A Senior Design Project: The Design of an Experimental Carbon Dioxide Capture System for Enhancing Student Learning on Green Energy Manufacturing

Dr. Richard Chiou, Drexel University

Dr. Richard Chiou is Associate Professor within the Engineering Technology Department at Drexel University, Philadelphia, USA. He received his Ph.D. degree in the G.W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology. His educational background is in manufacturing with an emphasis on mechatronics. In addition to his many years of industrial experience, he has taught many different engineering and technology courses at undergraduate and graduate levels. His tremendous research experience in manufacturing includes environmentally conscious manufacturing, Internet based robotics, and Web based quality. In the past years, he has been involved in sustainable manufacturing for maximizing energy and material recovery while minimizing environmental impact.

Dr. Michael G. Mauk, Drexel University

Michael Mauk is Assistant Professor in Drexel University's Engineering Technology program.

Prof. Tzu-Liang Bill Tseng, University of Texas, El Paso

Dr. Tseng is a Professor and Chair of Industrial, Manufacturing and Systems Engineering at UTEP. His research focuses on the computational intelligence, data mining, bio- informatics and advanced manufacturing. Dr. Tseng published in many refereed journals such as IEEE Transactions, IIE Transaction, Journal of Manufacturing Systems and others. He has been serving as a principle investigator of many research projects, funded by NSF, NASA, DoEd, KSEF and LMC. He is currently serving as an editor of Journal of Computer Standards & Interfaces.

A Senior Design Project: The Design of an Experimental CO_2 Capture System for Enhancing Student Learning on Green Energy Manufacturing

Abstract

The paper presents a senior design project that engages in educational activities to enhance learning on green energy manufacturing, including design, development, and testing of a CO_2 capture system. The project is leveraged towards engineering student skills in CAD, material processing, instrumentation, and control. Students had to utilize manufacturing methods and techniques to create such a system for the future construction of manufacturing plants in industry. In order to achieve this, the amine material, Polyethylenimine (PEI), was used as adsorbent for the capture system in the project. PEI has the capability to bind to CO_2 at room temperature and pressure and then release it when heated. The PEI was impregnated onto a porous material, fumed silica, in order to increase its surface area and adsorption capability. Air is passed over this adsorbent mixture using a vacuum pump, and with the use of CO_2 sensors, the amount of CO_2 adsorbed is accurately measured. The adsorption stage continues until the mixture is fully saturated; after which, a series of valves are toggled, and the regeneration stage begins. A prototype with conditioning electronics for sensors was constructed. Data acquisition software was written using LabVIEW™ and Arduino to measure environmental parameters including temperature, and CO_2. For the sake of achieving the student learning outcomes, experiments were conducted, including sensor monitoring and process control. A concluding section discusses the student learning experiences during this project.

Introduction

Many impacts of climate change already observed, the environmental and social effects of global warming pose a significant challenge to the infrastructure, economic, and social fabric drivers of the global community. To address the challenge of global warming, this paper discusses an educational effort that integrates socioeconomic, ethics, and leadership skills to address emerging workforce needs in the areas of greenhouse gases (GHG) reduction and mitigation. A critical component of a national "green industries/ green/ energy jobs" effort is to motivate student communities and workforce to become proficient in STEM and associated manufacturing fields and trades, thus ensuring a 21st-century workforce. This senior design project engages students in the implementation of an innovative method for improving design and measuring energy efficiency[1-3]. Through this project, students learn how to provide a design method for evaluating the characteristics of green energy manufacturing.

The main objective of senior design courses in the engineering curricula is to bridge the gap between academic theory and real-world practice. Accordingly, the proposed senior projects should include elements of both credible analysis and experimental proofing as mentioned in ABET criteria[4]. The primary intent of this effort is to foster learning of class concepts and to impact the breadth of student learning (in terms of ABET outcomes "(2) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" and (6) "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions". The senior design project can serve as an excellent culminating experience in the program of study when it focuses on research and design projects that have practical value to consumers or to industry. For the Engineering Technology Department at Drexel University, the senior design course is a year-long educational journey (three quarters) that takes an idea generated by a student or an industrial sponsor and culminates in a product or project. This course is an excellent capstone experience, which requires both teamwork and individual skills in solving a modern industrial problem. Senior design projects in fall, winter, and spring quarters bring the students, faculty, and industrial partners together to see the student's results and to give them the additional experience of public presentation of their work.

