 414 °C. At higher temperatures the decomposition of CsNO₃ takes place. The decomposition temperature of CsNO₃ is 450 °C, which means, the adsorption of NO is not possible beyond this temperature. This might be the reason for the negligible increase of the sorbent's weight at this temperature. However, in the presence of nitrogen oxide a loss in sorbent weight was observed at high temperatures and particularly at 675 °C due to the decomposition of CsNO₃ into metallic cesium. Because of this phenomenon a rapid adsorption of CO₂ was observed in the presence of NO (Figure 9).

The promising adsorption characteristics of the cesium doped calcium oxide with its high CO₂ adsorption capacity, zero adsorption affinity for water, nitrogen, oxygen and

nitrogen oxide promise an advanced practical use for CO₂ separation from flue gas at high temperatures as 600 °C.

Effect of Various Gas Mixtures

Adsorption experiments with different mixtures of CO₂ and other compounds found in flue gas (H₂O, N₂, O₂) were tested to investigate the effect of the flue gas composition on the CO₂ adsorption at 600 °C. Our results presented in Figure 9 show that nitrogen and oxygen have no effect for the CO₂ adsorption since we observed the same adsorption capacity with the case of using only CO₂ (Figure 9), where 66 wt% CO₂/sorbent was reached under identical operating conditions. This finding offers a chance for highly selective CO₂ separation if one considers that nitrogen is the component flue gas with a highest concentration (<75vol%). In addition, it was observed that nitrogen oxide does not have any negative influence for the carbon dioxide adsorption. The results in Figure 9 furthermore demonstrate that the water vapors affected significantly, namely increase the CO₂ adsorption. In the presence of 10vol% water, the highest adsorption 77wt% CO₂/sorbent after 5 h adsorption time was recorded. The fact that the sorbent particle size decreased after water adsorption (see Table 2) clearly indicates that the sorbent is more porous than prior to the water adsorption. It might be that the water vapor increases the porosity of the sorbent and acquire uniform pore diameter (see Figure 10). This enhances the high CO₂ adsorption, due to the fact that the building of Cs₂CO₃ CaCO₃ layers is not able to plug the pore mouths. In this manner, the diffusion of CO₂ is enhanced into the core levels of the sorbent. Gupta and Fan [1] also reported low surface area CaO sorbents, which, demonstrated high CO₂ uptake due to larger pore diameters. The pore diameter and pore size distribution of our sorbents treated in different environment are shown in Figure 10. The addition of NO and water at high temperatures promotes the formation of uniform pore size distribution, which causes the more effective sorbent towards CO₂ adsorption. In addition, Shimizu and Inagaki [12] reported that water affect higher mobility of Ca²⁺ and O²⁻ and this enhanced higher reaction with acidic gases as CO₂.

The result of the particle size distribution after the calcinations and after the addition of CO₂, H₂O and NO are depicted in Figures 2. The mean particle sizes are summarized in Table 2. As one can observe the mean particle size of the un-calcined sorbent is the largest after O₂ calcination. The increasing of sorbent particle size might be due to the formation cesium super oxide on the surface of the sorbent during the calcinations under oxygen atmosphere. The particle size decreased in the presence of NO and water during the calcination. It can be explained due to the formation of a mesoporous type of sorbent in the presence of NO and water. The largest particle size was found for the sample after CO₂ adsorption, reasonable by the formation of CaCO₃ and Cs₂CO₃ particle on the sorbent surface.

Adsorption/Desorption Cycles.

A limited number of experiments was dedicated to investigate the effect of the cyclic operation of the sorbent (Figure A1). One can observe that the sorption capacity of the sorbent decreases after some adsorption/desorption cycles. The uptake finally reaches a lower value. Further investigations aim at the development of time stable sorbents by incorporating dopants or reinforcement fibers.

4. Conclusions

Experiments were performed with 20wt% Cs/CaO sorbent in a TGA. The objective of these experiments was to verify the effect of CO₂ adsorption on the sorbent with consideration to flue gas conditions.

- 1) The carbonation rate of the new sorbent was improved reasonably by a full oxidation of the cesium support because of oxygen as calcination gas.
- 2) In order to develop selective adsorbents for carbon dioxide at high temperature our findings show a zero adsorption affinity for N₂, O₂, H₂O, NO at 600°C.
- 3) At high temperatures NO and H₂O promote sintering and shrinking effects by the fact that decreasing particle size and simultaneously forming uniform pore sizes
- 4) The presence of water vapor significantly promotes the CO₂ sorption capacity of the sorbent.
- 5) In the presence of nitrogen oxide a rapid CO₂ uptake was observed within the first two minutes.

