Machine vs. Nature: Carbon Capture

A Major Qualifying Project Report submitted to the Faculty of the Chemical Engineering Department at

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the Degree of Bachelor of Science

By:
Makayla Carmichael
Isabella Piccione

April 28, 2022

Approved by:

Professor Kristin Boudreau (Advisor)
Professor David DiBiasio (Advisor)

Acknowledgements:

Stephen Kmiotek
Doug White

Abstract

With the curriculum given in the chemical engineering major primarily focusing on reiterating theory, it is important that students also obtain an understanding on how to utilize their knowledge to help the betterment of people in crisis. To do so, integrating humanitarian principles into the current curriculum should be looked into and tested. The project team developed new curricula that can be implemented into the existing curriculum given for the current Unit Operations Laboratory course. In doing so, the team was able to successfully integrate humanitarian principles into the current curriculum, allowing students to utilize the engineering principles taught to solve a real world crisis that is currently happening today.

Table of Contents

Introduction

As global warming has become an increasingly relevant topic of interest and debate in the political sphere, the causes of said phenomenon have been put into question with the legitimacy being debated as well. It has been determined that a substantial contributor to global warming would be the excess CO_2 being released into the atmosphere, as a result of industries and production. This excess CO_2 negatively impacts the Earth as it increases the planet's average temperature by trapping in greenhouse gasses and disrupts the production of food crops. The increase in temperature results in the number of severe storms and drought increasing and becoming more frequent. As the temperature changes causes changes in rainfall which drastically affects food supply and also causes severe natural disasters such as floods and mudslides, which poses new hazards to different communities (Denchak 2022).

In response to this, engineers have created different processes which remove CO_2 from the air to help lower the total amount of atmospheric carbon. One process created is Direct Air Capture (DAC) which directly captures CO_2 from the atmosphere ("Direct Air Capture Technology"). The resulting CO_2 would then be compressed into a more pure form in which it can safely be stored permanently underground, this method however is expensive to produce on a larger scale and does require some large scale funding ("Direct Air Capture Technology"). Another option would be CO_2 plants that take in CO_2 emissions from a production plant nearby and pump it into correlating green houses that produce food for the local communities ("Ice On Fire", 2019). This process however requires an industrial plant that produces large amounts of CO_2 followed by heat to allow the plant to run ("Ice On Fire", 2019). This poses some problems in relation to producing these on a larger level, while it does take in 5% of all of Earth's atmospheric CO_2 it is not plausible to mass produce more of these plants due to all the associating constraints ("Ice On Fire", 2019).

A more natural option for absorbing CO_2 would be carbon sinks, which are different environments located throughout the world that naturally are able to store excess CO_2, some examples would be boreal forests, mangrove forest, and peat lands. All of which are able to store an ample amount of CO_2 into the ground and help lower the total amount of atmospheric carbon present. There are many protection groups that work in order to help protect and restore these carbon sinks thereby helping the nearby communities. The Mangrove Action Project (MAP) is one group that is based in the US and is working to restore mangrove forests globally. They aim to provide educational resources and funding to nearby communities to ensure that they are equipped with the proper resources to restore these environments back to a healthy state. Within this, it is important to note that normal engineering curriculum often does not discuss humanitarianism nor the importance of said subject. Our project introduces the work of the MAP to students through the use of an engineering design project in order to show

how the work done as chemical engineers can heavily impact the communities that reside in these locations.

With how viable mangrove forests are, it is to be believed that they would be a more feasible alternative compared to the aforementioned methods. While mangrove forests only absorb about 3.56×10^{-11} kg/yr of all of Earth's atmospheric CO_2, they are natural and provide resources back to the correlating communities that inhabit them including food and freshwater. Due to this, it is believed that mangroves would be more effective in solving the problem given above compared to industrial CO_2 plants. As mangrove forests do not require any major costs, equipment, nor do they negatively impact the land. This study aims to look at the effectiveness of mangroves in relation to absorbing atmospheric carbon, while subsequently comparing a natural carbon absorber to a man-made one in relation to how they would affect the nearby communities.

Background

Mangroves are an important ecosystem that can be found all around the world as they are able to give back to the communities that inhabit them. They offer a wide variety of species that creates a grand amount of biodiversity, which in turn allows for the local communities to utilize the mangroves for an abundant amount of resources as well. While mangroves offer resources to the local communities they also help with carbon sequestration and oxygen production, as mangroves are able to act as natural carbon sinks.

Mangroves and the Community

Mangroves can be found in a total of 123 different countries, and are able to generate up to $1.6 billion yearly in a variety of ecosystem services and supporting the local coastal communities. With mangroves being able to provide the communities with raw materials, food, coastal protection, soil erosion, water purification, fishery maintenance, and education (Constanza, 1997. Barbier,2011.). In addition to that mangroves also provide non-material resources to the communities such as spiritual enrichment, cognitive development, and reflection (MEA 2005a.).

Based on a study conducted in Cumbe, which is located along the coasts of the Jaguaribe River in Brazil, researchers collected data pertaining to the Cumbe community which homes over 500 individuals whose livelihoods are dependent on the local mangroves (Queiroz et al. 2017). This study shows that the local Cumbe community developed and practices a traditional system of natural resources management through a mutual respect and complicity towards nature, while also holding strong economic and symbolic ties to the land they inhabit (Queiroz et al. 2017). The study concluded that mangroves should be conserved and restored as there are communities that rely on them both in the material aspect and spiritual aspect, while also being able to profit off of them without harming the mangroves.

Mangroves and Carbon Capture

As mangroves are able to capture, transform, and store CO_2 from the atmosphere, they have become an increasing topic of interest when referencing climate change and global warming. This is because many people believe that they can help regulate the carbon cycle and help the world slowly become carbon neutral (Zhu & Yan 2022). This is because mangroves are known to be one of the most carbon-rich ecosystems on the planet, being estimated to be able to store up to 20 gigatonnes of carbon. (Gao et al,. 2016). With mangroves being a coastal ecosystem, they are able to sequester carbon to two different adjacent systems, with the ocean being able to convert the carbon into sediments called humus, which then further removes carbon from the present carbon cycle.

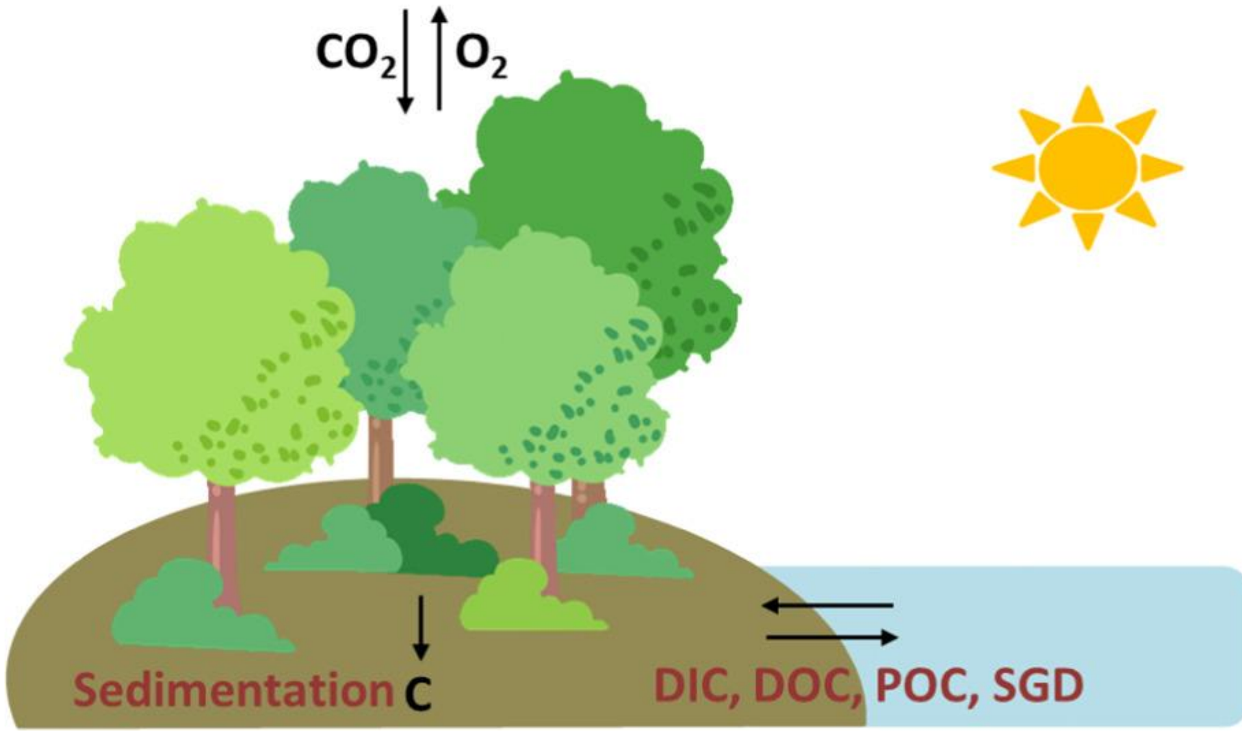


Figure 1 *: Diagram of carbon sequestration of a mangrove, with DIC standing for dissolved inorganic compounds, DOC for dissolved organic carbon, POC for particulate organic carbon, and SGD for submarine groundwater discharge (Zhu & Yan 2022)*

As mangroves account for about 1.4×10^7 hectares of land globally, it can be estimated that each hectare of forest can capture around 1000kg of CO_2 while producing about 730kg of O_2 a day (Wang et al., 2021a)(Xie and Zhou, 2005). While in turn the amount of carbon that the sea can sequester is affected by changes in water depth, salinity, and flooding time (Zhu & Yan 2022). A study conducted by Rogers et al. in 2019 in New Caledonia noted that the turbulence and water level changes directly affected the amount of carbon flux happening within the system, as the study showed that the amount of carbon storage increases 1.3 to 3.7 times in relation to the changing tides compared to areas with constant sea levels. With the same study showing that long term tidal flooding is also able to enhance anaerobic conditions in the soil which in turn allows for more organic carbon accumulation in the soil.

