JOURNAL OF
EMERGING INVESTIGATORS

Article

Use of drone with sodium hydroxide carriers to absorb carbon dioxide from ambient air

Tanay Jagannathan[1], Arvind Chandramouli[1], Kishan Ramachandran[1], Shlok Dev[1], Eriyat Lakshmi Devi[1], Kanchan Sharma[1], Christopher Rajamani[2]
[1] Gems Modern Academy, Dubai, UAE
[2] Al Hoty Stanger Laboratories, Dubai, UAE

SUMMARY

Global warming occurs when air pollutants collect in the atmosphere and absorb sunlight and solar radiation, and as much as 80% of global warming is caused by carbon dioxide alone. Many metropolitan cities like Delhi, India have carbon dioxide (CO_2) levels 11 times higher than the levels recommended by the World Health Organization. Prior research has mainly concentrated on removing CO_2 from sources like automobile exhaust and industry effluents. However, there has been limited research pertaining to the use of hydroxides to reduce CO_2 in ambient air. We therefore conducted experiments to identify the most suitable hydroxide in solid form to capture low concentrations of CO_2. Furthermore, we explored the possibility of using an electrically-charged drone to reduce CO_2 in the air using a solid hydroxide. Our results indicate that sodium hydroxide (NaOH) is most suitable for scrubbing CO_2 from air, with up to 90% reduction in carbon dioxide levels under the experimental conditions. Since the troposphere stretches up to 13 km above sea level and military drones can fly up to 18 km above sea level, drone attachments with CO_2-absorbing chemicals could potentially clean the air at all levels in the troposphere. Our study provides a possible solution to mitigate the harmful impacts of carbon dioxide present in the atmosphere.

INTRODUCTION

Carbon dioxide (CO_2) in air is a major contributor to global warming and climate change. CO_2 and other pollutants trap radiation at ground level, thus stopping the Earth from cooling at night (1). Besides global warming, atmospheric CO_2 can promote diseases ranging from mild drowsiness to high blood pressure and respiratory disorders (2). As long as fossil fuels are in use, air pollution cannot be completely eliminated. Electric cars and other innovations will help to reduce this problem in the future, but the CO_2 already present in the atmosphere has to be cleaned.

The average CO_2 concentration in air currently is 400 ppm (0.04%). This is 47% higher than the CO_2 levels before the third industrial revolution (1960), which was 280 ppm (0.028%) (1). In confined spaces like spacecraft, the CO_2 concentration can get much higher and cause toxicity. Lithium hydroxide (LiOH) canisters were used in the Apollo 13 spacecraft to remove CO_2 (3). In order to remove CO_2 from industrial effluents, either strong alkalis like sodium hydroxide (NaOH) and potassium hydroxide (KOH) or a weak alkali like aqueous ammonia are typically used (4). Adsorbents such as activated carbon are also used for removing CO_2 from effluents (4). Recent studies have shown that LiOH can be used to absorb CO_2 from automobile exhaust (5). The CO_2 absorbing capacity of LiOH is greatest at higher temperatures (90-120˚C), which is similar to the temperature of vehicular exhaust. The reaction between hydroxides and carbon dioxide is exothermic in nature and causes the temperature to rise further (5). Although commercial products like Decarbite, an NaOH based chemical, is available to remove CO_2 from atmospheric gases, it is predominantly used for removing CO_2 from gas streams. Researchers have tried using NaOH spray (6) and polyamine based solid adsorbents (7) to capture CO_2 from air, but both these methods are not effectively scalable. We hypothesized that lithium hydroxide (LiOH) is a suitable hydroxide for cleaning CO_2 from air. When air containing CO_2 is passed through solid LiOH, two hydroxide molecules react with CO_2 to form lithium carbonate (Li_2CO_3) and water, thus removing CO_2 from the air (3). The Li_2CO_3 generated from this reaction can be either recycled or used for other purposes like production of ceramics and treatment of mental disorders (8).