5. Acknowledgement

The authors acknowledge the financial support from U.S. Department of Energy (Innovative Phase II Project #: DE-FG03NT41810).

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Table 1 Various gas mixtures used in this study

Type of Gas Mixture	Components	Composition, %
1	CO₂	28.6%
	H₂O	10.0%
	He	61.4%
2	CO₂	28.6%
	NO	0.4%
	He	71.0%
3	CO₂	28.6%
	SO₂	0.4%
	He	71.0%
4	CO₂	28.6%
	N₂	22.6%
	O₂	6.0%
	He	42.8%
5. Simulated flue gas	CO₂	11.0%
	H₂O	10.0%
	N₂	71.0%
	O₂	2.0%
	NO	0.05%
	SO₂	0.05%
	He	5.9%

Table 2: Mean particle sizes

Sorbent	Mean particle size
	mm
20wt%Cs/CaO (after O ₂ calcination)	19.4
20wt%Cs/CaO (after H ₂ O adsorption)	11.2
20wt%Cs/CaO (after NO adsorption)	13.9
20wt%Cs/CaO (after CO ₂ adsorption)	20.4

Table 3: BET surface area before and after H₂O injection on 20 wt% Cs/CaO

BET measurement	adsorbed volume	sample amount	BET surface area
	MI	mg	m²/g
1	0.431	101.1	18.57
2	0.313	101.1	13.49

Table 4. CO₂ captured at different temperature after 300 minutes of adsorption

Temperature	50°C	225°C	300°C	375°C	450°C	525°C
CO ₂ captured/ gram sorbent	1.5grams	3.1grams	4.5grams	10.4grams	34.0grams	45.5grams

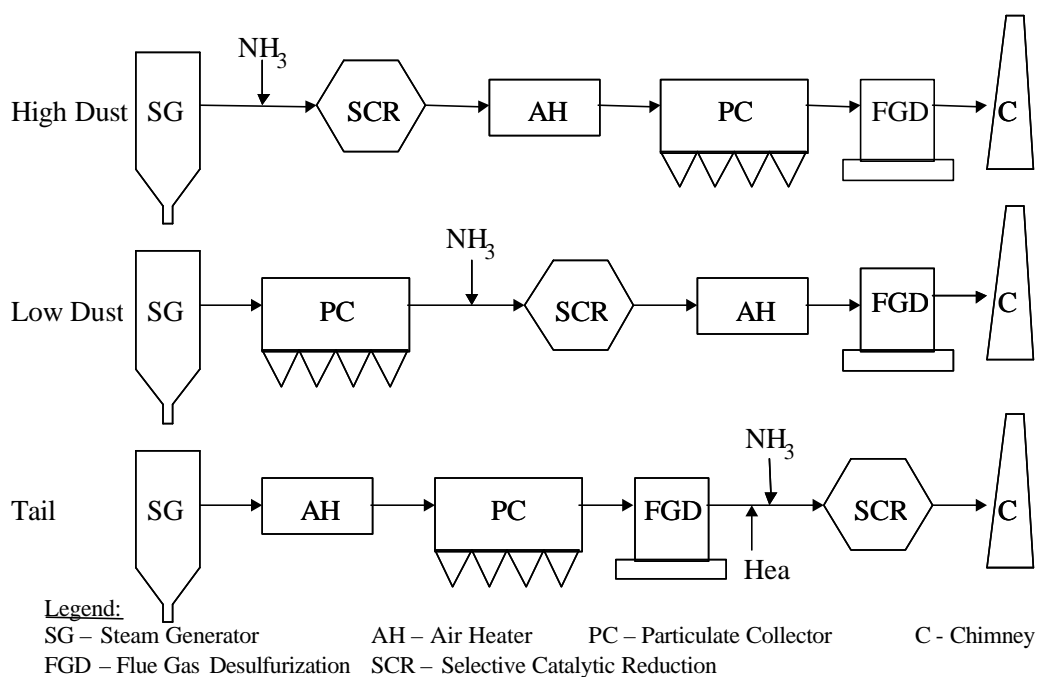


Figure 1 Various Configurations and Purification Procedures for Coal fired Plants (J. Armor, Environmental Catalysis, 205th National ACS Meeting, p. 206, 1994)