The purpose of this paper is to describe a capstone senior design project involved in the environmentally conscious manufacturing[5]. The experience to improve industrial working environment and process costs in the project is discussed. The senior design project course is a 3-term core course usually taken by the students during their terminal year in the Engineering Technology Department at Drexel University. The design involves an educational effort that incorporates environmental consciousness in the senior design project. Several design approaches are pursued as part of the project for green energy manufacturing. The paper discusses the steps taken and apparatus used for performing design, assembly, and temperature control measurements of greenhouse. For the sake of comparisons for greenhouse design, experiments were conducted, including CO_2 measurement and efficiency analysis. A concluding section discusses the experiences from this project.

The goal of the project was to create a system to remove CO_2 from the atmosphere through DAC using a Polyethylenimine (PEI) membrane and to repurpose the captured CO_2. In particular, the project was focused on dissolving that carbon dioxide in water so that it could be used to feed an algae farm and aid in producing biofuel. Although the algae biofuel industry has taken off in recent years, algae farms often resort to buying CO_2. This CO_2 that is purchased is generally produced by methods that add to our global emissions problem. With the system, carbonated water is produced by taking CO_2 straight from the air which is not only better for the environment, but more cost effective. The offset of the industrial revolution and its CO_2 emissions has caused a problem that affects nearly all of life on earth; as a solution for this issue. The team has designed a device that will utilize solid membrane technology to adsorb CO_2 directly from the atmosphere and repurpose it for production of sustainable energy[6-13].

Background and Problem Statement

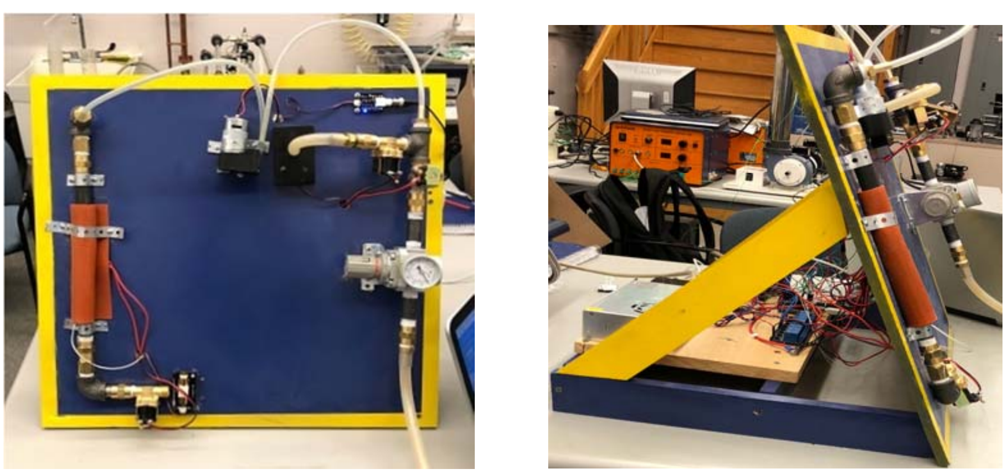
As the global population grows and the fossil fuel dependency increases, greenhouse gases continue to be a problem for the foreseeable future. This not only poses a problem to environment, but to health as well. With CO_2 levels rising, it is crucial to explore technologies that can help remove greenhouse gases from the atmosphere. Traditional modes of carbon capture such as pre-combustion and post-combustion CO_2 capture from large point sources only partially help to slow the rate of atmospheric CO_2 concentration increase. Large scale direct removal of CO_2 from the air, or direct air capture (DAC), on the other hand, can potentially have a much greater impact at reducing the global atmospheric CO_2 concentration. The filter technology is developed in the senior design project so that the CO_2 is removed as air passes over. When the filter is saturated, the system is closed and then heated which then releases the CO_2 to be compressed in tanks. Aside from use in biofuels, CO_2 has many uses in the society--from carbonated drinks to CO_2 bubblers for fish tanks. But current manufacturing methods of CO_2 produces even more CO_2 (and other harmful gases) in the atmosphere. The device can not only clean the air of excess CO_2, but it can also be an energy efficient source of CO_2 for industries that need it.

