Functionalization of Metal Organic Frameworks for Enhanced Stability under Humid Environment for CO$_2$ Capture Applications

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By

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ABSTRACT

Global climate change has been subjected to widespread research interest in recent decades while being attributed for its reason to CO₂ anthropogenic accumulation in the atmosphere. Metal-organic frameworks (MOFs) are an emerging new class of nanoporous crystalline solids built of metal coordination sites linked by organic molecules, which have attracted increasing attention since their well-defined porosity, high surface area and tunable functionalities. Among them, Mg/DOBDC, also named as Mg-MOF-74 or CPO-27-Mg, is considered as a strong candidate for CO₂ capture in flue gas even in the ambient air, but its hydrophilic properties limit its application since its CO₂ uptake capacity dramatically decreases in humid conditions. In this work, we try to impregnate ethylenediamine into the pores of Mg/DOBDC to yield a new porous material ED-Mg/DOBDC that exhibits stability after exposure to water vapor. To investigate structural changes and CO₂ uptake capacity in moist conditions, accelerated steam treatment of all samples were performed. Pore characteristics and CO₂ uptake capacity of Mg/DOBDC and ED-Mg/DOBDC before and after steaming were measured. ED-Mg/DOBDC showed higher CO₂ uptake capacity for both the non-steamed and steamed samples. Also, different ED loadings were suggested by our group’s previous work, and we further investigated the effect of pore characteristics of different ED loadings in the pores of ED-Mg/DOBDC to find the impact of ED molecules in ED-Mg/DOBDC for CO₂ capture applications.
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1.0 INTRODUCTION

According to the Stern Review on the Economics of Climate Change,\(^1\) rising global carbon dioxide levels in the atmosphere are one of the major contributors to global climate change.\(^2\) Therefore it is important to establish efficient, environmentally friendly, and economically efficient methods to capture carbon dioxide. Capture of carbon dioxide from flue gas or ambient air is a promising method to reduce CO\(_2\) emissions into the environment and decrease heightened CO\(_2\) concentration in the air.\(^{26}\) One of the promising approaches to reduce CO\(_2\) emissions is to design an efficient technology for carbon capture and sequestration (CCS) where CO\(_2\) could be captured from the exhaust gas (flue gas) of coal burning power plants and then transported and buried underground or in the deep sea waters.\(^{39}\) Alternatively, captured carbon dioxide could be used in other useful applications.\(^{48}\) To design an effective method for carbon dioxide capture from gas streams, the conditions of the stream of interest should be considered. A typical flue gas contains not only CO\(_2\) but also other gases including N\(_2\), H\(_2\)O, SO\(_x\), NO\(_x\), etc. In general, composition ratios of the main gases present are approximately 6.5:1:1 (N\(_2\):H\(_2\)O:CO\(_2\)) by weight.\(^3\) For flue gas or ambient air capture, pressure is around atmospheric. With the low CO\(_2\) concentrations in these gases separation of CO\(_2\) has become one of the main challenges for effective capture and has been intensely studied by many researchers in recent years.

Hybrid porous solids are considered strong candidates for CO\(_2\) capture.\(^{35}\) Among those, metal organic frameworks, (MOFs), an emerging class of nanoporous
crystalline solids built of metal coordination sites linked by organic molecules, show promising properties for gas capture applications. These materials offer well-defined porosity, high surface area, and tunable chemical functionalities demonstrating applications in catalysis\textsuperscript{19,20}, separations\textsuperscript{14,15}, gas storage\textsuperscript{17,18} (such as methane\textsuperscript{6}, hydrogen\textsuperscript{8,16}, acetylene\textsuperscript{18}), biomedicine,\textsuperscript{21} and exhibit luminescent properties leading to their being considered for sensors.\textsuperscript{33} In the past decades, they are also attracted a great attention as CO\textsubscript{2} capture materials.\textsuperscript{17,38}
2.0 Critical Literature Review

Currently one of the benchmark implemented solutions for carbon dioxide capture is absorptive capture by alkylamine-containing liquids such as mono- and triethanolamines.\(^4,5\) However, the use of these materials has a number of drawbacks. Regeneration of such absorbents is only possible at high temperatures which require a high energy input, something that should be avoided for design of an environmentally friendly CO\(_2\) capture material. In addition, inhibitors for corrosion control need to be used with aqueous amine materials, and amine vapors could cause contamination of the gas streams being treated.\(^17\) These limitations call for an improved method to capture CO\(_2\) for industrial applications. Adsorption processes onto porous solid media could be a better option to capture carbon dioxide, since those materials operate through physisorptive and chemisorptive processes and potentially could be easier to regenerate for cyclic operations.