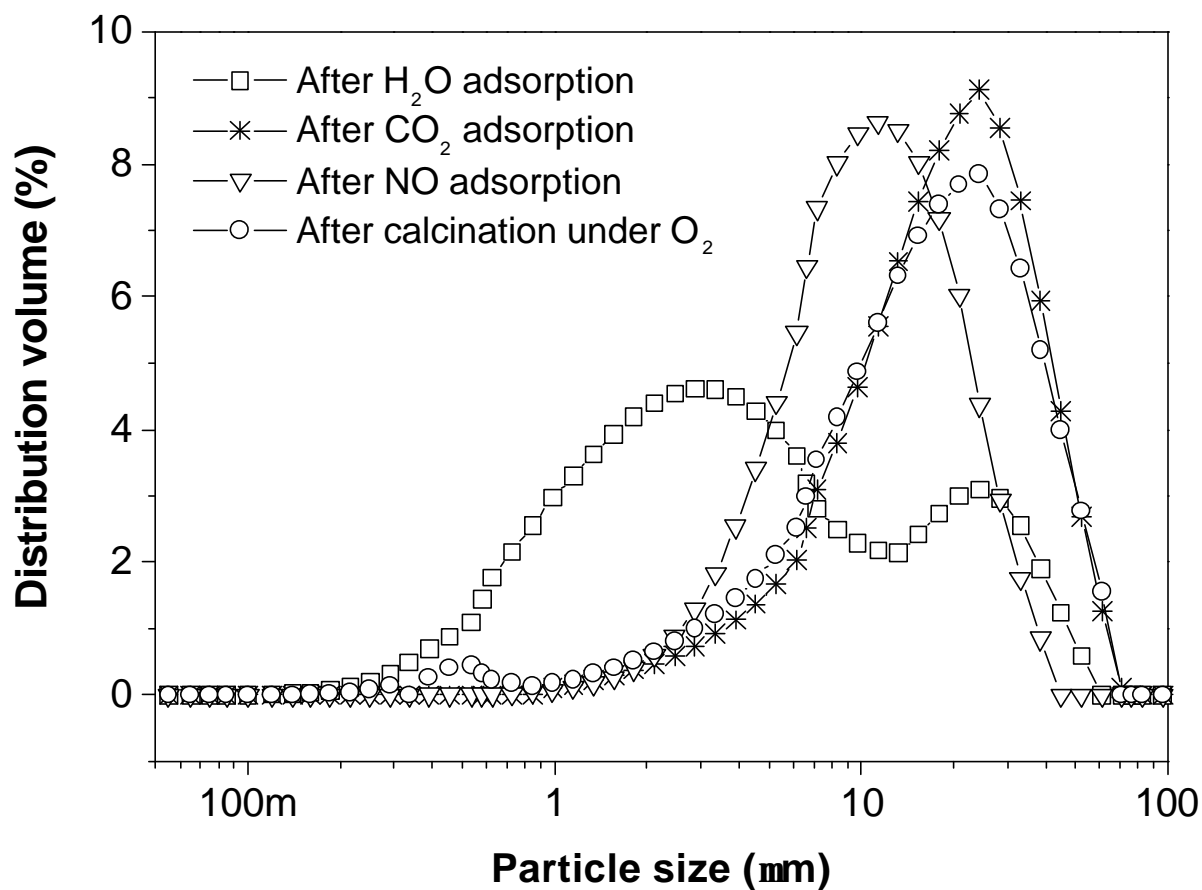


Figure 2: Particle size distribution of the sorbent 20wt.%Cs/CaO after calcinations at 750°C under and after adsorption of different gases at 600°C