Design Process and Material Selection

The most important part of this project is the CO_2 capture material. Almost all large-scale commercial methods of CO_2 capture involve chemical solvents. It was found in a study that at a low working temperature (less than 200°C), the best adsorbents were the ones with high surface areas (porous materials). The carbon nanofibers and graphene nanoplates have impressive absorption rates at 16.36 mmol g and 56.36 mmol g, respectively. In particular, PEI impregnated silica had been first used for the purpose of filtering air in aircrafts[14]. The reaction with PEI that captures the CO_2 can be seen in the process, where the reaction between CO_2 and CH_2 forms to combine carbamate, and the addition of H_2O increases this binding ability by creating bicarbonate. In the design project, the H_2O was supplied by the humidity in the air. An experiment performed in 2011 provides an insight as to how to prepare PEI mixture. PEI alone is not efficient enough to capture CO_2 because of its low surface area[15]. The branched PEI received from Sigma Aldrich is a thick liquid material. Therefore, in order to increase the surface area, it had to be impregnated onto a porous material. The fumed silica was chosen so the porous material could be formed as filter for the senior design project.

Development and Testing of Prototype

A simple steel pipe was used to contain the PEI mixture. On the ends of the pipe, two micron filters were used to contain the filter material inside of the pipe. This pipe has a rated operating temperature of 177°C which is well above out 80°C heating requirement. This design is expandable because the team used fittings and pipes, and the option could be provided to expand the filter size indefinitely or to have multiple filters[16-20]. The prototype is shown in Figure 1.



(a) (b)

Figure 1. Prototype Design with (a) Front view and (b) Side view

The prototype device consists of one inlet and two outlets (one exhaust and one leading to a water tank). The inlet and outlets are all equipped with solenoid valves. Near the inlet and exhaust are carbon dioxide sensors that are constantly monitoring the concentration of CO_2. In between the inlet and outlets is a vacuum pump air compressor. The prototype design is a two-stage system: Adsorption and Regeneration. During the Adsorption stage, the inlet and exhaust solenoid valves are open and the vacuum pump is pumping air through the device. As the air moves through the system, the PEI mixture adsorbs the CO_2, and this can be confirmed by the CO_2 sensor readings; the inlet sensor continues to show a normal room concentration of CO_2 while the exhaust sensor shows less. Once the exhaust sensor reading climbs back up to the inlet sensor reading, the PEI mixture is saturated and no longer adsorbing CO_2. At this point, the Regeneration stage begins. The inlet and exhaust solenoid valves are shut, and the water tank valve is opened. The heater, which is wrapped around the pipe containing the PEI mixture, is turned on, and the mixture is heated to 80°C; this releases the adsorbed CO_2. A pressure gauge near the water tank can adjust the pressure at which the CO_2 is dissolved. The water tank is equipped with a pH sensor to ensure that the optimal pH is maintained for growing algae.

Prototype Materials

All of the items for the prototype were purchased from Amazon except for the PEI which was bought directly from Sigma Aldrich. For the container of the PEI, a threaded 1/2" by 12" steel pipe of specification ASTM A53^ASME B16.64 was used. The upper temperature rating of this pipe is 177°C. The maximum working pressure is 300 psi which is well above the intended pressure of 30 psi. Attached to both ends of this pipe are two micron filters to prevent the PEI mixture from escaping the pipe enclosure. The filters are 40 micron filters made of bronze. They have a maximum temperature of 150°C which is well above the regeneration temperature of 80°C. It is important to consider this because as the filter housing pipe is heated up, the attached micron filters will inevitably heat up as well. Teflon thread sealant tape was used throughout the prototype to ensure an airtight fit. For the heating system, a silicone rubber 8" x 8" heater was used. This heating pad can heat up to 180°C, and it was wrapped around the PEI mixture pipe using double-sided adhesive heater tape; this tape has a heat resistance of up to 200°C.

In order to pump air through the device, a 12 V vacuum pump air compressor was used. The pump can attain a maximum vacuum of -70 Kpa and maximum pressure of 250 Kpa. Additionally, it has the capability to work for 5 hours straight. The PEI mixture pipe is connected to the vacuum pump through a brass coupling followed by a 90 degree iron elbow, a 1/4" hose barb and a 1/4" vinyl airline tube which is connected to the vacuum pump. The vacuum pump leads to an iron tee fitting which branches off to two solenoid valves (one acting as the exhaust and other as the lead to the water tank). Three solenoid valves with high temperature (120°C) brass electromagnetic solenoid valves are used. These are normally closed, and they open when current is passed through, and they can handle a maximum pressure of 115 psi. In the water outlet portion of the device, a pressure regulator was attached through some brass couplings and 3" steel pipes. This regulator is made from die-cast aluminum and can regulate a range from 0 to 150 psi. Following the regulator, a 1/2" hose barb is used lead a hose to the water tank.