In particular, zeolites have attracted attention as solid adsorbents for carbon dioxide capture.\(^38\) Compared to aqueous alkanolamine absorbents, zeolites require significantly less energy input for adsorbent regeneration,\(^43\) but their hydrophilic properties\(^44,45\) limit their applications in this area. Activated carbon is another solid adsorbent which is considered a strong candidate carbon dioxide adsorbent. It requires less energy for regeneration\(^40\) and its hydrophobic properties lead to better performance under moisture conditions compared to zeolites.\(^41\) While the high surface area of activated carbon contributed to much higher carbon dioxide capture capacities at high pressures,\(^42\) it does not perform very well at low pressure range due to its low
enthalpy of adsorption.\textsuperscript{40} Therefore, solid adsorbents for carbon dioxide capture still need further improvement, and in recent years another class of porous material, metal-organic frameworks (MOFs) have attracted attention for their unique properties and potential applications in carbon dioxide capture.

Many MOFs have been reported in the past few decades and some exhibit exceptional CO\textsubscript{2} capacities over large pressure ranges (up to 42 bar) at room temperature,\textsuperscript{7} overcoming other physisorbents such as zeolites and activated carbons.\textsuperscript{36,37} Nevertheless, in the pressure range of interest (low pressure), not many metal organic frameworks perform well. A series of MOFs, M/DOBDC are currently reported to have the best capture capacity in low pressure range and are considered to be the strongest candidate for carbon dioxide capture. Yaghi et.al.\textsuperscript{7} reported the M/DOBDC series of MOFs (M=Ni, Zn, Co), where the organic linker was formed by 2,5-dioxido-1,4-benzendicarboxylate(DOBDC), connecting metal ions like magnesium, nickel, zinc and cobalt as metal sites.\textsuperscript{10}

Mg/DOBDC is a MOF composed of 2, 5-Dihydroxyterephthalic acid linkers coordinated to magnesium centers.\textsuperscript{10} This material was successfully synthesized by the solvothermal method\textsuperscript{9,12,13} and was reported to have high CO\textsubscript{2} adsorption capacity and CH\textsubscript{4} selectivity over CO\textsubscript{2}.\textsuperscript{10,11} At low CO\textsubscript{2} partial pressure a competitive adsorption capacity of 0.38 g CO\textsubscript{2}/g sorbent was observed.\textsuperscript{23} There are, however, some difficulties encountered with this adsorbent. For instance, a high energy input is required to regenerate the material which is not cost-effective or energy-effective when scaled up for industrial applications.\textsuperscript{10} In addition, the application of this MOF
to CO$_2$ capture demands partial or complete drying of the gas stream due to its hydrophilic metal-ligand bonds.$^{17}$ Previous experiments have shown that in humid conditions, the BET surface area of Mg/DOBDC dropped from 1406 to 38 m$^2$/g, and the CO$_2$ adsorption capacity is also reduced by more than half.$^{13}$ It was also reported that even under dry conditions, after long-term storage in sealed containers for one year, the BET surface area declined by about 70% and CO$_2$ adsorption capacity decreased as well. Kizzie et al. developed a breakthrough experiment of N$_2$/CO$_2$ for M/DOBDC series to show the hydrophilic properties of these materials.$^{22}$ In their experiment, M/DOBDC series, especially Mg/DOBDC showed a novel capacity for CO$_2$ capture in dry gas mixtures but its capacity dramatically decreased when N$_2$/CO$_2$/H$_2$O breakthrough experiments were performed. It was found that with an increase in relative humidity, carbon dioxide capture capacity decreases drastically even after regeneration.

Amine functionalization of pore surfaces within various materials has been performed by several groups.$^{23,27-32,34}$ These modifications are known to be effective in carbon dioxide capture due to amines high affinity towards CO$_2$ gas molecules. In Arstad’s report,$^{27}$ three different amine-functionalized MOFs were tested for carbon dioxide capture. The results showed that even if surface areas and pore volumes decreased to some extent after functionalization, carbon dioxide capacities showed better results than for the non-functionalized original structures of tested MOFs.