With mangrove systems storing carbon in either the soil or large underground dead root pools (Swangjang and Paniskhan 2021). The high carbon sequestration that mangroves are known for can be reflected in the burial rate of the sediments and exchange of dissolved carbon seen throughout the system (Lovelock and Duarte 2019). With one study conducted by Alongi and Maukhopadhyay in 2015 finding that there exists a positive relationship between carbon burial and sediment accumulation rate present in mangroves, as the amount of sediments present in the Leizhou Peninsula was 9.1-25.0 mm per year which is higher than the world average of .1-1.0 mm a year. This in turn shows how much more carbon a mangrove is able to sequester versus other ecosystems as the sediments made are from the carbon sequestered from the atmosphere. With these numbers showing that the amount of carbon sequestered is about 50 times greater compared to other tropical forests (Sandilyan and Kathiresan, 2012). With another research showing that mangroves could reduce the total amount of CO_2 in the atmosphere by a total of 7% (Nellemann et al.,2009).

Carbon Capture and Sequestration

Climate change and global warming are two important topics of interest that relate back to one another and are gaining relevance in the political sphere. With climate change relating back to long-lasting and irrevocable shifts in weather conditions and patterns and global warming relating back to the increased amount of trapped greenhouse gasses which in turn increases the world's temperature. With one of the main fears of global warming being the increased sea levels, and the main fears of climate change being the more frequent and intense storms. As the two topics are related the causes for the two are believed to be connected as well, one cause that's been unanimously agreed on would be the increase of carbon dioxide in the atmosphere, which is caused by the increase of population and technology. One proposal to counter the increase of carbon dioxide in the atmosphere would be carbon capture.

Carbon capture and storage refers to the process of capturing carbon dioxide from major emitters, usually from industry, and storing the sequestered carbon dioxide at a given storage site, which in turn prevents the carbon dioxide from re-entering the atmosphere (Nanda et al., 2016). This process costs on average about $40 for every ton of CO_2 that is being separated and compressed before the emissions enter the atmosphere again (Nanda et al., 2016). With there being three main categories that carbon storage can follow; biological, physicochemical, and geological (Nanda et al., 2016). With the physicochemical process being the most popular when storing industrial gas streams, as the process involves applications of absorption, adsorption, gas separation membranes, and cryogenic distillation (Nanda et al., 2016).

The process of carbon dioxide capture occurs in three ways; postcombustion, precombustion, and oxy-fuel combustion(Nanda et al.,2016). With the postcombustion process being able to capture CO_2 directly from the flue gasses being emitted as fossil fuels are being combusted for power(Nanda et al., 2016). Compared to precombustion and oxy-fuel combustion which both have prior steps that need to be done before any carbon can be captured.

Depletion of Mangrove Forests

Mangrove forests are at risk of depletion due to the rising effects of global warming and excess human consumption. As mentioned earlier, mangroves are important fixtures in communities, providing ecosystems for aquaculture, materials to convert to biofuel, and fertile land for rice paddies.

Due to lack of federal protection of mangrove forests, massive deforestation has occurred for the cultivation of seafood and logs for burning. In the Mekong River Delta in Vietnam, 70% of the mangrove forests have been converted into shrimp farms (Truong and Do, 2018). This expansion is well above the listed allowance of 20-40%, showing poor enforcement of ecosystem protection policies. In Ayeyarwady, Myanmar, charcoal derived from mangroves is a key source of income for villagers, leading to an over 20% decrease of mangrove land mass in just a 10 year period (Veettil et al., 2018). In Rakhine, Myanmar, the Wunbaik Reserved Mangrove Forest has experienced a 40% degradation from expansion of rice paddies, in addition to shrimp farming and logging. In all these cases, practices of unsustainable production methods are contributing to massive decrease in land mass of mangrove forests.

Additionally, worsening weather conditions are testing the strength of mangrove forests and leading to irreversible damage. One benefit of mangroves forests is the protection they provide to the communities surrounding them to natural disasters and the rising water levels caused by such. However, increasing frequency and intensity of weather phenomena like cyclones and monsoons, combined with the thinning of mangrove forests, has caused great damage to the mangroves and is leaving coastal communities more exposed. The Food and Agriculture Organization of the UN attributed the over 100,000 fatalities caused by Cyclone Nargis in Myanmar to the destruction of mangroves (Veettil et al., 2018). As mentioned earlier, a 20% decrease in mangrove coverage in Ayeyarwady has left coastal communities without protection from cyclones, and the resulting fatalities show the importance of this protection. In 2016, a study was performed in Brazil to observe the impact of hailstorms and changing weather conditions on Mangrove coverage. After a particular hailstorm in June 2016, over the course of one year, degradation of 29.3% of conserved Mangrove area was seen (Servino et al., 2018).

The effects of global warming and human consumption trends are doing immense damage to mangrove forests across the globe, and we must work fast to save them.

Mangrove Forest Remediation Methods

There are several organizations taking action to restore mangrove forests through different methods. The Mangrove Action Project (MAP) is a non-profit based in the U.S that aims to rehabilitate mangroves through their “Community-Based Ecological Mangrove Restoration” (*CBEMR Mangrove Restoration,* 2021). In this method, the mangroves of the focused area are studied to determine what caused their degradation, and then the local ecology is studied to determine which species could be replanted and thrive in this specific environment, to ensure little to no failure in new plant growth.

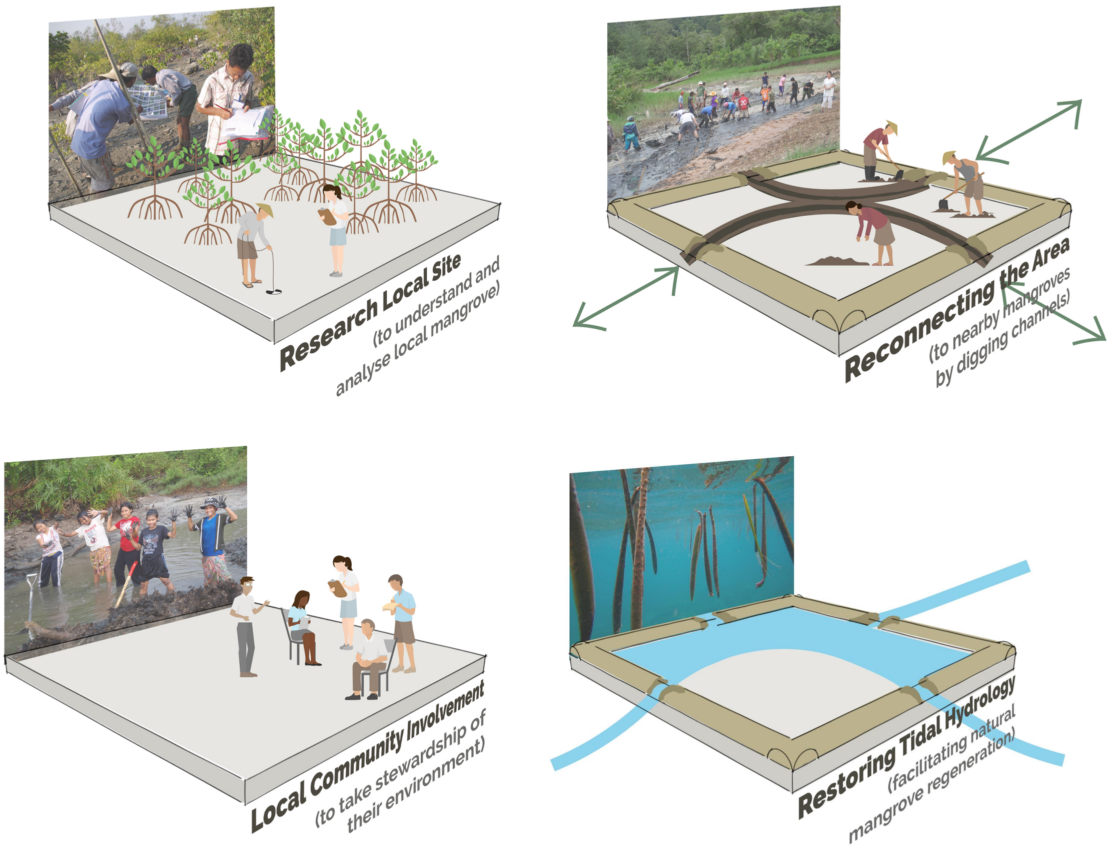


Figure 2. *Steps of the CBEMR Method of Mangrove Restoration*

The MAP works with the local communities not only to help with this restoration, but also provide education to allow for continued restoration and creation of jobs once they leave their focused area. In 2010, the MAP provided resources and help for the El Llorón mangrove patch in El Salvador, and over the course of 7 years a significant increase in forest coverage was observed (Ahern, 2020). In the photos below, the green tree coverage begins to fill in the tan barren land, showing this regrowth in mangrove foliage.