We conducted experiments to identify the most suitable hydroxide for absorbing low concentrations of CO_2 present in ambient air. We tested the CO_2 absorbing capability of LiOH, NaOH, KOH and Calcium hydroxide ($Ca(OH)_2$) in solid form. Our results indicate that NaOH and KOH are much better at absorbing CO_2 from ambient air as compared to LiOH and $Ca(OH)_2$. This discovery provided us with an opportunity to use NaOH and KOH to clean CO_2 from earth's atmosphere. As presence of CO_2 is not localized to certain heights and locations, we propose to use a drone with hydroxide carriers for cleaning CO_2 from air. A drone with an appropriate attachment can carry solid hydroxide that absorbs CO_2 as it flies through the air.

RESULTS

Initially our goal was to identify the hydroxide most effective at absorbing CO_2. To start, 30 g of different hydroxides were placed in impingers. Next, a steady flow of 0.5% CO_2, 99.5% nitrogen was passed through the impinger containing the hydroxide and CO_2 concentration was measured in the outlet gas to determine absorption over time (**Figure 1**). The CO_2 absorption capacity of NaOH and KOH was found to be overlapping, but the CO_2 concentration in the inlet gas was higher when NaOH was used as the absorbent. NaOH showed 75% absorption of CO_2 in the first minute whilst KOH showed 62% absorption of CO_2 in the first minute. No further change in absorption of CO_2 was observed both in case of NaOH and KOH. On the other hand, LiOH absorbed 28% CO_2

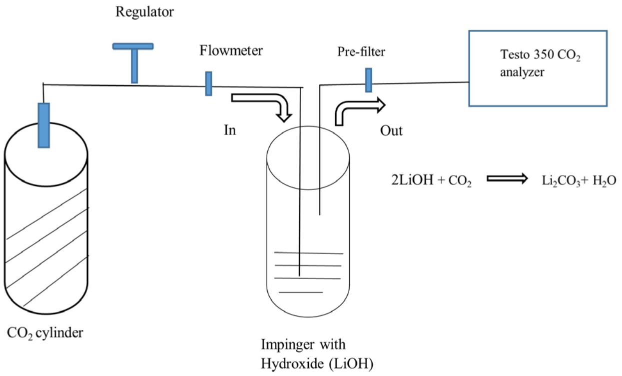

Figure 1: Impinger setup with CO$_2$ cylinder for inlet gas. Impinger was filled with CO$_2$ absorbing hydroxide. The inlet gas flow rate was fixed at 1 L/min. CO$_2$ concentration in the outlet gas was analyzed using a calibrated flue gas analyzer.

and Ca(OH)$_2$ absorbed 24.5% CO$_2$ in the first minute. There were minor fluctuations in CO$_2$ concentration of the outlet gas for three minutes and thereafter it remained constant up to six minutes for both LiOH and Ca(OH)$_2$ (**Figure 2**)

When a single impinger was filled with NaOH it absorbed 75% of CO$_2$ present in the inlet gas in the first minute. In order to check if one impinger is sufficient to achieve maximum reduction in CO$_2$ we conducted the next experiment with two consecutive impingers, filled with 30 g of NaOH each. The outlet from the first impinger was connected as inlet to the second impinger. 4800ppm (0.48%) CO$_2$ gas was used at a flow rate of 1L/min in the inlet of the first impinger. The outlet gas had only 500 ppm (0.05%) CO$_2$ indicating 90% reduction after 2-3 seconds of passing through the second impinger. No further reduction or increase of CO$_2$ concentration was observed in the outlet gas up to six minutes. (**Figure 3**)