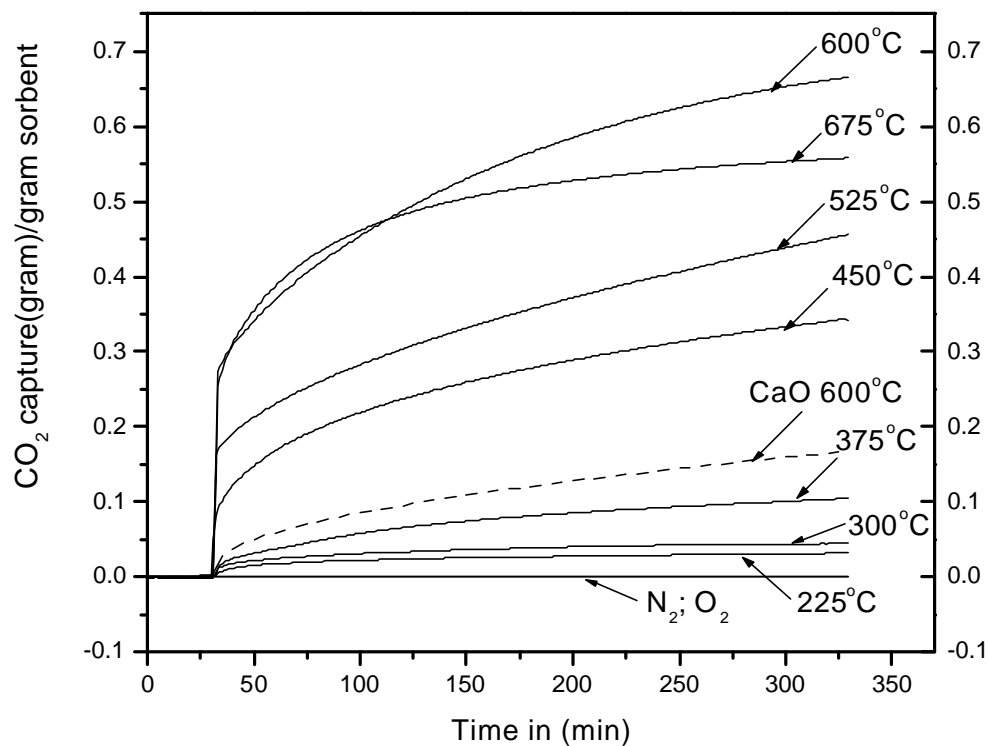


Figure 3: Effect of temperature for CO₂ adsorption over 20 wt% Cs/CaO: concentration of CO₂ = 28.6% balanced on helium; total flow = 70ml/min