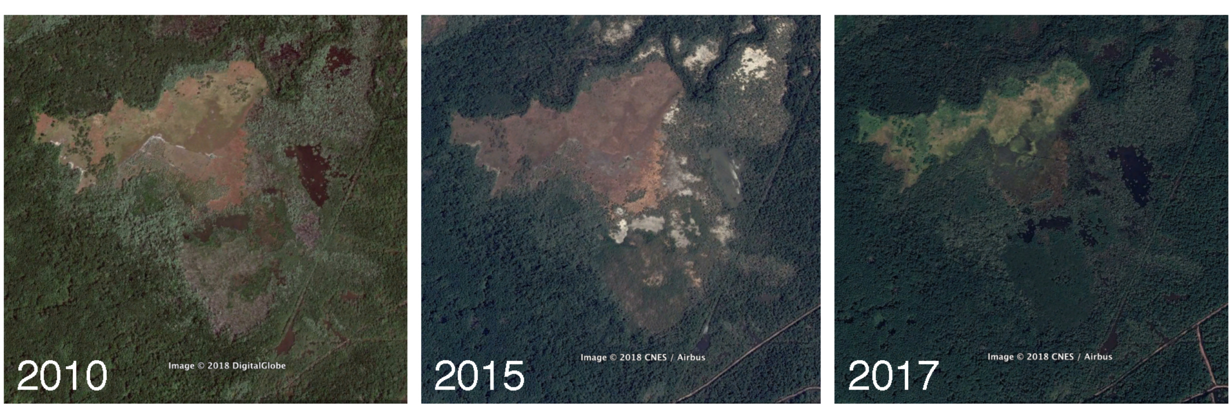


Figure 3. *Mangrove Coverage increase in El Llorón mangrove patch, El Salvador*

Another organization working to restore mangroves is the United Nations, with their Communities of Ocean Action initiative in support of Sustainable Development Goal 14 (SD-G 14). SD-G 14 is a goal created by the Department of Social and Economic Affairs at the United Nations that aims to “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” (United Nations, 2015). There are nine communities they wish to focus on restoration of, and mangrove forests are one of them; their methods include replanting and implementing protection policies. Through voluntary recruiting of countries to participate, they have replanted over 100,000 hectares of mangroves in Guanaja, help Fiji’s government to develop at “Integrated Coastal Management Plan” that places protections on usage of mangrove areas, and encourage Indonesia to expand their conserved wetlands to 20,000,000 hectares, including mangroves (United Nations, 2019).

There are many methods to conserve and remediate mangrove forests, and these organizations mentioned are just a few of many groups that are fighting to save these important ecosystems.

Mangroves and Humanitarian Engineering

The restoration of mangroves is not only a scientific issue, but a humanitarian issue. The methods developed to save these ecosystems are developed out of the necessity to save the communities surrounding these ecosystems; not only is the health of the trees involved, but also of the people living in the communities. In order to bridge the gap between the humanities and STEM fields at WPI, this project introduced humanitarian engineering to chemical engineering students through mangrove remediation.

Humanitarian Engineering can be defined as “(the) application of engineering skills or services for humanitarian aid purposes, such as disaster recovery or international development” (Campbell and Wilson, 2011). Traditional engineering education is generally focused on coming up with a singular solution to a problem, with a focus on high-tech innovation and exclusively considering technical solutions. However, real-life solutions usually contain both technical and non-technical parts, and there are many solutions possible for a single issue. Additionally, the emphasis on high-tech ignores the barriers that can prevent the usage of this technology, including economic restraints (Arshad-Ayaz et al., 2020). Many communities surrounding mangrove forests are not equipped with the materials, education, and finances to implement expensive high-tech solutions to restore their forests (*CBEMR Mangrove Restoration,* 2021). However, the most successful methods of remediation of mangroves do not require intricate technology, but rather work to provide education and easy-to-replicate planting methods. Through developing their own restoration method of mangroves, using both engineering knowledge and integrating humanitarian knowledge, students will hopefully learn to understand the immense value of humanitarian engineering to our field.

Approach

The intended focus of our project was to integrate humanitarian principles into pre-existing chemical engineering curricula at WPI. In order to achieve this goal a preliminary plan was created with the following steps outlined below:

1. Look for courses in the WPI Chemical Engineering department with subject matter pertaining to humanitarian crises
2. Research and develop our curricula material

Exploring WPI Chemical Engineering Courses

The chemical engineering department at WPI offers a multitude of courses, and it was important to find one that both opened the door for further exploration into humanitarian crises but also wouldn't be too overly changed by this addition. The Unit Operations lab sequence was chosen for its hands-on approach to learning, and its senior level material. Picking a lab-heavy course was ideal in order to allow us to add a reading and writing based assignment without it becoming overbearing and provide contrast to the coursework. Additionally, picking an advanced level course rather than an entry level one ensured we could delve into complex topics such as direct air capture technology and it being better understood by the students, as well as being able to increase the course load without much pushback.

The Carbon Absorption experiment in Unit Operations 2 was the chosen experiment to alter. The main goal of the lab is to observe the effects of changing flow rate on gas absorption into solvent, the solvent being water and absorbent being CO_2 (Abu-Lail). This lab discusses the field of climate change remediation technology, and how factories lessen their carbon footprint by pulling carbon out of their effluent gas streams; however, the lab does not explore this topic much further than using it as the introduction to the laboratory experiment. We decided to use this introduction as a stepping stone to creating a humanitarian element for this experiment. Climate change is both a humanitarian and technological crisis that affects everyone, more so less privileged areas and peoples. Its prevalence in our society and existence in the lab already is what led to us choosing it as the topic of our humanitarian addition in the chemical engineering curricula at WPI.

Researching and Development of Curricula

As students, we have extensive experience with assignments and the formatting of educational material. However, being put into the shoes of the educator and tasked with writing that material was a new skill that we had to become better acquainted with. When researching courses to choose as our focus, we made sure to pay close attention to the wording of these assignments, as well as drawing on our own experience with classes we've taken. Additionally, we had to find the specific focus of our assignments, beyond the broad topic of climate change technology. In order to draw in students' attention, we searched for an ecosystem in danger that provides great benefit to communities and our planet as a whole.

Whilst rummaging through past project assignments we completed as part of chemical engineering courses, we looked for those that particularly blended a research and writing component with a technological aspect. The Titan II Missile Accident assignment from ChE2014 Advanced Chemical Processes and the Cameroon Renewable Energy project from ChE2012 Elementary Chemical Processes stuck out as projects that understood this balance well. In the Titan Missile assignment, in addition to producing calculations to quantify the fuel leak that occurred at the Titan Missile site, students were tasked with researching other large scale chemical accidents and writing an analysis of them. Looking into accidents beyond the main one we were focusing on gave real world context to the frightening reality of the dangers of working around chemical equipment, and drove home the idea of practicing safety protocols to avoid these accidents that are more common than we think (DiBiasio). The Cameroon Renewable Energy project involved developing a pilot plant in Cameroon, Africa, to convert palm sugar into ethanol. The unique aspect of the project that led to us using it as a reference for our material was the role-playing aspect. Students were tasked with researching roles in the organization planning to build this pilot plant, and their responsibilities for the project, and write an analysis (Zurawsky et. al, 2019). This allowed us to better understand the real-world application of our skills we're learning into jobs in industry, and how we can utilize them on projects in the future.

The common denominator between these two assignments was the research and writing aspect. By making us look past the provided material and do our own research, we were able to assign faces and roles to these projects and give them more depth and see them beyond the classroom, and potentially inspire us to do our own independent research into these ideas. For our assignment, we wanted to give students this same feeling and opportunity to spread their wings and become better acquainted with the topic beyond just our educational material, though we hope that serves as an adequate resource.

We chose mangrove forests as our focused ecosystem for the assignment because of their importance to the Earth as both a carbon sink and as a resource to communities. Carbon sinks are naturally occurring carbon capture machines, essentially, and we felt they would lend themselves nicely to the technical side of the assignment. Additionally, they touched on the humanitarian aspect by being an important resource for communities in terms of food, economic growth, and protection from harsh weather conditions, and mangroves being threatened by climate change puts these communities in harm's way. We hope by pushing students to address this side of the climate crisis they can look beyond the lab experiment and understand how impactful their work can really be to the planet and people in need.

Results

The culmination of our research led to the development of three new goals that can be implemented in the current carbon absorption lab. With the original goals of the lab being heavily theory based compared to the more environmentally based introduction given, the developed goals incorporate the intended humanitarian principles while also referring back to the equipment and engineering principles that the lab already utilized. A final experimental packet was created that inhabited both elements from the original carbon absorption lab and the aspects developed over the course of this project. The three goals developed each have a different primary principle they focus on, which can be seen as:

1. Chemical Engineering
2. Design
3. Humanitarian

Chemical Engineering

One of the original goals from the lab asked students to observe the effects of gas and liquid flow rates in relation to the overall mass transfer coefficient. Students are then tasked to calculate the overall mass transfer coefficient of carbon dioxide in reference to a determined gas flow rate and water flow rate. The new goal developed intends to ask students compute a variety of absorption rates, that are still close in value to the flow rates they are able to witness in lab, in relation to a given time frame over a period of thirty minutes, the values given can be seen below:

Mock Tidal Flow Rates

Time (min)	5	7	3	4	2	6	3
Flow Rate (L/min)	5	2	7	6	0	2	8

Table 1. *Given flow rates for students to utilize to observe the theoretical effect of tidal waves*

This is done to mimic the unsteady flow of tidal waves that naturally occur out in mangrove biomes. From there the students will then be asked to compute the overall mass transfer coefficient and compare it to the one they calculated from the column. In doing so students are able to see how mangroves can be an effective alternate carbon sequestration method.

Design

The original design problem given asks for the student to determine the outlet vapor and liquid compositions for a given absorption process. In order to integrate humanitarian principles but still keep the design basis, students are asked instead to calculate an absorption column's parameters based off of the absorption rate of a mangrove tree. However, after test calculations were done it was determined that the absorption rate given for a tree is not large enough for a proper column, and instead results in parameters that are not realistic. Due to that, the absorption rate of a tree was altered in order for design calculations to produce more realistic parameters. The design question guidelines can be seen below:

1. A single tree can absorb 12.3 kg/yr of carbon dioxide, for the purpose of this lab however we will say it absorbs 12.3 kg/min of carbon dioxide.
2. Water flow rate is 4.6gpm
3. Gas flow rate is 100 cfm, with a .04 wt% of CO_2

As a mangrove biome faces many unstable conditions, to accurately depict a mangrove tree as a column the given guidelines values developed for the gas composition is done to mimic the atmosphere. All of the flow rate values given are values that the column is able to operate at and were chosen at random.