After testing the impact of two impingers on CO$_2$ absorption capability of NaOH pellets, we tested the CO$_2$ absorption capacity of solid NaOH pellets at higher CO$_2$ concentrations to model automobile exhaust or factory effluents that have CO$_2$ compositions in the range of 10-15% (**Table 1**). In the case of 5% CO$_2$, the outlet gas showed 92.5% reduction in CO$_2$ concentration after one minute and 96% reduction after six minutes. In 10% CO$_2$, the outlet gas showed 73% reduction in CO$_2$ concentration after the first minute, but the outlet gas concentration started increasing thereafter. After six minutes, the CO$_2$ concentration was reduced by 34.2% relative to inlet concentrations. A similar trend was observed with 15% CO$_2$, with the outlet CO$_2$ concentration being reduced by 45% after a minute but increasing to a net 12% reduction after six minutes. In all three experiments, we placed the impinger in an ice tray as the impinger temperature increased due to the exothermic nature of the reaction and higher concentration of the reactants. The results of this experiment indicate that NaOH in pellet form is not very effective in reducing CO$_2$ concentration when the inlet gas has 10-15% CO$_2$ concentration. Thus, NaOH in pellet form may not be suitable for scrubbing CO$_2$ from automobile exhaust or industry effluents.

In our next experiment, we sought to identify a suitable material for carrying NaOH in the drone attachment. Based on literature search, we identified perforated Teflon sheets as a potential candidate, but we did not proceed with this material as the results of our previous experiment indicated that NaOH in pellet form may not be most effective at higher concentrations of CO$_2$ and we may have to use powder form of NaOH. Instead, we used porous cellulose thimbles and glass microfiber thimbles as carriers of NaOH. In order to check the CO$_2$ absorption capacity of NaOH when placed in a thimble, the inlet gas was passed through the thimble and

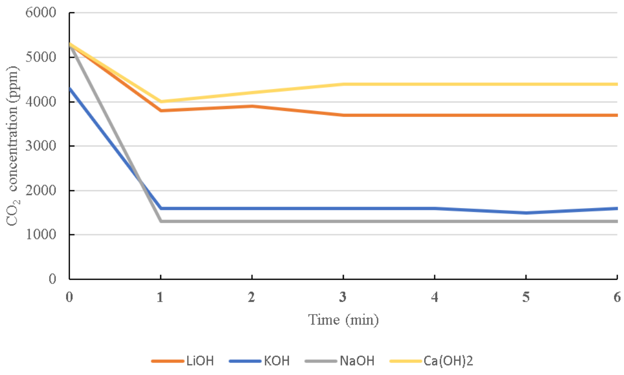

Figure 2: Concentration of CO$_2$ in outlet gas after passing through various hydroxides. 30 g of each hydroxide was taken in the impinger and nitrogen-CO$_2$ mixture was passed through the impinger at 1 L/min. The carbon dioxide concentration of outlet gas was measured at one-minute intervals for six consecutive minutes.

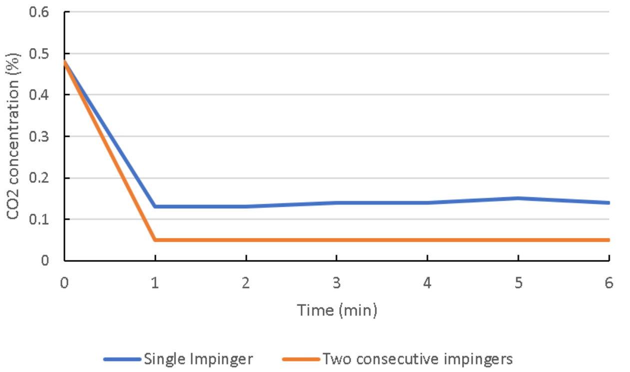

Figure 3: Impact of two consecutive impingers on CO$_2$ absorption. Two impingers were filled with NaOH and inlet gas with 0.48% CO$_2$ concentration was passed through the first impinger. The outlet of the first impinger was connected to the inlet of the second impinger. CO$_2$ concentration was measured in the outlet gas of the second impinger.

Table 1: CO$_2$ absorption capacity of solid sodium hydroxide pellets at higher concentrations of CO$_2$ when placed in an impinger. Inlet gas with varying CO$_2$ concentration was passed through NaOH pellets to observe the CO$_2$ absorption capacity of NaOH at higher levels of CO$_2$. This experiment was conducted to check the suitability of NaOH as a CO$_2$ scrubber for industry effluents or automobile exhaust.