The pH sensor is an analog meter that is compatible with Arduino. It runs on 5 volts. It also measures from 0 to 14 pH with a response time of less than one minute. It works by outputting a voltage based on the pH level of the water. It was calibrated using a standard solution whose pH is 7 (distilled water). Near the inlet and exhaust outlet of the device are carbon dioxide sensors.

These sensors are crucial in analyzing whether the device is successful or not. For these two sensors, an analog gas sensor called the MG811 made by DFRobot was used. This was an electrochemical sensor that could detect CO_2 at room temperature at a range of 400 to 10000 ppm. This sensor works by using a highly CO_2 sensitive MG-811 sensor module as well as an onboard heating circuit that raises the temperature so that the sensor may function. As the CO_2 concentration decreases, the output voltage of this sensor increases, and the sensor has an onboard circuit that can amplify the output signal which makes it easy to perform a qualitative analysis.

During the testing process, it was found that the CO_2 sensors has to be changed. The MG811 sensors, which had a logarithmic scale output voltage to ppm conversion, were too erratic and had large shifts in value over time. Figure 7 shows the unstable values received from the sensors when attempting a baseline reading. Over 2 hours, the readings had a standard deviation of 62.3 ppm. It can be seen that this sensor was unreliable for the application. Because of this, Infrared CO_2 sensors were which had a much better stability.

The infrared CO_2 sensors were also made by DFRobot. The graph of Figure 8 shows the baseline for the infrared (IR) sensor. This sensor has a standard deviation of 5.65 ppm over an hour. Therefore, this sensor is better suited to work for the application. The only downside of the IR sensor has a slow response time of 120 seconds compared to the MG811 sensor which had a response time of about 1 second. The slow response time, however, does not adversely affect the device since the measurements are taken over long periods of time. Additionally, the IR sensor's range is half that of the MG811; it can only detect from 0 to 5000 ppm. However, this is not an issue for the device because the readings will stay well below 5000 ppm.

Mechatronics Engineering Design

The sensors, pumps, and valves of the project are electronically controlled and monitored using an Arduino Uno microcontroller interfaced with LabVIEW. The electrical set up is shown in Figure 9. The sensors include two CO_2 sensors, a current sensor, a pH sensor and a thermistor for temperature readings. All sensors, excluding the thermistor, require a 5 volt power source. All sensor outputs are connected into the Arduino's analog inputs and are then read by the program. The main power source comes from an AC to DC converter which takes the wall voltage of 120 VAC and rectifies it to 12 VDC with a maximum current of 30 amps. A 12 V power supply is used for Arduino, sensors, relays, valves and pumps. A current sensor will be placed right after the 12 V power supply and it runs in series to measure current. This sensor uses the Hall Effect to induce a voltage on a conductor based on the amount of current running through the circuit. Two CO_2 sensors have onboard heaters which draw more current than the Arduino can supply; to overcome this, the team incorporated a 5 V regulator with a heat sink. This drops 12 V coming from the AC/DC converter and supplies up to 1.5 A at 5 V which is more than enough to power those sensors. The Arduino also controls four relays from its digital outputs. The relays are active low and a grounding path is provided from the controller. The relays are opto-isolated from the Arduino—having the Arduino only turn on an infrared LED which then turns on a transistor to ground the relay coil. These infrared LEDs are the only load on the Arduino controller. The relays supply 12 V power to three solenoid valves and to the vacuum pump. The heater is being monitored using a thermistor with a paired 9.6k resistor which is monitored by a PID controller against the set temperature. It then outputs a PWM signal sent from the microcontroller to a MOSFET; this grounds the heater and thus turns it on until the temperature is achieved--at which point the duty cycle is reduced to maintain temperature. A wiring diagram of the setup is shown in Figure 2.