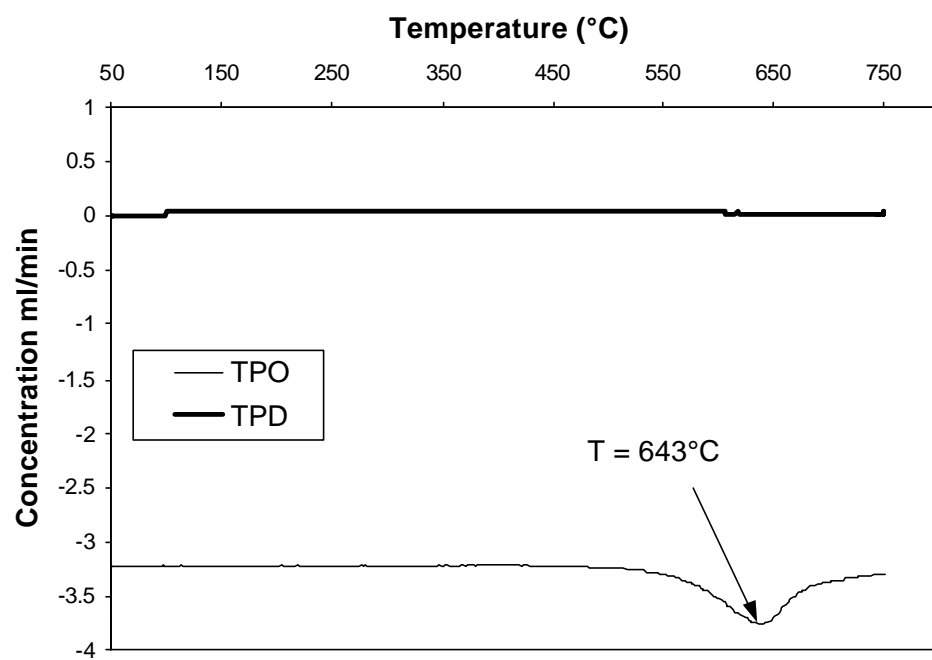


Figure 4: Oxygen adsorption on the cesium side during calcinations

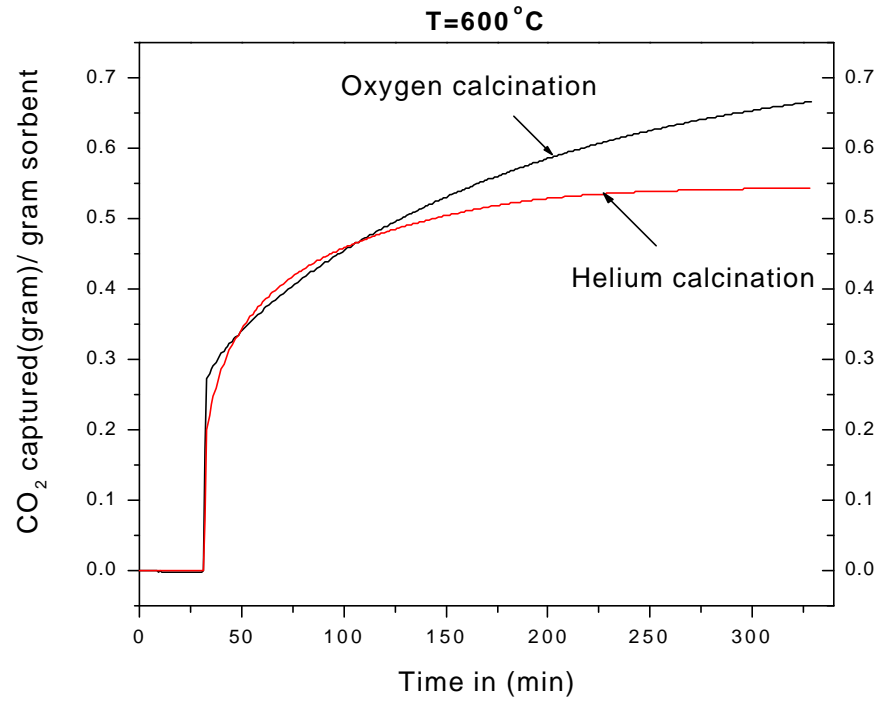


Figure 5 Effect of calcination gases on 20 wt% Cs/CaO; complete adsorption isotherm;

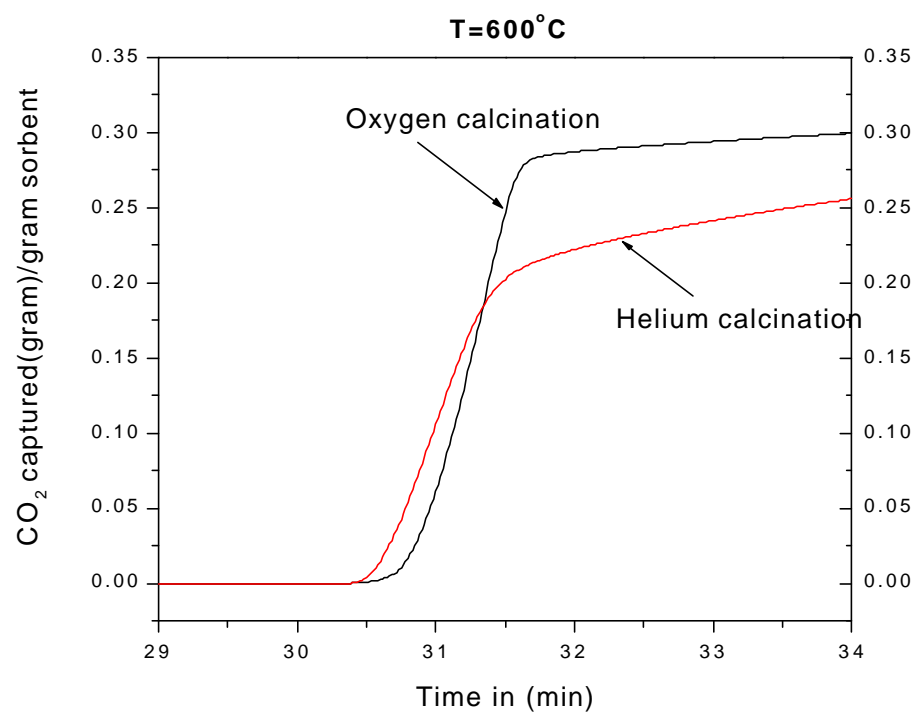


Figure 6: Effect of calcination gases on 20 wt% Cs/CaO; adsorption isotherm of rapid adsorption step