	Concentration of CO$_2$ in the outlet gas after 'x' minutes (%)					
Concentration of CO$_2$ in the inlet (%)	1	2	3	4	5	6
5.07	0.38	0.37	0.36	0.34	0.33	0.31
9.85	2.65	3.93	5.12	6.23	6.37	6.49
14.87	8.25	11.56	12.80	13.52	13.75	14.02

Table 2: CO_2 absorption capacity of solid sodium hydroxide pellets when placed in cellulose thimble and glass microfiber thimble. Porous thimbles will be used as carriers of NaOH in the drone attachment. This table indicates that the CO_2 absorption capacity of NaOH is not impacted when placed in porous thimble made out of cellulose and glass microfiber.

Time (min)	1	2	3	4	5	6
% CO_2 in outlet gas when Cellulose thimble is used. Concentration of CO_2 in inlet gas was 0.44%	0.04	0.04	0.04	0.05	0.04	0.05
% CO_2 in outlet gas when glass microfiber thimble is used. Concentration of CO_2 in inlet gas was 0.42%	0.03	0.03	0.03	0.04	0.04	0.03

then into two consecutive impingers filled with 30 g of NaOH. Despite the thimble, there was more than 90% reduction of CO_2 in the outlet gas. This reduction was in the same range as double impingers without thimble. Thus, we concluded that porous cellulose and glass microfiber thimbles can be used for carrying NaOH and they do not impede the gas flow or CO_2 absorption of the hydroxide (**Table 2**).

The goal of our final experiment was to design a suitable drone with attachment. We used Tinkercad, a 3D modelling software to design a drone with an attachment inspired by Google Wing. The belly of the model drone was fitted with three parallel attachments for carrying NaOH in packs made out of glass microfiber or cellulose. Forward movement of the drone will create minimum drag. However, sideways (horizontal) movement of the drone will cause heavy drag, but this will create a result similar to air passing through two or three consecutive impingers, thus stripping CO_2 from air more than once. The actual building and testing of the drone is not included in this phase of the research (**Figure 4**).

DISCUSSION

We conducted experiments to identify the most suitable hydroxide to absorb CO_2 from ambient air. In order to maximize CO_2 absorption, we studied the effect of two consecutive impingers. We further tested the use of the selected hydroxide for scrubbing CO_2 from other sources like automobile exhaust. We proposed the use of a drone and designed a virtual model of a drone with attachment for carrying hydroxides to clean CO_2 from air as it flies through the air. We also evaluated potential materials for carrying hydroxide in the drone attachment.

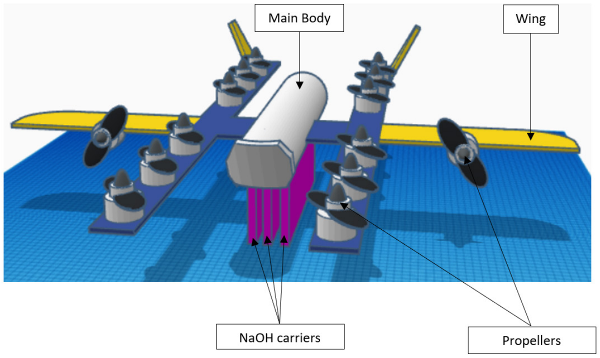

Figure 4: Drone design to carry 1.5 kg load. A vertical view of the drone with attachment. The pink vertical lines indicate the attachment that will carry hydroxide filled in porous material made out of cellulose or glass microfiber impinger.

Table 3: Brand, purity and form of various hydroxides used in the experiments.

Hydroxide	Brand details	Purity (%)	Form
LiOH	Labchem Products	99	Powder
KOH	SD Fine Chemicals	85	Pellets
NaOH	SD Fine Chemicals	98	Pellets
$Ca(OH)_2$	SD Fine Chemicals	90	Powder

Our results indicate that LiOH is not the best hydroxide to capture carbon dioxide from ambient air. Instead, NaOH is a good option to remove carbon dioxide from ambient air. KOH was also found to be effective in reducing CO_2 concentration. We used only 85% pure KOH for our experiments (**Table 3**), while the purity of NaOH was 98%. The price of 90% KOH is three times the price of 98% NaOH. The molecular weight of KOH is 1.4 times the molecular weight of NaOH. This means that there will be fewer moles per gram of KOH in comparison to NaOH for absorbing CO_2. Hence, we preferred NaOH over KOH for our subsequent experiments. We also found that two consecutive impingers can reduce the carbon dioxide concentration more than 10-fold (>90% reduction) when solid NaOH pellets are used for absorption. This result supports the validity of our proposed approach. When NaOH reacts with CO_2, sodium carbonate (Na_2CO_3) is formed which can be used for various purposes like treating hard water and manufacturing soaps and detergents (10).