In order to accurately access the performance of the material under humid conditions, material stability was tested via accelerated steam treatment. Accelerated
steam treatment would provide an exaggerated humid environment to test for the materials stability, and can be taken as a worst case scenario, as in the real application relative humidity would be much lower. Steam treatment could also be considered as a possible method for material regeneration. Generally, large amounts of unused or waste steam is available at industrial plants and its use for regeneration of CO$_2$ capture adsorbent could be easily implemented. It would be, therefore, interesting to see whether or not steam treatment could be used as a new adsorbent regeneration process and simultaneously test for the materials stability.

Currently, Mg/DOBDC is made in a very small amount, on the milligram scale, in laboratory settings$^{9,12}$ but few reports discuss scale-up of this material.$^{22}$ Another goal of this work is to find an efficient, one-pot synthetic route to generate Mg/DOBDC on a larger scale.

The same technique was used to functionalize Mg/DOBDC with ethylenediamine (ED) by our group. As shown in Figure 1, ethylenediamine was impregnated on the surface of the pores where one amine group coordinated directly to a metal site of Mg while the other amine group was free within the pore and available to interact with guest molecules.$^{23}$ It was found that such modification of the material increase the CO$_2$ adsorption capacity and lowers the energy requirement for regeneration of the adsorbent. Besides, it increased its structure stability, bare Mg/DOBDC showed clearly degradation of CO$_2$ adsorption capacity after four cycles of adsorption of CO$_2$ by TGA. While for ethylenediamine functionalized Mg/DOBDC, even after four cycles of adsorption and desorption under dry conditions, CO$_2$ capacity stayed
constant at about 1.51 mmol/g. But the CO₂ capture ability in humid conditions was not tested previously despite the fact that these conditions are more similar to those which will be encountered in industrial applications. The carbon dioxide capture ability under humid conditions of ED functionalized Mg/DOBDC was tested and will be presented in this work.
3.0 EXPERIMENTAL

3.1. Scale Up of Mg/DOBDC Synthesis

The scale up of eight times the original recipe for Mg/DOBDC synthesis\textsuperscript{9,12} was performed based on previously reported procedures. 2, 5-dihydroxyterephthalic acid (H\textsubscript{4}DOBDC; 0.888 g, Sigma-Aldrich) and Mg (NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O (3.8 g, Fisher) were mixed together in a 250 ml Pyrex flask. A solvent solution of dimethylformamide (352 ml, Fisher), ethanol (24 ml, Fisher) and DI water (24 ml) was then added to the flask. The resulting solution was sonicated for 1 hour to ensure mixing and then placed into the oven for 20 hours at 125 °C. Once the heating was done, the flask was removed from the oven and immediately the mother liquor was decanted and replaced with methanol. The solution was set to cool down for 5-6 hours. Methanol replacement was then performed every 12 hours over the next two days. The mixture was then evaporated for three days to result in a yellow microcrystalline powder. The resulting material was then activated by heating under vacuum at 250 C for five hours to yield ~0.95 mg of Mg/DOBDC.

3.2. Accelerated Steam Treatment Experiments

Steam treatment procedures were borrowed from previous reports of similar experiments performed on amine-functionalized mesocellular foam (MCF) materials\textsuperscript{24} and on mesoporous alumina-supported amines.\textsuperscript{25} About 200 mg of material was put into glass test tubes which were then placed into an 80-ml Teflon lined Parr reactor. The Teflon liner was carefully filled with about 20 mL of DI water. It should be noted that water in the liner did not touch the solid samples in the test tubes. The whole set
up prior to steam stripping was maintained in a glove box, establishing an inert nitrogen environment. Once the Parr reactor was sealed, it was transferred into the oven. The Parr reactor was heated at 110 °C for 48 hours. The steam pressure in the reactor was autogenous. Once heating was finished, the reactor was let to cool down to room temperature. No liquid was observed in the test tubes indicating that solid material only interacted with water vapor. Test tubes were then taken out and the solid samples were dried under vacuum for 80 °C overnight. Dried powder samples were then ready for characterization.

### 3.3. Functionalization

As mentioned before, some MOFs have already been amine-functionalized. Functionalization with ethylenediamine was performed based on those reports and on the recent paper by Choi et.al.\(^4\) About 40 ml anhydrous toluene and 1.0 g ethylenediamine (Fisher) was added into the flask with 200 mg of solid dry Mg/DOBDC sample. The contents of the flask were stirred at 400 rpm under reflux. After 12 hours, the mixture was washed with 100 ml DI water and then 100 ml ethanol. The filtered material was dried at room temperature for 14 hours to yield ethylenediamine functionalized Mg/DOBDC which was named as ED-Mg/DOBDC.