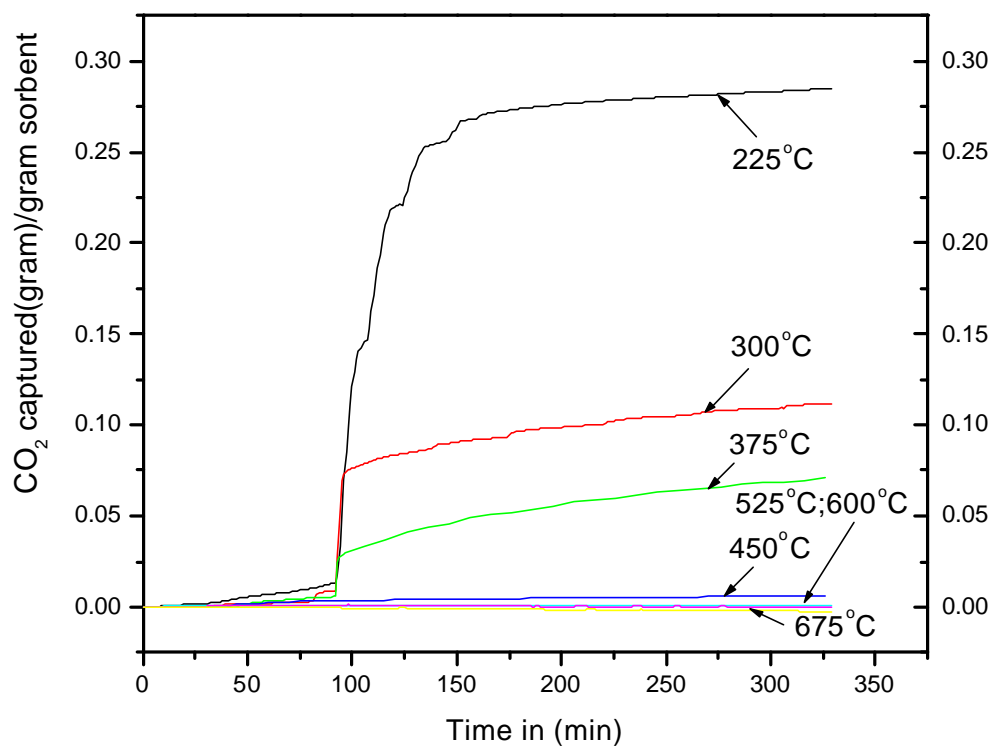


Figure 7: Effect of temperature for H₂O adsorption over 20 wt% Cs/CaO: concentration of H₂O = 10% balanced on helium; Total flow = 70ml/min