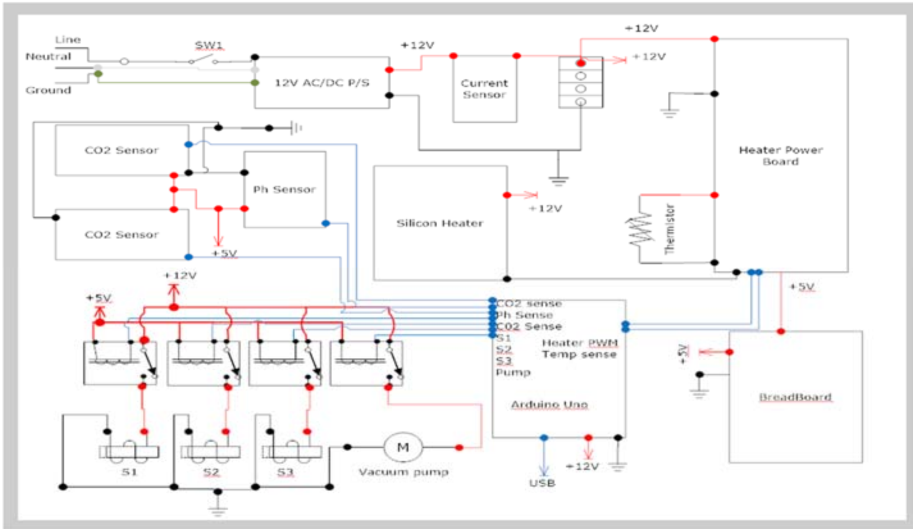


Figure 2. Electrical Wiring Diagram

Figure 3. LabVIEW front panel

Figures 3 shows the LabVIEW codes for the project. LabVIEW is used to monitor all the input sensors and to control all the outputs of the Arduino. The temperature is monitored by using a thermistor which was chosen due to its low cost and minimal need of additional components. The output is brought into the analog input. Then, using the Steinhart equation, the electrical signal is converted into a temperature data. This signal is then sent to a PID controller within the software which monitors the input of "Desired temperature" compared to sensor temperature. The error output of the PID is then sent out as a PWM value sent from a digital out pin to the heater MOSFET. The current sensor uses the Hall Effect to monitor current. The sensor has a zero-current offset at 2.5 V with sensor outputs 100 mV per 1 amp of current sensed. A PH Sensor is used to monitor the water pH level. The goal is to maintain a water pH conducive to algae growth. The PH sensor has an output between 0-4 V, which is then multiplied by 3.5 to convert the voltage to PH level. An offset can be applied through addition or subtraction from the value, and the offset can be found by measuring the output while the input is shorted; the resulting voltage will be the zero offset.

The LabVIEW front panel contains two graphs for monitoring intake CO_2 (ppm) and output CO_2 (ppm). Next to the graphs, it can be seen whether the sensors are ready, preheating or showing an error. Additionally, the front panel shows indicators to monitor current, power, pH level, and heater temperature. It also has a control box where the desired temperature can be typed in and controlled. Another feature it has is that it contains four buttons represented as toggle switches; these are for turning on and off each valve as well as the vacuum pump. As a fully automated process, the device can adsorb CO_2, sense when the PEI material is saturated, shut and open the appropriate valves, begin the Regeneration stage, sense when all the CO_2 has been released by the PEI mixture, and repeat the cycle continuously.

Experimental Results

The experimental results are shown in Figures 4 through 7. Two different concentrations of PEI were tested; one mixture with 33% PEI and one with 50%. For the 33% percent mixture, during the desorption period, it showed a significant increase of CO_2 output which confirms that this material can release the capture CO_2.