The results of our next experiment to study the effectiveness of NaOH at higher concentrations of CO_2 indicate that sodium hydroxide pellets get saturated before the respective molar quantities are used up in the experiment. As per molar calculations, 30 g of NaOH should absorb 16.5 g of CO_2. When 5% CO_2 is used with 30 g of NaOH pellets, the CO_2 concentration in the outlet gas was reduced by 15-fold. However, with 10% and 15% CO_2 in inlet gas, there is a rise in the concentration of CO_2 in the outlet gas after the first minute of passing through the impinger. We believe this occurs due to the formation of sodium carbonate and water that stick to the pellet surface. The sodium carbonate layer on the surface of the NaOH pellet prevents further reaction between the hydroxide and CO_2. Further, the exothermic nature of the reaction especially at higher concentration of CO_2 significantly heated up the experimental setup. We could not repeat the experiments with powdered sodium hydroxide to overcome this limitation. Therefore, it appears that NaOH in pellet form is not ideal for removing CO_2 from automobile exhaust or industry effluents.

The goal of our next experiment was to identify the most suitable material to carry NaOH within the theoretical drone attachment. We initially thought a perforated Teflon bag could be used in the drone attachment to carry sodium hydroxide pellets. This idea was rejected as perforated Teflon bags are not suitable for carrying prills or powder form of NaOH. We then conducted experiments with cellulose and glass-microfiber thimbles as potential carriers for NaOH. Cellulose and glass microfiber were both equally effective in regards to porous properties, as air could easily pass through both the materials. The cellulose and glass microfiber thimbles were not impacted by sodium hydroxide when placed in contact with NaOH for 3-5 hours. Impact of prolonged exposure to

NaOH on the cellulose and glass microfiber thimble was not tested. We believe it would be best to remove the hydroxide from the container when not in use with the drone in order to avoid damage to the drone and its attachments.

Lastly, we designed a drone attachment for the purpose of testing our hydroxide as discussed previously. Use of a drone with sodium hydroxide in porous attachments is a better option than NaOH spray or polymer impregnated with hydroxide to absorb carbon dioxide. NaOH spray has the risk of causing damage to people and property; plus, the end product cannot be collected and used for other purposes. Polymer based adsorbents can be used in fixed towers but to combat climate change CO_2 has to be scrubbed from various layers of troposphere and at various locations around the globe.

Our drone design was inspired by the Google Wing that has already been tested for carrying a load of 1.4 kg. All of our laboratory experiments were conducted at a gas flow rate of 1 L/min, but the airflow rate while using a drone could be higher, thereby limiting the contact time for the reaction between NaOH and CO_2 present in the air. Instead of a single attachment, we proposed to include three parallel attachments to increase the possibility of two consecutive scrubs. In case the airflow rate is significantly higher than 1 L/min, the three consecutive attachments will ensure sufficient contact time for the reaction. In all our experiments, CO_2 reduction in outlet gas was greatest in the first minute. This indicates that contact time should not be a limitation while using a drone. Further drone speed can be increased, decreased or the drone can be made to hover at a specific location also. Weather balloons could be a possible lower-cost alternative to drones. However, we will have limited control over the movement of weather balloons and often they land in oceans, thus polluting them.

While all tested hydroxides could be used for absorbing CO_2, NaOH was found to be the most effective in the experimental conditions. In addition, passing CO_2 through consecutive impingers reduces the CO_2 concentration by 90%. The drone design replicates the double impinger effect, thus enhancing the effectiveness of the proposed method to reduce CO_2 from ambient air.