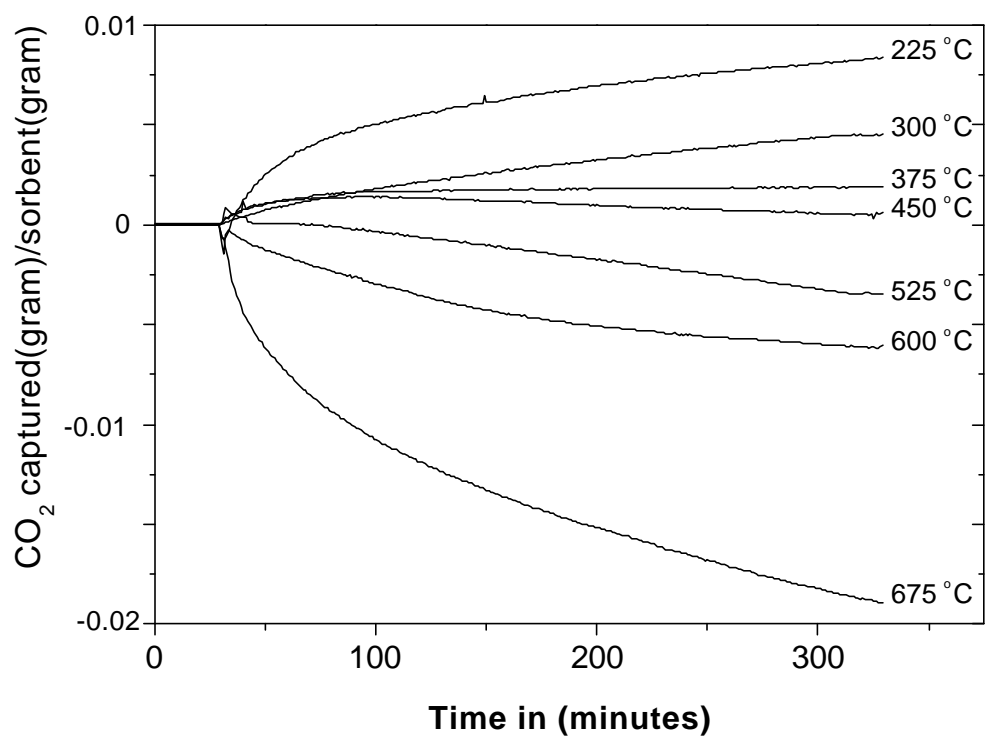


Figure 8: Effect of temperature for NO adsorption over 20 wt% Cs/CaO: concentration of NO = 4000ppm balanced on helium; Total flow = 70ml/min

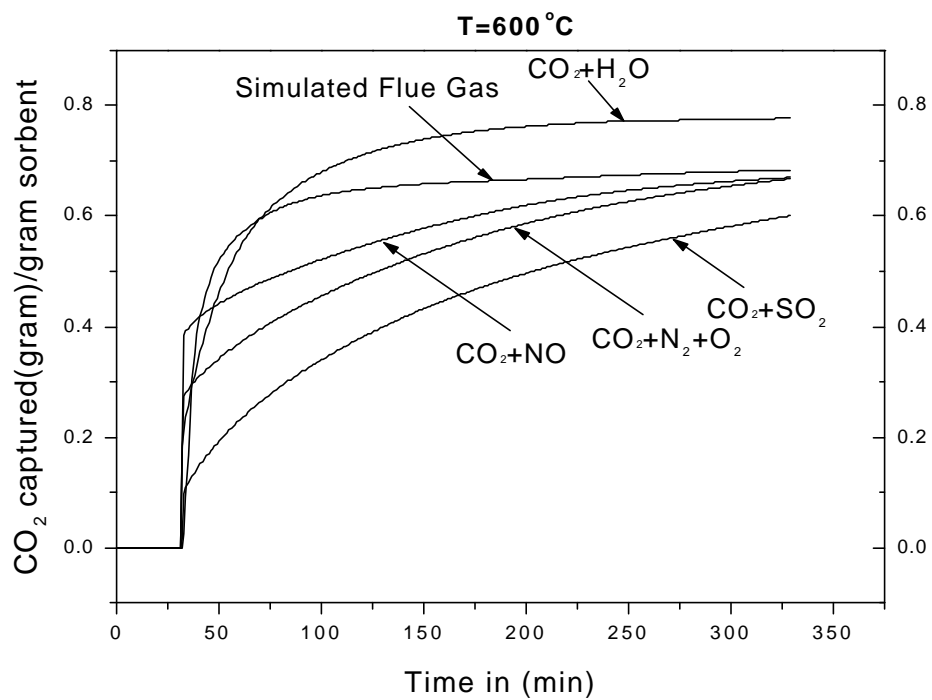


Figure 9: Effect of flue gas compound for CO₂ adsorption: concentrations: CO₂ = 28,6%; H₂O = 10%; NO = 500ppm; balanced on helium; Total flow = 70ml/min