Humanitarian

For the humanities aspect of this assignment, students will be tasked with researching a community that benefits from mangrove forests in any form. In our own research into organizations that are working to save mangroves from depletion due to climate change effects, we were introduced to so many coastal communities with a deep connection to these ecosystems and a strong desire to save them from worsening conditions. Students will be provided with a robust collection of articles, websites, and videos to serve as reference for strengthening their understanding of mangroves' place in the world as a priceless resource to our environment and the people living in it. With the addition of these resources, students will be required to do their own research, focus on a particular coastal community, and write a 500-word piece that "Determine(s) how they utilize mangroves in day-to-day life, if climate change has affected that reliance, and if any steps have been taken to remediate the forests" (Carmichael & Piccione, 2022).

In terms of educational material produced for this, in addition to the experimental packet students will receive, they will also be provided with a master document linking multiple articles and scholarly journals that address the political implications of mangrove protection and organizations working to remediate mangroves. Climate change protection has become a politically controversial matter, and it would be unfair to ignore that aspect of climate change technology and the fight to preserve the ecosystem. There are many prominent organizations that solely focus on remediating mangrove forests, and we have highlighted some like the Mangrove Action Project, Mangrove Together, and United Nations Ocean Action Initiative in the master document, but we also will encourage students to find more on their own and look into their impact.

We have also created two short educational videos that quickly address mangrove forests benefits to the earth and how they're in danger of depletion. Students will watch these videos whilst reading the initial experimental document to give a short rundown of the topics at hand. They were created using the software Animaker, and run at around 1 minute each. The first video is titled "Mangroves and their Benefits," where we explain what mangrove trees are, where they are located, how they act as carbon sinks, and how they're beneficial to the communities that surround them. The second video is titled "Mangroves are in trouble?" In this, we highlight the effects climate change has had on the forests, what this may mean for the communities surrounding them, how they can be remediated, and who is taking action.

Figure 4. *Screenshots from "Mangroves and their Benefits" video*

Figure 5. *Screenshots from "Mangroves are in Trouble?" video*

Discussion and Conclusions

As the goal of this project was to integrate humanitarian principles into the current chemical engineering curriculum offered it is important that the developed curricula is able to merge well with the curriculum of the class. The team believes that there is a great value in incorporating these principles into the current curriculum given, as students should learn how to use their knowledge to better help the world. As the team executed this goal and created three new goals to be implemented in the current carbon absorption lab, it should also be stated that improvements can be made for further development and integration of humanitarian principles into the chemical engineering curriculum.

Improvements

The curricula developed should execute this goal well, however there was no testing outside of the project team. Due to this, there is no feedback that can be used to further improve the new curricula the team developed. For further research and development, any newly created curricula should be given to students who have either completed the given class already, or have taken the proper supplementary classes. By doing so, the students are able to give feedback on the new material allowing for alterations and improvements to be made.

The team faced issues when creating a design problem to accompany the experiment and humanitarian writing assignment. We recommend future groups make another attempt at adapting the current design project included in the original experiment, and making it fit the topic at hand.

With the given courses in the chemical engineering curricula offered, the team also believes that it would be possible to integrate humanitarian principles into more courses given. For future research the team believes that incorporating humanitarian topics into some of the other core classes, such as the sophomore year chemical engineering sequence that all chemical engineering students are required to take, would also be beneficial.

We believe that incorporating and including humanitarian curricula that is relevant in both the unit operations lab course and the plant design course could also prove to be useful as these classes are taken in tandem to one another. Therefore having curricula that can be utilized in both classes helps strengthen the theory learnt in one course to the equipment and processes executed in the other. As this project integrates humanitarian concepts into unit operations labs, researching and experimenting how to integrate said concepts into the plant design class could also be looked at.

References

Abu-Lail, L. (n.d.). (rep.). Gas Absorption in a Packed Tower (pp. 1–12). Worcester, MA.

Ahern, A. L. (2020, March 13). *Mangrove Restoration Beginning to Bear Fruit*. EcoViva. Retrieved February 7, 2022, from https://ecoviva.org/mangrove-restoration-beginning-to-bear-fruit/

Arshad-Ayaz, A., Naseem, M. A., & Mohamad, D. (2020). Engineering and Humanitarian Intervention: Learning from Failure. *Journal of International Humanitarian Action*, *5*(1). https://doi.org/10.1186/s41018-020-00073-5

Campbell, R. C., & Wilson, D. (2011). (rep.). *The Unique Value of Humanitarian Engineering* (pp. 1–12). The American Society of Engineering Education.

Carbon Engineering. (2021). *Direct Air Capture Technology*. 1PointFive. Retrieved December 1, 2021, from https://www.1pointfive.com/technology

Carmichael, M., & Piccione, I. (2022). (rep.). *Modeling CO2 Absorption in Mangrove Trees* (pp. 1–12). Worcester, MA.

CBEMR Mangrove Restoration. Mangrove Action Project. (2021, October 22). Retrieved February 7, 2022, from https://mangroveactionproject.org/mangrove-restoration/

Denchak, M. (n.d.). Are the effects of global warming really that bad? NRDC. Retrieved April 28, 2022, from https://www.nrdc.org/stories/are-effects-global-warming-really-bad

HBO Films. (2019). *Ice on Fire*. *HBO Max*. Retrieved 2021, from https://www.hbo.com/movies/ice-on-fire.

Lovelock, C.E., Duarte, C.M., 2019. Dimensions of blue carbon and emerging perspectives. Biol. Letters 15,20180781.

Nanda, S., Reddy, S. N., Mitra, S. K., & Kozinski, J. A. (2016). The progressive routes for carbon capture and sequestration. Energy Science & Engineering, 4(2), 99–122. https://doi.org/10.1002/ese3.117

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., DeYoung, C., Fonseca, L., Grimsditch, G., 2009. Bluecarbon: A rapid response assessment. GRID‐ Arendal

Queiroz, L. de S., Rossi, S., Calvet-Mir, L., Ruiz-Mallén, I., García-Betorz, S., Salvà-Prat, J., & Meireles, A. J. de A. (2017). Neglected ecosystem services: Highlighting the socio-cultural perception of mangroves in decision-making processes. Ecosystem Services, 26, 137–145. https://doi.org/10.1016/j.ecoser.2017.06.013

Sandilyan, S., Kathiresan, K., 2012. Mangrove conservation: A global perspective. Biodive. Conserv. 21,3523–3542.

Servino, R. N., Gomes, L. E. de O., & Bernardino, A. F. (2018, February 13). *Extreme Weather Impacts on Tropical Mangrove Forests in the Eastern Brazil Marine Ecoregion*. ScienceDirect. Retrieved February 6, 2022, from https://www.sciencedirect.com/science/article/pii/S004896971830456X

Swangjang, K., Panishkan, K., 2021. Assessment of factors that influence carbon storage: An important ecosystem service provided by mangrove forests. Heliyon 7, e08620

Truong, T. D., & Do, L. H. (2018, February 21). *Mangrove Forests and Aquaculture in the Mekong River Delta*. ScienceDirect. Retrieved February 6, 2022, from https://www.sciencedirect.com/science/article/pii/S0264837717308815

United Nations. (2015). *Goal 14 | Department of Economic and Social Affairs*. United Nations. Retrieved February 7, 2022, from https://sdgs.un.org/goals/goal14

United Nations. (2019). The Community of Ocean Action for Mangroves – Towards the Implementation of SDG14 (Interim Report to UN-DESA).

Veettil, B. K., Pereira, S. F. R., & Quang, N. X. (2018, June 5). *Rapidly Diminishing Mangrove Forests in Myanmar (Burma): A Review*. SpringerLink. Retrieved December 8, 2021, from https://link.springer.com/article/10.1007/s10750-018-3673-1.

Wang, F.M., Sanders, C.J., Santos, I.R., Tang, J.W., Schuerch, M., Kirwan, M.L., Kopp, R.E., Zhu, K., Li, X.Z.,Yuan, J.C., Liu, W.Z., Li, Z.A., 2021a. Global blue carbon accumulation in tidal wetlands increases with climate change. Natl. Sci. Rev. 8, nwaa296

Xie, R.H., Zhou, Z.D., 2005. A Summary of the Ecosystem and Function of Mangrove. J. South China Trop. Agri.Univ. 11, 48-52.

Zhu, J.-J., & Yan, B. (2022). Blue carbon sink function and carbon neutrality potential of mangroves. The Science of the Total Environment, 153438, 153438. https://doi.org/10.1016/j.scitotenv.2022.153438

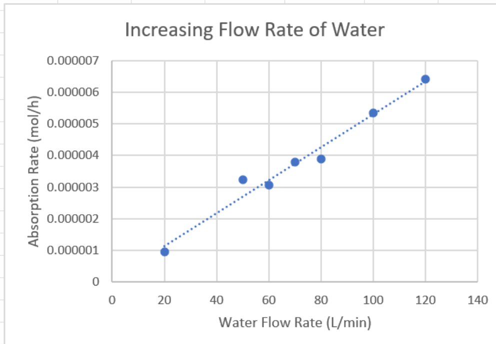
Zurawsky, W., Stewart, E., & DiBiasio, D. (2019). (rep.). *Cameroon Renewable Energy Project* (pp. 1–4). Worcester, MA.