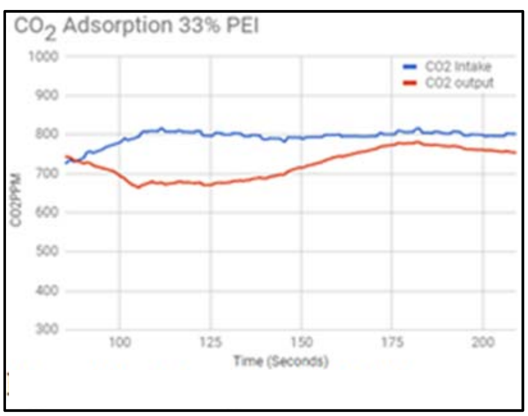


Figure 4. Adsorption at 33% PEI

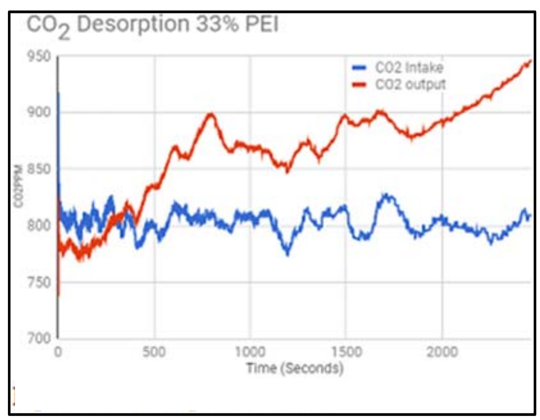


Figure 5. Desorption at 33% PEI

The adsorption phase shows a decrease in the CO_2 level between the two sensors which confirms that the PEI mixture is adsorbing CO_2. This adsorbing phase proved to be much slower than the previous research results - the CO_2 concentration should have dropped close to zero very sharply during the adsorption phase. From the results, it was found that the experiment can only have about a 100 ppm drop in concentration during adsorption. This can be due to many factors, such as sensor placement or flow rate; it is possible that the flow rate was too fast which did not allow the PEI to fully adsorb the CO_2 from the air before it left the membrane.

For 50% mixture, similar results were found. One difference, however, is that with the desorption phase, there is a much sharper increase in the output than with the 33% mixture. This is closer to what was expected to happen during the desorption process. As time progressed forward, the CO_2 concentration steadily drop as the PEI finishes releasing the CO_2. For the adsorbent phase of the 50% mixture, a drop in CO_2 concentration is similar to 33% mixture of around 100 ppm. Again, many factors could attribute to this slow adsorption rate such as flow rate, sensor placement etc. Overall the device did perform the function of adsorbing and desorbing CO_2. The next steps would be to overcome the hurdles presented and have the device performing in a similar way to how studies have shown PEI to work.

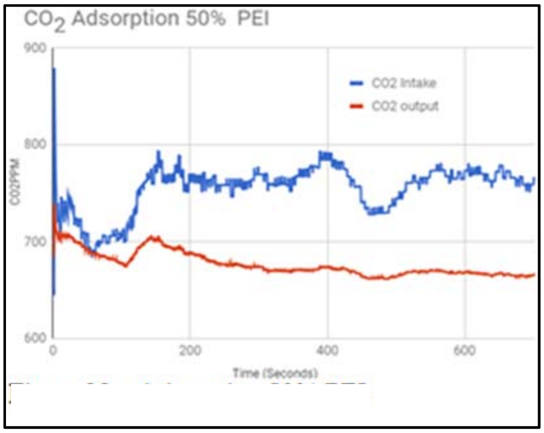


Figure 6. Adsorption at 50% PEI

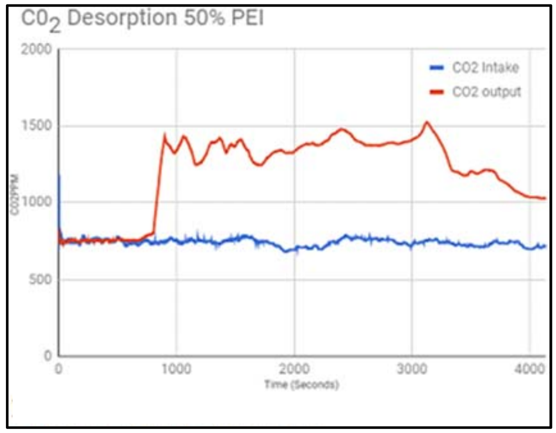


Figure 7. Desorption at 50% PEI

Conclusion

The project begins by defining a performance problem associated with applications and ends with a prototype for a green design solution. The problem drives the learning required to complete the project. Managing the project requires the students to demonstrate effective teamwork, clear communication and the ability to balance the social, economic and environmental impacts of the project. The prototype has been created as a two-stage device that adsorbs CO_2 from room temperature and pressure conditions, and then regenerates the CO_2 through the use of heat and a vacuum. Through the use of Arduino and LabVIEW, while CO_2 sensors, the current usage and power are monitored, the heater, vacuum pump and solenoid valves are controlled. Additionally, the overall design can be improved to produce better data. To summarize, this device is a fully automated device that can capture and repurpose CO_2 from room temperature and pressure conditions. The design completed herein will also contribute vastly to the Drexel community at large as it can be used to demonstrate renewable energy systems to students for years to come.

Acknowledgement

This work has been supported by the US Department of Education under the joint DHSIP Program with the University of Texas at El Paso, PR/Award No.: P031S120131. The authors wish to express sincere gratitude for their financial support.