### 3.4. Characterization

The pore characterization of the synthesized and activated material was performed by using a NOVA 2200e surface area and pore volume analyzer. This instrument provided nitrogen adsorption-desorption isotherms, where samples were degassed under vacuum flow at 250 °C for 16 hours prior to the analysis. X-ray
diffraction (XRD) patterns of material were obtained by a Rigaku Ultima IV X-RAY Diffractometer (CuKα) over the range of 5-50° 2θ with a stepsize of 0.1° 2θ and a one second integration time per step.

3.5. CO2 Adsorption

The CO2 adsorption capacity was measured by NOVA 2200e. This instrument was used to detect the CO2 (UHP grade 100%, Airgas) adsorption isotherms in room temperature. We degassed samples under vacuum at 80 °C for 16 hours before analysis, and the CO2 adsorption/desorption isotherms were collected at room temperature.

CO2 uptake was also measured by thermogravimetric analysis, TA Q500. Each sample was heated up to 110 °C initially to draw out any excess water, was let to equilibrate back to room temperature, and then exposed to 100 % CO2 gas for two hours. The total CO2 uptake was calculated based on the weight increase of the sample from the point when CO2 was first introduced until the saturation point was reached where no more weight increase was observed.

3.6. ED Loadings

Thermogravimetric analysis (TGA), TA Q500 was used to determine amine loadings on the functionalized material. Each sample was heated at the rate of 10 °C/min from room temperature to 600 °C. For further research of ED loadings effect on CO2 adsorption, we synthesized two different batches of ED-Mg/DOBDC with different ethylenediamine loadings. Batch 1 was loaded with 1 g of ethylenediamine, and batch 2 was loaded with 0.8 g.
4.0 RESULTS AND DISCUSSION

4.1. Structure Changes of Functionalization

Mg/DOBDC, a microporous material, exhibits unsaturated metal centers after the activation step, which could further be functionalized by other organic molecules.\(^{13,46}\) In the previous research of our group\(^ {23}\), it was claimed that structural changes can improve its stability after several adsorption – desorption cycles in a dry gas mixture of 400 ppm CO\(_2\). ED-Mg/DOBDC was regenerated under 110 °C with Ar purge, conditions which are milder than for the bare Mg/DOBDC which is regenerated under 250 °C in vacuum. In another words, ED-Mg/DOBDC requires less energy input for full regeneration.

Since amine sites are considered to be effective for CO\(_2\) capture in the presence of moisture,\(^ {38}\) in this work the pore structure and CO\(_2\) adsorption capacities were investigated for functionalized Mg/DOBDC MOF. For further industrial application consideration, a scale up Mg/DOBDC synthesis on the gram scale was performed by modification of the original recipe.\(^ {9}\) XRD and N\(_2\) adsorption – desorption isotherms for this material and its derivatives were also measured.

Figure 2 illustrates XRD patterns of Mg/DOBDC and its derivatives, with characteristic peaks at 6.9 and 11.9° \(^ {20}\), which identify with the values which were reported in the previous report.\(^ {12,23}\) As we can see in the figure, after functionalization, the peak locations did not change too much which indicates the basic crystal structure of our material did not change during functionalization. However, in the meantime, degradation of the characteristic peaks could be clearly seen for functionalized
samples indicating that amine functionalization affects the structure of Mg/DOBDC. With respect to steaming experiment, we may observe the similar trend that the crystal structure retained after steaming, but the characteristic peaks have shown obviously degradation which illustrates the water vapor destroyed the framework of Mg/DOBDC’s.