Appendix

Testing Experimental Problem

Finding Absorption Rate, W	
Variables	
Viscosity, μ (Ns/m2)	1.47E-05
density, ρ (kg/m3)	1000
Diffusivity (in water), Dab (m2/s)	1.60E-09
Water Schmidt's Number, Scw	9.19E+00
Diffusivity (in air), Dab (m2/s)	1.60E-05
Gas Schmidt's Number, Scg	9.19E-04
Log Mean, Δyc	8.25E-02
Gas Phase Driving Force, Noy	3.16E-01
fp, relative mass transfer coeff	1.50E+00
Gx, liq mass velocity (kg/m2s)	4.63E-02
Gy, gas mass velocity (kg/m2s)	5.58E-02
Hx	2.87E-02
Hy	2.84E+00
Flow Rate, V (L/min)	2.08E-03
Flow Rate, L (L/min)	2.78E+00
Overall gas phase driving force, Hoy	2.84E+00
Over Mass Transfer coeff, Kya	6.12E-03
Absorption Rate, W	3.96E-06

Calculated



Appendix Figure 1. *Determining Absorption Rate from sample values*

Determining Dynamic Gx Values	L Values	V Values	Interval (s)	Gx	Hx	Gy	Hy	Hoy	Kya	W	Averages
Changing Water Flow Rate, L											
	50	0.05	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
	50	0.05	60	0.833333	0.068376	1.003333	1.839454	1.839472	0.005768	3.73E-06	
	50	0.05	120	0.416667	0.055539	0.501667	2.041002	2.041017	0.005199	3.36E-06	
	50	0.05	180	0.277778	0.049178	0.334444	2.168987	2.169001	0.004892	3.16E-06	
	50	0.05	240	0.208333	0.045111	0.250833	2.264633	2.264645	0.004685	3.03E-06	
	50	0.05	300	0.166667	0.04219	0.200667	2.341717	2.341728	0.004531	2.93E-06	3.24366E-06
	20	0.02	360	0.055556	0.030344	0.066889	2.76123	2.761238	0.001537	9.94E-07	
	20	0.02	420	0.047619	0.028973	0.057333	2.82582	2.825828	0.001502	9.71E-07	
	20	0.02	480	0.041667	0.027835	0.050167	2.882991	2.882999	0.001472	9.52E-07	
	20	0.02	540	0.037037	0.026869	0.044593	2.934379	2.934386	0.001446	9.35E-07	
	20	0.02	600	0.033333	0.026033	0.040133	2.981123	2.98113	0.001424	9.21E-07	9.54817E-07
	70	0.07	660	0.106061	0.03684	0.127697	2.505985	2.505995	0.005928	3.83E-06	
	70	0.07	720	0.097222	0.035891	0.117056	2.538907	2.538917	0.005851	3.78E-06	
	70	0.07	780	0.089744	0.03504	0.108051	2.569574	2.569584	0.005781	3.74E-06	3.78575E-06
	60	0.06	840	0.071429	0.032721	0.086	2.659077	2.659086	0.004788	3.1E-06	
	60	0.06	900	0.066667	0.03205	0.080267	2.686738	2.686747	0.004739	3.07E-06	
	60	0.06	960	0.0625	0.031436	0.07525	2.712874	2.712883	0.004693	3.04E-06	
	60	0.06	1020	0.058824	0.030869	0.070824	2.737657	2.737665	0.004651	3.01E-06	3.0515E-06

Appendix Figure 2. *Testing whether altering water flow rate produces significant results*

Affect of Changing Packing Size	L Values	V Values	Interval (s)	Gx	fp	Gy	Hx	Hy	Hoy	Kya	W
Changing fp, packing diameter	50	0.05	60	0.833333	1.5	1.003333	6.84E-02	1.84E+00	1.84E+00	2.27E-01	1.47E-04
	50	0.05	120	0.416667	1.5	0.501667	5.55E-02	2.04E+00	2.04E+00	2.05E-01	1.32E-04
	50	0.05	180	0.277778	1.5	0.334444	4.92E-02	2.17E+00	2.17E+00	1.93E-01	1.25E-04
	50	0.05	240	0.208333	1.5	0.250833	4.51E-02	2.26E+00	2.26E+00	1.84E-01	1.19E-04
	50	0.05	300	0.166667	1.5	0.200667	4.22E-02	2.34E+00	2.34E+00	1.78E-01	1.15E-04
	50	0.05	360	0.138889	1.5	0.167222	3.99E-02	2.41E+00	2.41E+00	1.74E-01	1.12E-04
	50	0.05	420	0.119048	1.5	0.143333	3.81E-02	2.46E+00	2.46E+00	1.70E-01	1.10E-04
	50	0.05	480	0.104167	1.5	0.125417	3.66E-02	2.51E+00	2.51E+00	1.66E-01	1.08E-04
	50	0.05	540	0.092593	1.5	0.111481	3.54E-02	2.56E+00	2.56E+00	1.63E-01	1.06E-04
	50	0.05	600	0.083333	1.5	0.100333	3.43E-02	2.60E+00	2.60E+00	1.61E-01	1.04E-04
	50	0.05	660	0.075758	1.5	0.091212	3.33E-02	2.64E+00	2.64E+00	1.58E-01	1.03E-04
	50	0.05	720	0.069444	1.5	0.083611	3.24E-02	2.67E+00	2.67E+00	1.56E-01	1.01E-04
	50	0.05	780	0.064103	1.5	0.077179	3.17E-02	2.70E+00	2.70E+00	1.55E-01	1.00E-04
	50	0.05	840	0.059524	1.5	0.071667	3.10E-02	2.73E+00	2.73E+00	1.53E-01	9.89E-05
	50	0.05	900	0.055556	1.5	0.066889	3.03E-02	2.76E+00	2.76E+00	1.51E-01	9.79E-05
	50	0.05	960	0.052083	1.5	0.062708	2.98E-02	2.79E+00	2.79E+00	1.50E-01	9.69E-05
	50	0.05	1020	0.04902	1.5	0.05902	2.92E-02	2.81E+00	2.81E+00	1.48E-01	9.60E-05
	50	0.05	1080	0.046296	1.5	0.055741	2.87E-02	2.84E+00	2.84E+00	1.47E-01	9.52E-05

Appendix Figure 3. *Testing whether changing packing size of column produces significant results*

Sample Calculations for Design Problem

Design Problem

→ we want to model a tower based on the engineering capabilities of a mangrove tree, however b/c a mangrove tree

→ we have a 100 cfm gas flowrate @ 298°K & 1 bar, .04 wt% CO_2

→ water flow = 4.5 gpm = 283.9 cm³/s

→ $velocity_{air}$ = 400 cm/s $velocity_{water}$ = 2.58 cm/s

→ ρ_{air} = .0012 g/cm³s ρ_{water} = 1 g/cm³

→ μ_{air} = .00016 g/cm³s μ_{water} = .00894 g/cm s

→ $D_{AB\,air}$ = .16 cm²/s $D_{AB\,water}$ = 1.67×10^{-5} cm²/s

Air

$Re = L v \rho / \mu = (1)(400)(.0012) / .00016 = 3000$

$Sc = \mu / D_{AB} \rho = .00016 / .16 (.0012) = .83$

$Sh = 1.17\, Re^{.585}\, Sc^{1/3} \rightarrow 118.94$

$k_y = Sh (D_{AB} / L) = 118.94 (.16/1) = 19.03$ cm/s

Water

$Re = (1)(2.58)(1) / .00894 = 288$

$Sc = (.00894) / (1)(1.67 \times 10^{-5}) = 535.33$

$Sh = 1.17\, Re^{.585}\, Sc^{1/3} = 260.9$

$k_x = Sh (D_{AB} / L) = 260.9 (1.67 \times 10^{-5}) = .0044$

k_y & k_x

$$K_y = \frac{1}{(H/k_x)\,(1/k_y)} \quad \rightarrow H = 3.6 \times 10^{-2}$$

$$\hookrightarrow \frac{1}{(3.6\times10^{-2}/.0044)\,(1/19.03)} = 2.33$$

$$K_x = \frac{1}{(1/k_x) + (1/H k_y)}$$

$$\hookrightarrow \frac{1}{(1/.0044) + (1/.036 \times 19.03)} = .041$$

Appendix Figure 4. *Test calculations done to see if design problem stated was possible, part 1*

HOG

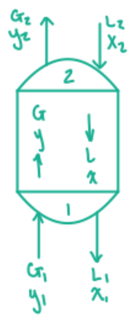
→ $a = 3.7$

$$H_{TOG} = \frac{\mu_{gas}}{K_y a} = \frac{400}{2.33(3.7)} = 46.39 \text{ cm}$$

$$H_{TOL} = \frac{\mu_{water}}{K_x a} = \frac{2.58}{.041(3.7)} = 17.01 \text{ cm}$$

NOG

Material balance



$G = 100$ cfm $= 47195$ cm^3/s

↳ $= 61.02$ g/s × .04% = .024

$G = 61.02$ → $G = 61.02$

$y_1 = .02$ g → .015 g → (more than the .02% a mangrove forest can absorb, but number was too small)

$L = 283.9$ cm^3/s

↳ 283.9 g

$L = 283.9$ g/s $L = 283.9$

$x_1 = 0$ $x_2 = .005\%$

$$G y_1 + L x_1 = G y_2 + L x_2$$

$$61.02(.0003) + 0 = 61.02(.0002) + 283.9(x_2)$$

$x_2 = .005$

$$61.02 \text{ g Air} \left(\frac{1 \text{ mol}}{29 \text{ g}}\right) = 2.104 \text{ mol} = G$$

$$.02 \text{ g} \left(\frac{1 \text{ mol}}{44 \text{ g}}\right) = 4.5 \times 10^{-4} \text{ mol} = y_1$$

$$.015 \text{ g} \left(\frac{1 \text{ mol}}{44 \text{ g}}\right) = 3.4 \times 10^{-4} \text{ mol} = y_2$$

$$283.9 \left(\frac{1 \text{ mol}}{18}\right) = 15.8 \text{ mol} = L$$

Appendix Figure 5. *Test calculations done to see if design problem stated was possible, part 5*

Sample Calculations for Original Mass Transfer Problem

Current Calculations Needed

from lab data - calculate absorption rate

Schmitt #: $Sc = \frac{\mu}{\rho D_{AB}}$ → into water ⇒ $D_{AB} = 1.6 \times 10^{-9}\ m^2/s$