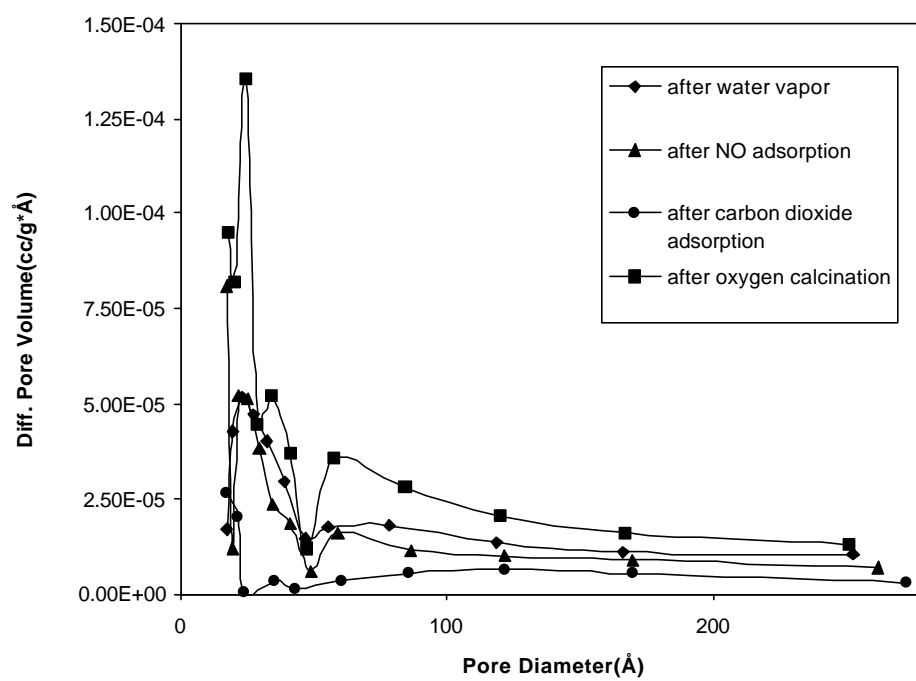


Figure 10: Effect of different adsorbed gases for morphological properties on 20 wt% Cs/CaO

US Patent Applications, Refereed Articles, Presentations, and Students Receiving Support from the Grant

US Patent Applications

N/A

Journal Articles (peer reviewed)

- 1) A. Roesch, Reddy, P. E. and P.G. Smirniotis, "Parametric Study of Cs/CaO sorbents with respect to simulated flue gases at high temperatures", **Industrial Engineering Research**, *accepted for publication*, 2005.
- 2) M. Hagen, P.E., Reddy, and P.G. Smirniotis, "CO₂ Sorbents based on SiC and CaO at High Temperatures", **Gas Separation and Purification**, *in preparation for submission* 2005.

Conference Presentations

This work was presented only at the 2004 Annual Contractors Meeting in Pittsburgh, PA in June 2004.

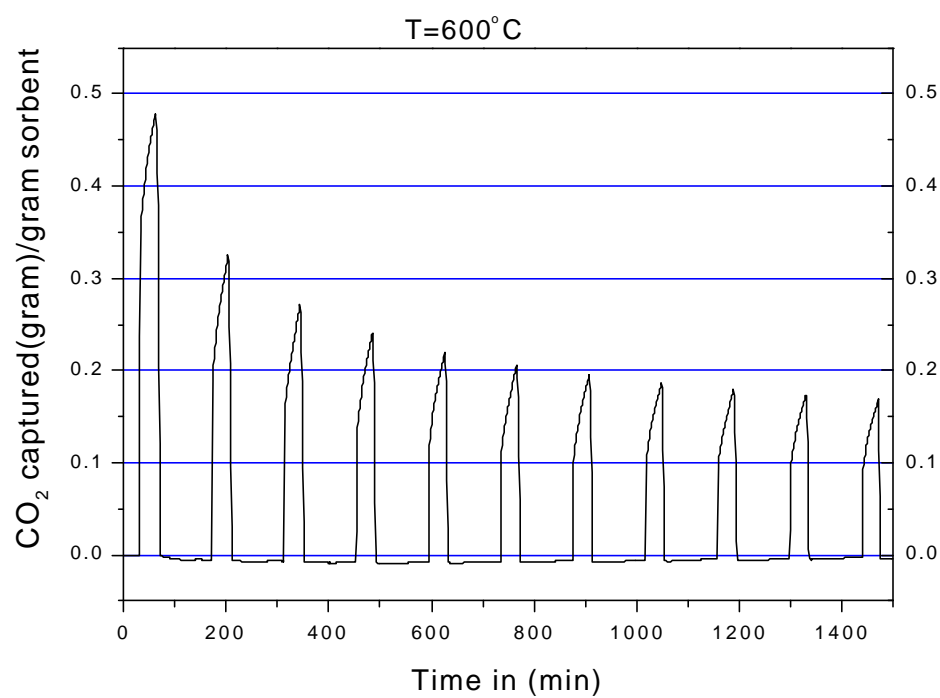
Students received support from the grant.

Graduate Students:

- 1) Mr. Hong LU, graduate (Ph.D.) student in Chemical Engineering

APPENDIX

A1. Multiple adsorption-desorption cycles of 20%Cs/CaO. Adsorption:60 minutes at 600°C; Desorption: 30minutes at 725°C



A2. Sample chart of TGA