The nitrogen isotherm is shown in Figure 3 and the pore characteristics are presented in Table 1 for comparison. As it can be seen from Figure 3, the original bare Mg/DOBDC shows apparent behavior of type I isotherm which indicates its microporous structure. Due to enhanced adsorption in micropores, the adsorption increases rapidly in low pressure range and then becomes saturated. After steam treatment, the pore structure dramatically degraded, and BET surface area decreased from 1082 m$^2$/g to 23 m$^2$/g. After functionalization of the bare material, even the BET surface area of ED-Mg/DOBDC dropped to 381 m$^2$/g, but its structure showed better hydrophobicity. After steaming treatment, the surface area of ED-Mg/DOBDC was 121 m$^2$/g, which is much higher than the steamed bare Mg/DOBDC. Also, compared to bare Mg/DOBDC, the total pore volume of the steam treated material decreased from 0.49 cm$^3$/g to 0.24 cm$^3$/g, while average estimated pore diameter (approximated from NOVA Win software, Quantachrome) decreased from 13.6 Å to 8 Å. The same trend was observed in total pore volume and average pore diameter parameters: while both properties degraded for steamed bare material, they increased for steamed functionalized material. These results show that after steam treatment functionalized Mg/DOBDC didn’t degraded as dramatically as bare Mg/DOBDC did in terms of
structural pore characteristics, which could mean enhanced stability under humid conditions for ED-Mg/DOBDC.

4.2. CO$_2$ Adsorption at Room Temperature

Some amine functionalized MOFs have been proved has higher capacities than parent MOFs.$^{27}$ Because CO$_2$ can react with amine group of the MOFs to form carbamate species by forming zwitterionic intermediates. Also, in the humid conditions, through the help of H$_2$O and OH$^-$, the potential CO$_2$ capture capacities of the amine group would increase.$^{38}$

Figure 4 presents the CO$_2$ isotherms in room temperature, based on these isotherms, adsorption capacity of bare Mg/DOBDC was about 5.08 mmol/g assuming ideal gas conditions (low pressure range), while steamed Mg/DOBDC only reached a capacity of 1.20 mmol/g. The functionalized Mg/DOBDC, ED-Mg/DOBDC showed the highest CO$_2$ adsorption capacity as 7.81 mmol/g, and 2.9 mmol/g after steam treatment which is higher than for the non-functionalized material. While under different settings, a similar trend was observed during CO$_2$ adsorption via thermogravimetric analysis (TGA). Figure 5 compares CO$_2$ capacity values of the same materials analyzed by TGA and NOVA 2200e. According to TGA, total CO$_2$ uptake reached the capacity of 3.73 mmol/g, steamed Mg/DOBDC has 0.42 mmol/g while ED-Mg/DOBDC has 4.30 mmol/g and steamed ED-Mg/DOBDC has 1.66 mmol/g. In general, CO2 capacity values were lower for samples analyzed by TGA which could be attributed to the way the machine operates. In TGA, gas flows over the material on the pan and therefore not all of the samples make contact with the CO$_2$. 

13
molecules, causing it not become fully adsorbed by the material.\textsuperscript{38} In conclusion; it was found that ethylenediamine functionalized Mg/DOBDC performed better for CO\textsubscript{2} capture capacities under both humid and dry conditions compared to non-functionalized material.\textsuperscript{49}

4.3. Effect of ED Loadings

Figure 6 shows the weight changes by heating the sample from 25 °C to 600 °C. The result suggests that ED-Mg/DOBDC lost more weight than bare Mg/DOBDC in the range of 100 °C to 300 °C. Since the ethylenediamine`s boiling point is around 120 °C, the previous report\textsuperscript{23} reported this change as being due to ED loss. Similar result happened to steamed samples of Mg/DOBDC and ED-Mg/DOBDC, the steamed ED-Mg/DOBDC showed more weight loss in the range of 100 °C to 300 °C. While comparing the sample before and after steaming, we may observe that the difference curvature between bare Mg/DOBDC and steamed bare Mg/DOBDC between the range of 0 °C to 100 °C due to the difference of initial moisture conditions. While after functionalization, steamed samples lost less weights than the parent material, since amine does not strong covalently bond to solid supports so it may leach from solid support at high temperature and humid conditions.\textsuperscript{38} Our steaming experiment occurs in the harsh conditions with higher concentration and higher temperature than the real-world flue gas capture applications so it may result amine leach in some extend. Nevertheless, we still can observe the ED molecules inside the pores after steaming experiment, so we may suggest that our materials have potential to be used in industrial application.
As I mentioned before, our group have been proved that there is not only one configuration for functionalized material ED-Mg/DOBDC. Figure 1 illustrated our group’s previous results that the different structures of ED-Mg/DOBDC. For each unit cell, there could be 1, 3, 6 or 18 ED molecules, which change the pore characteristics of the resulting material.\textsuperscript{23} In our work, by adding different amount of ethylenediamine during synthesis, we achieved two different batches of ED-Mg/DOBDC as shown in Figure 7. Compare the two different samples; we can see there is a different curvature in the range of 100 °C to 400°C which are considered to be due to the contribution of different ED loadings. By calculation, the batch 1 has \textasciitilde6.3% ED inside the pores while batch 2 has only \textasciitilde5.5% ED inside. This difference may result in different pore characteristics and it certainly would affect its CO\textsubscript{2} capture capacity. Further research of our group would include an investigation of different ED loadings on the materials structure and further CO\textsubscript{2} capture performance.
5.0 CONCLUSIONS