$\mu = 1.47 \times 10^{-5}\ Pa/s \rightarrow 1.47 \times 10^{-5}\ Ns/m^2$

$$Sc_{water} = \frac{(1.47 \times 10^{-5})}{(1000)(1.6 \times 10^{-9})} = 9.1875 = Sc_{water}$$

Sc_{gas} = into air ⇒ $D_{AB} = 1.6 \times 10^{-5}$

$$\frac{1.47 \times 10^{-5}}{(1.204)(1.6 \times 10^{-5})} = .941 = Sc_{gas}$$

Log Mean

$$\Delta y_L = \frac{(y_B - y_B^*) - (y_A - y_A^*)}{\ln\left(\frac{y_B - y_B^*}{y_A - y_A^*}\right)}$$ w/ previous data = .0825

Noy

$$\frac{y_B - y_A}{\Delta \bar{y}_L}$$ → w/ previous data $N_{oy} = .3159$

Gx

$G_x = L\,(MW/s) \rightarrow 3\ L/min \times 1\ kg/L \times 1/60s = .05\ kg/m^2s$

Gy

$G_y = 3\ L/min \times 1.204\ kg/1L \times 1/60s = .06\ kg/m^2s$

Hx $\frac{.357}{f_p}\left(\frac{Sc}{372}\right)^{.5}\left(\frac{G_x/\mu}{6.782/(.8937 \times 10^{-3})}\right)^{.3}$

↳ $\left(\frac{.357}{1.5}\right)\left(\frac{9.1875}{372}\right)^{.5}\left(\frac{.05/1.47 \times 10^{-5}}{6.782/(.8937 \times 10^{-3})}\right)^{.3} = .0294$

Hy

from previously calculated data = 73.2

Hoy

$H_y + m\,V/L\,H_x \rightarrow 73.2 + .27\,(2.08 \times 10^{-3}/2.78)\,(.0294) = 73.2\ m$

Kya

$$K_{ya} = \frac{V}{S\,H_{oy}} \rightarrow \frac{2.08 \times 10^{-3}}{\pi(1.5)(.0254)(73.2)} = .0062$$

W

$W = K_{ya}\,(V_t)\,\Delta \bar{y}_L$

→ from previous data

$.0062\,(7.84 \times 10^{-3})\,.0825 = 4.01 \times 10^{-6}$

Proposed Calculations

dynamic G_x

↳ have students calculate multiple W's in relation to different water flow rates & then determine the absorption rate over a given time period

Appendix Figure 6. *Test calculations done to see how the current mass transfer problem was solved for and to then see how to alter said problem, part 1*

↓ Example

30 Minute period w/ the following flowrates

time	0-5 min	6-12 min	13-15 min	16-19 min	20-21 min	22-27 min	28-30 min
Flow Rate	5 L/m	2 L/m	7 L/m	6 L/m	10 L/m	12 L/m	8 L/m

→ convert to weighted averages

Average	.167	.233	.100	.133	.067	.200	.100
Flow Rate	5	2	7	6	10	12	8

→ using excel or sheets calculate the new W-values & then apply the weighted averages → the sum the values together to obtain overall W

compare value to W value of constant water flowrate → using the average flowrate from values given above

Appendix Figure 7. *Test calculations done to see how the current mass transfer problem was solved for and to then see how to alter said problem, part 2*

Worcester Polytechnic Institute
Department of Chemical Engineering

ChE4402 Modeling CO_2 Absorption in Mangrove Trees B Term

Introduction

Concerns over global warming are a political reality even if the causes and effects are not clear. Carbon dioxide is considered to be the largest contributor to the manmade portion of this problem. With the removal of CO_2 from industrial gas streams becoming increasingly important due to the perceived notion, that controlling greenhouse gas emissions will in turn help the environment.[7] Though there are machines that have been designed to capture carbon, there are also plenty of natural carbon sinks existing in our environment that are able to absorb excess carbon while also providing additional resources to the local communities around them, which potentially make them more viable than their industrial counterparts.

Mangrove forests are coastal wetlands that act as natural carbon sinks, absorbing 3.56×10^{-11} kg/yr of Earth's atmospheric CO_2. While mangroves are able to help with carbon sequestration and oxygen production, they also home a wide variety of species that in turn create a grand amount of biodiversity. As mangroves can be found in a total of 123 different countries, and are able to generate up to $1.6 billion yearly in a variety of environmental services while also simultaneously supporting the local coastal communities.[8] As the species living inside are able to provide food and goods to sell to other communities, the brush can be used for fuel, and the scenery acts as places of interest for tourists visiting the surrounding area. However, overconsumption of the forests' resources has led to a decrease in mangrove density worldwide.[9] Organizations across the globe are popping up to counteract the effects of this overconsumption and remediate mangrove forests, including the Mangrove Action Project (MAP), and the UN's Communities of Ocean Action. The MAP is an organization that works closely with coastal communities to teach them remediation methods of the mangroves, to keep their regrowth progress steady well after MAP has left.[10]

It is vital that we as engineers consider the humanitarian impact of our work, beyond the technical aspects, to better understand our place in the world as innovators. The best solution isn't always the most complex and high tech, but rather simply the one that solves the problem at hand and is accessible to those that are in need of it.

Objectives

For the *experimental side of this lab*, you will be using the absorption tower in the Goddard Unit Ops lab to observe CO_2 absorption and get an understanding of how carbon sequestration occurs. You will study the absorption of CO_2 (absorbate) from air in a packed column using water as the solvent (absorbent); the main goal is to determine the effect of gas and liquid flow rates on the overall mass transfer coefficient for this absorption process. From there you will use the calculations done to then compare the absorption rate of the column to that of an active sea current. To simplify the flow rate of an active wave, flow rates are given below.

Time (min)	5	7	3	4	2	6	3
Flow Rate (L/min)	5	2	7	6	10	12	8

.

For the *design element in this lab*, you will try and replicate a mangrove tree as if it were an absorption column using the following information;

- A single tree can absorb 12.3 kg/yr of carbon dioxide, for the purpose of this lab however we will say it absorbs 12.3 kg/min of carbon dioxide.
- Water flow rate is 4.6gpm
- Gas flow rate is 100 cfm, with a .04 wt% of CO_2

To address the *last part of this lab*, you will be asked to find a coastal community in which mangrove forests play an important role in their culture, whether it be protection, economical, religious, or all of the above. Determine how they utilize mangroves in day-to-day life, if climate change has affected that reliance, and if any steps have been taken to remediate the forests. Write a 500-word piece about your chosen community and include at least 3 sources.

Apparatus

(1) Tower

The column is a 3-inch diameter glass column partially filled with ¼ in. glass Raschig Rings.

(2) Gas supply

CO_2 and air are available from tanks equipped with regulators. The regulator pressure should be set at 15 - 20 psig for each gas. Flow rates of the gasses are maintained at desired levels using flow control valves, rotameters, and digital flow meters. The gasses are mixed using a specially designed mixing tube located after the flow meters and prior to entering the bottom of the tower. **Note that neither the compressor on the absorber skid, nor house air supply, is used in this experiment and should remain off.**

(3) Liquid supply

Water is supplied from house water, through a rotameter, to the top of the column. **Note that the sump and pump assembly on the absorber skid is not used in this experiment and should remain off.** Water flows downward through the column and out to the drain using valves in the pipes below the column. During column operation with gas flowing upward, a liquid seal must be maintained in the pipes below the column by appropriate adjustment of the valve on the trap of the drain line. That is, the rate of water flow returned to the sump or diverted to the drain must be maintained at a rate equal to the inlet water flow rate to maintain a constant height of water in the pipe below the column. That way, water does not back up and flood the column and the gas entering the column at the bottom does not escape into the sump or out the drain.

(4) Measurements
Flow rates of air, CO_2 and water are obtained from rotameters and digital flow meters. For CO_2, the digital flow meter range is 100-500 ml/min. For air, the range is 1-5 L/min. For water, the range is up to 5.3 L/min (1.4 gpm full scale). Thermocouples at the column top and bottom provide temperature measurements that can be read on the column control panel. To check that pressure does not build up in the glass column, a water-filled manometer provides a measure of the difference between the pressure at the column top and atmospheric pressure; you must ensure that the column pressure remains at a safe level and does not exceed the manometer capacity. Inlet and outlet gas CO_2 compositions are measured with non-dispersive infrared sensors that report volume percent CO_2 in the air via a USB cable to a computer. These sensors also report temperature and relative humidity for display on the computer. A LabView computer program called New absorber 2017 is used to activate the CO_2 meters (sensors) as well as to read the digital flow meters. Another computer program called Gas Lab is used to collect and plot the CO_2 concentration readings at the bottom and top of the column. The procedures for using the LabView and Gas Lab programs, and the calibration curves for the air and CO_2 rotameters, are appended. For water, it is assumed that the flow rate is linear with the rotameter scale up to a full scale reading of 5.3 L/min.

Procedure

(1) Preliminary inspection of equipment
It is necessary that each student understand the arrangement and operation of the equipment before any experimental work is undertaken. A complete inspection of the equipment should be made and the function of each part of the apparatus should be determined. A detailed schematic should be drawn. Each member of the lab group will be expected to answer questions about the equipment during the lab session.

(2) Experimental conditions
Inlet gas CO_2 composition should be maintained at a nearly constant value somewhere between 8 and 16 % by volume. It is recommended that the air flow be no less than 750 ml/min and no more than 4000 ml/min. The CO_2 content of the entering stream should be compared with the expected value based on the flow meter readings and any discrepancy should be noted. The water flow can be varied between 0.5 and 5.0 L/min. Inlet CO_2 composition in the water entering the column can be assumed to be zero as long as the outlet water is completely diverted to the drain. It is suggested that you study four or five different water rates at a fixed gas rate, then repeat this process for 2 or 3 more gas rates all at the same inlet CO_2 composition. You might also want to repeat some of these runs with a different inlet CO_2 composition. Upon

making process changes, it is important to wait long enough for steady state to be achieved. The DAS program will allow you to record the CO_2 concentration with time.