One of the limitations of this study is, although we propose the use of a drone with hydroxide carrier, we have not completed actual experiments with a drone. School laboratory scale drone has been modified with an attachment; however, we need permission from Government bodies to conduct actual trials. Our next steps for this project include trials with drones in ambient conditions.

MATERIALS AND METHODS

Identifying the most effective hydroxide for absorbing CO_2

A mixture of nitrogen and CO_2 (0.5% CO_2 and 99.5% nitrogen) was passed through an empty impinger for a minute. The CO_2 concentration in the outlet was measured. This formed the zero reading of the experiment. Next, 30 g of KOH was placed in the impinger. The CO_2 content in the outlet gas, after passing through the impinger, was measured at one-minute intervals for six minutes. A Testo 350 Analyzer was used to measure CO_2 in the outlet gas. The same process was repeated for LiOH, NaOH and $Ca(OH)_2$ (**Table 3**).

It is worth noting that we conducted our first experiment with 85% pure KOH. Availability of high purity KOH with a price comparable to that of equal grade to NaOH is a challenge. The Testo 350 Analyzer has a resolution of 100ppm (0.01%) and the error percentage of the instrument used was +/- 0.12%. The CO_2 cylinders of various concentrations were from AIRTEC.

Impact of using two consecutive impingers on CO_2 absorption capability of NaOH

A mixture of nitrogen and carbon dioxide (0.5% carbon dioxide and 99.5% nitrogen) was passed through two consecutive empty impingers for a minute. The CO_2 concentration in the outlet was measured. This formed the zero reading of the experiment. The gas cylinder was connected to the inlet of the first impinger. A tube connected the outlet of the first impinger to the inlet of the second impinger. Next, 30 g of NaOH was placed in each impinger. The CO_2 content in the outlet gas, after passing through the second impinger, was measured at one-minute intervals for six minutes. The Testo 350 Analyzer was used to measure CO_2 in the outlet gas.

CO_2 absorption capability of NaOH at higher concentrations of CO_2

A mixture of nitrogen and carbon dioxide (5% carbon dioxide and 95% nitrogen) was passed through an empty impinger for a minute. The CO_2 concentration in the outlet was measured. This formed the zero reading of the experiment. Next, 30 g of NaOH was placed in the impinger. The CO_2 content in the outlet gas, after passing through the impinger, was measured at one minute intervals for six minutes. The Testo 350 Analyzer was used to measure CO_2 in the outlet gas. The same process was repeated with 10% and 15% CO_2 mixed with 90% and 85% nitrogen, respectively.

Porous cellulose and glass microfiber thimbles as potential materials for carrying hydroxides in the drone attachment

The inlet gas (0.5% CO_2 and 99.5% nitrogen) was passed through a Munktell Filtrak thimble and then through two consecutive empty impingers for a minute. The CO_2 concentration in the outlet was measured. This formed the zero reading of the experiment. The gas cylinder was connected to the inlet of the thimble holder. A tube connected the outlet of the thimble holder to the inlet of the first impinger, while the outlet of the first impinger was connected to the inlet of the second impinger. Next, 30 g of NaOH was placed in each impinger. The CO_2 content in the outlet gas, after passing through the second impinger, was measured at one-minute intervals for six minutes. The Testo 350 Analyzer was used to measure CO_2 in the outlet gas. The experiment was conducted with cellulose and glass microfiber thimbles.

Drone design with attachment

The drone was designed using Tinkercad. Tinkercad is an online 3D modeling tool. 'Google Wing' was taken as starting point for the design and modified with an attachment for carrying hydroxide in porous bags made out of cellulose and glass microfiber.

ACKNOWLEDGEMENTS

We would like to thank the Principal, Ms. Nargish Khambatta, and Dr. Vimaldeep Kaur of Gems Modern Academy, Dubai for their encouragement and guidance. We would also like to thank the Environmental lab team from Al Hoty-Stanger Laboratories for their support.

Received: January 5, 2021
Accepted: February 23, 2021
Published: June 3, 2021

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