In conclusion, Mg/DOBDC MOF was successfully functionalized with amine groups for applications in carbon dioxide capture. Such functionalization increased the hydrophobicity in a humid environment which is characteristic of both flue gas and ambient air conditions. Steam treatment was performed to evaluate the structural degradation and CO₂ adsorption capacity in ultra-high moisture conditions.²⁴,²⁵

As a result, Mg/DOBDC showed significant degradation after exposure to steam but less degradation was observed for amine- functionalized Mg/DOBDC. As for CO₂ uptake, ED-Mg/DOBDC showed higher capacity at room temperature even though its surface area and pore volume decreased. These results suggest that ethylenediamine functionalization of Mg/DOBDC increased its structural stability against water vapor, which further led to better performance in CO₂ capture.

According to the previous report of our group,²³ there are several possibilities for different loadings of one ED molecule. For those different structures, the CO₂ uptake capacities are not the same. From our research, we found that by increasing the ED loadings, the surface area decreases as presented in Figures 7 and 8. Further studies are required in this area to figure out the best ED loadings to design the most efficient CO₂ adsorbent.
6.0 RECOMMENDATIONS

For short term plans of this project, evaluation of different ED loadings should be addressed. Based on the estimates of Choi et al.\textsuperscript{23}, there are several possibilities for ethylenediamine loading in the Mg/DOBDC MOF. Fourier Transform Infrared Spectroscopy (FT-IR) and Transmission Electron Microscopy (TEM) might be used to help find the structural differences between all of the synthesized materials with various loadings.

For long-term consideration and industrial applications despite the fact that bare Mg/DOBDC exhibits an exceptional capacity for carbon dioxide capture under dry conditions, it needs to be optimized for stable and efficient capture in a humid environment. Amine-functionalized Mg/DOBDC showed better structural stability and working capacity in the presence of moisture. Nevertheless, there are many other factors that should be accounted for in this process, such as the materials performance under a real environment of flue gas or ambient air. Moreover, even though the scale up the Mg/DOBDC to around 1 gram per batch was performed without any observed structural changes, there is still the potential for structural degradation and pore distribution variation on the larger scale, such as in kilograms and higher orders of weight magnitudes. The steam treatment performed in this work mimics conditions with the largest relative humidities possible and tests whether the material can withstand the stress. While it might be a good test for stability, the material still needs to be tested on its adsorption in the presence of water and corrosive gases such as SOx, NOx, and HCl which are commonly present in flue gas. In parallel, we can investigate
some other hydrophilic MOFs such as MIL-53,\textsuperscript{28,32} USO-1,\textsuperscript{27} CuBTTri,\textsuperscript{29} UMCM-1\textsuperscript{30} and HKUST-1,\textsuperscript{31} which have high carbon dioxide capacity to find out if functionalization would enhance their performance as well.

In addition, carbon dioxide capture from ambient air is another topic that requires attention. In comparison with capture from flue gas generated at coal fired power plants, air capture is more challenging since CO\textsubscript{2} gas is more dilute in the ambient air (about 400 ppm).\textsuperscript{1} In the near future, there is a need to build a large carbon dioxide capture system which would be energy efficient and economically viable.

Carbon dioxide capture by Mg/DOBDC only accounts for a small portion of possible research and further studies need to be done on the implementation of such adsorption technology in an industrial setting.
### 7.0 NOMENCLATURE

<table>
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<tr>
<td>MOF</td>
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<td>FTIR</td>
<td>Fourier Transform Infrared Spectroscopy</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron microscopy</td>
</tr>
</tbody>
</table>
8.0 REFERENCES

13. Liu, J., A. I. Benin, A. M. B. Furtado, P. Jakubczak, R.R. Willis, and M. D. LeVan, Stability effects on CO2 adsorption for the DOBDC series of