(3) Start-Up

Following equipment inspection, turn on the main power switch on the control panel. Carefully and slowly open the main valves on the air and CO_2 gas cylinders and adjust the delivery pressure to 15 – 20 psig as indicated on the pressure gauge. Also open the flow valve at the regulators. Ensure that drain valves are closed. Then, on the control panel, open the air and CO_2 flow control valve to the desired air flow rates. Calibration curves for the rotameters are appended. Position the valves on the sampling line such that you are reading the concentration at the base of the column.

(4) CO_2 Measurement

This document contains information needed to obtain CO_2 concentration measurements at the top and bottom of the column via computer controlled IR CO_2 sensors. It also shows how to follow the air, CO_2, and water flow rates using digital flow meters on the computer. For air and CO_2 flow rates, it is recommended however, that the rotameters be used with calibration curves that are included below.

You will use the LabView file called New Absorber 2017 to access the digital flow meter readings and to turn on the CO_2 detectors. Double click the "Shortcut to New Absorber 2017" icon on the desktop to open the file as indicated by the solid arrow in Figure 1. This file can be found in the folder called "Absorber Controls 2012" if the shortcut is missing. Once the LabView virtual instrument (New absorber 2017) file opens, you should see something like Figure 2. Click the "Run" button indicated by the dashed arrow in Figure 2, to turn on the absorber controls.

Figure 1. Shortcut to New Absorber.vi

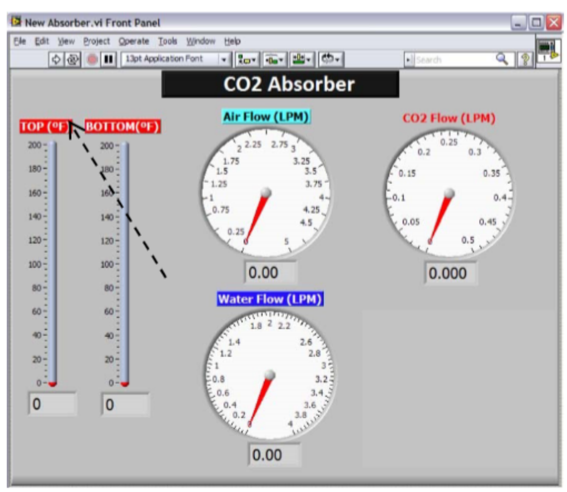


Figure 2. New Absorber.vi Front Panel

To read the CO_2 concentrations, you will need to open the Gas Lab program indicated by the dashed arrow in Figure 1. Once opened, you should select the port input as Com4, the series input as K series, and the series model input as K33 BLG 30%. Now you can start collecting Realtime data by selecting the start logging option. This will open the "Realtime" dialog box and you will be prompted to select a file name for your data file. Figure 3 shows the resulting data plot. Figure 4 shows data after a few minutes of running. CO_2 concentration is reported as "Flow CO_2 (%)" but is actually the volume percent of CO_2 in the stream.

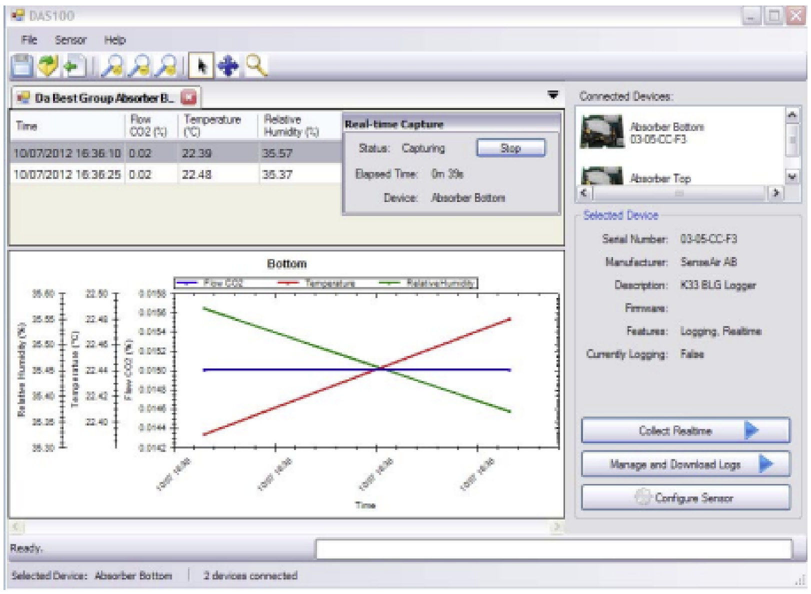


Figure 3. Gas Lab program captures and plots $\%CO_2$, temperature, and relative humidity data every 15 seconds

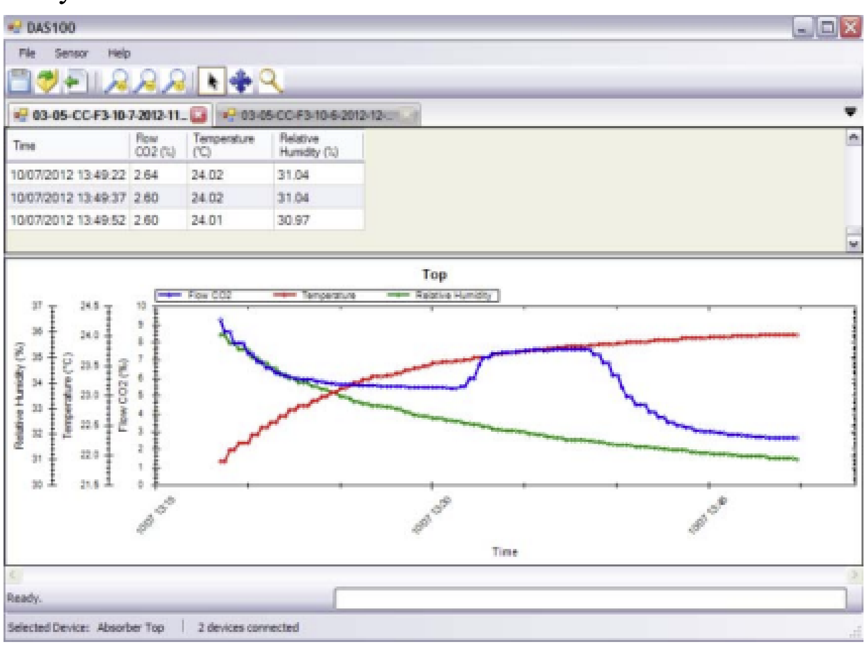


Figure 4. Meter readings at column top

Initially, the valves on the sampling lines should be set to record the CO_2 concentration at the bottom (gas inlet) to the column. You should verify that the measured CO_2 concentration is equal to that calculated based on gas flows. If the values vary significantly (rare condition), you may need to calibrate the CO_2 meter.

Once the system is ready, you may start the water. First, open the drain valve. Then start the water flow by first turning on the two shut-off valves from the house water and then opening the flow control valve on the water rotameter to the desired condition. When the water flow has stabilized, you must partially close the drain valve at the end of the trap until a steady level of liquid is seen in the sight tube (steady indicating that the water discharge is equal to the water flow into the tube). Note that when you adjust water flow, you will likely have to adjust the drain valve. The specific height of the liquid is not critical, just that it remains steady.

During the run, move the valve positions to record the CO_2 concentration at the top of the column. You should not change conditions until the CO_2 concentration has reached steady state, as witnessed on the curves. Steady state conditions will likely require between 5 and 30 minutes depending on the magnitude of the change. At the conclusion of a run, you should again verify the concentration at the bottom of the column has not changed.

(5) Shut-Down
This system is shut down in reverse order.

First, stop water flow to the column by closing the flow valve and then the two shut-off valves.

Next, turn off the CO_2 flow valve on the rotameter on the control valve. Then close the flow valve and the main cylinder valve on the CO_2 cylinder. Verify that the CO_2 flow and concentration decrease to zero.

Next, turn off the air flow valve on the rotameter on the control valve. Then close the flow valve and the main cylinder valve on the air cylinder. Verify that the air flow decreases to zero.

Finally, save the data files, close the programs, and make copies of the data files for your use. You can save the data files as CSV files for ease. Note that you may choose to save some screen shots for your report.

When complete, notify the TA and/or professor, who will verify safe shut-down and set the column to drying.

Theory

The engineer who is required to design an absorption tower is interested in the rate of absorption of the material under the desired operating conditions. Considerable experimental work on a few systems has been reported in the literature that will enable the designer to predict the effect of certain operating variables on the rate of absorption for a given type of apparatus. The absorption rate is generally expressed as an overall mass transfer coefficient, K, which may be based on either a gas or a liquid-phase driving force. In most cases it is impossible to determine the area of contact of the gas and liquid. Therefore, the coefficients are reported on a volume basis. For dilute systems with straight operating and equilibrium lines, a design equation for the volume of a gas absorption tower may be written as:

$$W = K_Y a(V_t)\Delta\overline{y}_L \quad (1)$$

Where

W = absorption rate of solute gas; mol/h

$K_y a$ = overall mass transfer coefficient based on the gas-phase driving force, $mol/h/m^3$

V_t = gross tower volume occupied by packing, m^3

$\Delta\overline{y}_L$ = logarithmic mean driving force; logarithmic mean of (y_b-y_b^*) and (y_a-y_a^*)

y_b = mole percent CO_2 in the gas phase at the column bottom

y_a = mole percent CO_2 in the gas phase at the column top

y_b^* = mole percent CO_2 in the gas phase that would be in equilibrium with the liquid at the column bottom

y_a^* = mole percent CO_2 in the gas phase that would be in equilibrium with the liquid at the column top