Bibliography

1. Scientists Say Climate Change Efforts Must Go Beyond Reducing Greenhouse Gases. http://us.cnn.com/2017/11/29/world/climate-change-geoengineering/index.html
2. ASEE Public Affairs, Saturday, July 29, 2017, Capitol Shorts: Biofuels Debate; Senate R&D Priorities; HBCU Funding and More, https://www.asee.org/papers-and-publications/blogs-and-newsletters/capitol-shorts-newsletter
3. "Gasoline and Diesel Fuel Update," (U.S. Energy Information Administration, 2012), http://www.eia.gov/petroleum/gasdiesel/. Annual averages were calculated using weekly U.S. regular conventional retail gasoline prices.
4. Criteria for Accrediting Engineering Programs, 2019 – 2020, https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/
5. Ashutosh Gupta, William Brown, Tochi Ehirim, and Tanvir Khan, "Direct Air Capture of CO_2 Using Polyethylenimine Membrane," Senior Design Project III, XXXXXX, MET – 423 – 601, 2017 – 2018.
6. Advanced BioFuels USA » NASCAR Uses Sunoco Fulton Ethanol. https://advancedbiofuelsusa.info/nascar-uses-sunoco-fulton-ethanol-facility-for-race-fuel/
7. Biofuels Digest, December 8, 2017, http://www.biofuelsdigest.com/bdigest/tag/sunoco/
8. "Biofuel," Merriam-Webster, 2012, http://www.merriam-webster.com/dictionary/biofuel.
9. Wikipedia, "Algae Fuel," Wikimedia Foundation, 7 Oct. 2017, Accessed November 2017. en.wikipedia.org/wiki/Algae_fuel.
10. Business Insider, "CO_2 European Emission Allowances PRICE Today | Price of CO_2 European Emission Allowances and Chart," 14 Nov. 2017, markets.businessinsider.com/commodities/co2-emissionsrechte.
11. Carbon Engineering, "Direct Air Capture," http://carbonengineering.com/about-dac/. Accessed 20 Nov 2017.
12. Eisenberger, Peter. System and method for carbon dioxide capture and sequestration. U.S. Patent 13,098,370 filed April 29, 2011, and issued August 6, 2013.
13. Wikipedia, "Emissions Trading," Wikimedia Foundation, 14 Nov. 2017, en.wikipedia.org/wiki/Emissions_trading.
14. Goeppert, Alain, et al. "Carbon Dioxide Capture from the Air Using a Polyamine Based Regenerable Solid Adsorbent," Journal of the American Chemical Society, vol. 133, no. 50, 2011, pp. 20164–20167., doi:10.1021/ja2100005.
15. Goldman, Joel C.; Porcella, Donald B.; Middlebrooks, Joe E.; and Toerien, Daniel F., "The Effect of Carbon on Algal Growth--Its Relationship to Eutrophication" (1971). Reports. Paper 462. http://digitalcommons.usu.edu/water_rep/462.
16. Irfan, Umair. "New, Reusable Materials Could Pull CO_2 Straight from Air," Scientific American, 6 Jan. 2012, Accessed November 2017. www.scientificamerican.com/article/new-reusable-materials-pull-co2-from-air/.
17. New Mexico State University, "New Material Captures Carbon Dioxide with High Capacity," Phys.org - News and Articles on Science and Technology, 4 Mar. 2015, Accessed November 2017. phys.org/news/2015-03-material-captures-carbon-dioxide-high.html#jCp.
18. Rendón, Sebastián Mejía, et al., "Effect of Carbon Dioxide Concentration on the Growth Response of Chlorella Vulgaris Under Four Different Led Illumination," International Journal of Biotechnology for Wellness Industries, vol. 3, no. 3, 28 Oct. 2013, pp. 128–130.
19. Wang, Junya & Huang, Liang & Yang, Ruoyan & Zhang, Zhang & Wu, Jingwen & Gao, Yanshan & Wang, Qiang & O'Hare, Dermot & Zhong, Ziyi. (2014). Recent Advances in Solid Sorbents for CO_2 Capture and New Development Trends. Energy Environ. Sci.. 7. . 10.1039/C4EE01647E.
20. Yue, L., and W. Chen. 2005. Isolation and determination of cultural characteristics of a new highly CO_2 tolerant fresh water microalgae. Energy Conversion and Management 46(11-12):1868-1876.