The equilibrium relation for CO2 dissolved in water can be represented by Henry's law

$$y_{CO2} \times P = H(x_{CO2})$$

Henry's constant may be assumed to be 1400 atm at 20 o C [1]. Under certain assumptions, a design equation for the column height is given by [2]:

$$Z = \frac{V/S}{K_y a}\int_a^b \frac{dy}{y-y^*} \quad (2)$$

Where

S = cross sectional area, m^2

V = molar flow rate of the gas phase, mol/h

The integral in this equation represents the change in vapor composition divided by the average driving force and is called the number of transfer units based on the overall gas phase driving force, NOy. The other part of Equation 2 has units of length and is called the height of a transfer unit based on the overall gas phase driving force, HOy. Thus the height of the column is given by:

$$Z = H_{Oy}N_{Oy} \tag{3}$$

For dilute systems or those with otherwise straight operating and equilibrium lines, the integral in Equation 2 is easily determined using the logarithmic mean and the number of transfer units is given by:

$$N_{Oy} = \frac{y_b - y_a}{\Delta y_L} \tag{4}$$

The overall resistance to mass transfer can be considered to be made of a gas phase film resistance and a liquid phase film resistance and the height of a transfer unit can be considered to be made up of a contribution from the liquid film and a contribution from the gas film as given by [3]:

$$H_{Oy} = H_y + m\frac{V}{L}H_x \tag{5}$$

where m is the slope of the equilibrium line and V and L are the average molar flow rates of the gas and liquid. This formulation is useful for design purposes because correlations are available for Hx and Hy. For example, Geankoplis [4] gives;

$$H_y = \left(\frac{0.226}{f_p}\right)\left(\frac{Sc}{0.660}\right)^{0.5}\left(\frac{G_x}{6.782}\right)^{-0.5}\left(\frac{G_y}{0.678}\right)^{0.35} \tag{6}$$

and

$$H_x = \left(\frac{0.357}{f_p}\right)\left(\frac{Sc}{372}\right)^{0.5}\left(\frac{G_x/\mu}{6.782/(0.8937\times10^{-3}}\right)^{0.3} \tag{7}$$

Where H_x and H_y have units of meters,
Sc = Schmidt number = $\mu/(\rho D_{AB})$
μ = viscosity
ρ = density
D_{AB} = diffusivity of solute A in B (gas phase for H_y and liquid phase for H_x)
f_p = a relative mass transfer coefficient for a given packing material compared to a reference packing material. f_p can be assumed to be 1.5 for ¼ Raschig rings.
G_y = gas mass velocity in kg/m^2 s
G_x = liquid mass velocity in kg/m^2 s

These correlations are not generally expected to give accurate quantitative predictions, but they should provide reasonable rough estimates and show appropriate trends in mass transfer behavior.

Note that:

$$K_y a = \frac{V}{S\,(H_{Oy})} \tag{8}$$

For design purposes, the height of the column required to provide a specified separation can be obtained from Equation 3, if correlations like Equations 6 and 7 are used together with equilibrium information to estimate HOy in Equation 5. Alternatively, if the column height is given, and an estimate is obtained for HOy, the outlet compositions that will result for given inlet flows and compositions can be determined from Equation 3 together with a mass balance. Equations 3 and 8 could also be used to evaluate HOy from experimental data obtained on a given column.

Also note that mass transfer coefficients and transfer units can alternatively be based on the liquid phase driving force and that although HOy HOx and NOy NOx design results in terms of column heights or product stream compositions based on the two methods should be similar.

<u>Calculations</u>

The following calculations should be performed:

(a) A value of K_ya should be calculated for each run. The value of W to be used in this calculation should be obtained from a material balance on CO_2 in the gas phase. Note that if the system is not dilute or if experimental uncertainties preclude the calculation of a log mean driving force, Equation 1 will not work and an integral formulation of the mass balance will be required.

(b) Estimates of error should be attached to any value of K_ya and error bars should be provided on all plots.

(c) Plots of K_ya versus liquid mass velocity, G_x, should be made and a correlation of K_ya as a function of liquid mass velocity should be attempted. G_x should be based on the total cross sectional area of the tower, and has units of kg/m^2-h.

(d) Estimates of H_{Oy} and K_ya should be obtained from theory and/or empirical correlations and compared with the experimental results, including a comparison of the expected and experimental dependence of K_ya on G_x and G_y

<u>Design Requirements</u>

Determine the size an absorption column would be given that a single tree can absorb 12.3 kg/yr of carbon dioxide, water flow rate is 4.6gpm, and gas flow rate is 100cfm with a .04 wt% of CO_2, which is accurate to the amount of CO_2 that currently exists in our atmosphere. For the purpose of this lab however instead of the absorption rate being 12.3 kg/yr of CO_2 it will be 12.3 kg/min.

For ease the column diameter will remain the same as the tower found in the lab, however the height of the column should be determined.

Results and Discussion

A discussion of the errors in the results due to experimental uncertainty and their effect on the results through propagation of error should be included. How meaningful are your results when errors are considered. It is not sufficient to simply state your results in numerical form. They should be interpreted in terms of physical phenomena occurring within the process. Do the trends in the data make sense? Do your results agree with published information or correlations? What is happening physically inside the column when the water rate is changed that can account for the observed dependence of the mass transfer coefficient on the water rate?

Report Requirements

Just like all the other experiments this term, a formal preliminary lab report is required for the absorber experiment. The pre-lab report should contain an introduction stating the objective of the experiments, including the rationale for expecting K_ya to depend on the liquid flow rate, some background on gas absorption and carbon capture technology in the context of climate remediation, a detailed derivation of the design equation from first principles, including the assumptions and simplifications made, and the coastal community your lab group will be researching. Additionally, a description of the equipment and purpose of each item, including a detailed schematic drawing, and a stepwise procedure, that would allow someone who is unfamiliar with the equipment to perform the experiment should be included. Write a brief discussion of safety issues related to this experiment as well.

Following the first week of experiments, calculations of K_ya for all liquid flow rates should be made and correlated against G_x.

Results from the first week are to be presented informally to the instructor before the second week's experiments. Error analysis is not required at this stage.

The final report should contain the usual sections as specified in the course descriptions. In addition, an error analysis is required for all calculated values of K_ya, and error bars are to be included on all plots.

References

1. McCabe, W. L., Smith, J. C., and Harriott, P., Unit Operations of Chemical Engineering, 7th Ed., McGraw-Hill, New York, (2005), p. 580.
2. Ibid, p. 581.
3. Ibid, p. 584.
4. Geankoplis, C. J., Transport Processes and Separation Process Principles, 4th Ed., Prentice Hall, Upper Saddle River, NJ, (2003), p. 686.
5. Ibid, p. 665.
6. Cussler, E. L., Diffusion: Mass Transfer in Fluid Systems, 2nd Ed., Cambridge University Press, NY, (1997), p. 260.
7. Carbon Engineering. (2021). Direct Air Capture Technology. 1PointFive. Retrieved December 1, 2021, from https://www.1pointfive.com/technology
8. Chadwick, N., & Malentaqui, P. Y. (2010, April 9). *Mangrove Forests in Worldwide Decline*. IUCN. Retrieved December 2021, from https://www.iucn.org/content/mangrove-forests-worldwide-decline
9. Truong, T. D., & Do, L. H. (2018, February 21). Mangrove Forests and Aquaculture in the Mekong River Delta. ScienceDirect. Retrieved February 6, 2022, from https://www.sciencedirect.com/science/article/pii/S0264837717308815
10. CBEMR Mangrove Restoration. Mangrove Action Project. (2021, October 22). Retrieved February 7, 2022, from https://mangroveactionproject.org/mangrove-restoration/
11. Abu-Lail, L. (n.d.). (rep.). Gas Absorption in a Packed Tower (pp. 1–12). Worcester, MA.

The instructional materials in this document are adapted from the Gas Absorption in a Packed Tower experiment in ChE4402 Unit Operations 2, taught by Professor Laila Abu-Lail.

APPENDIX

Rotameter Calibration Curves

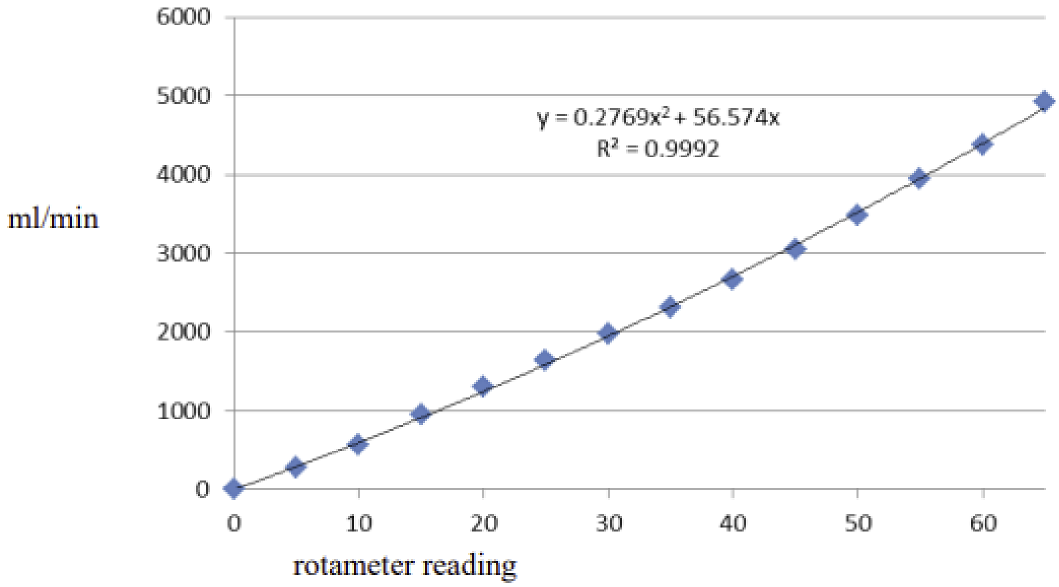


Figure 9. Air rotameter calibration curve.

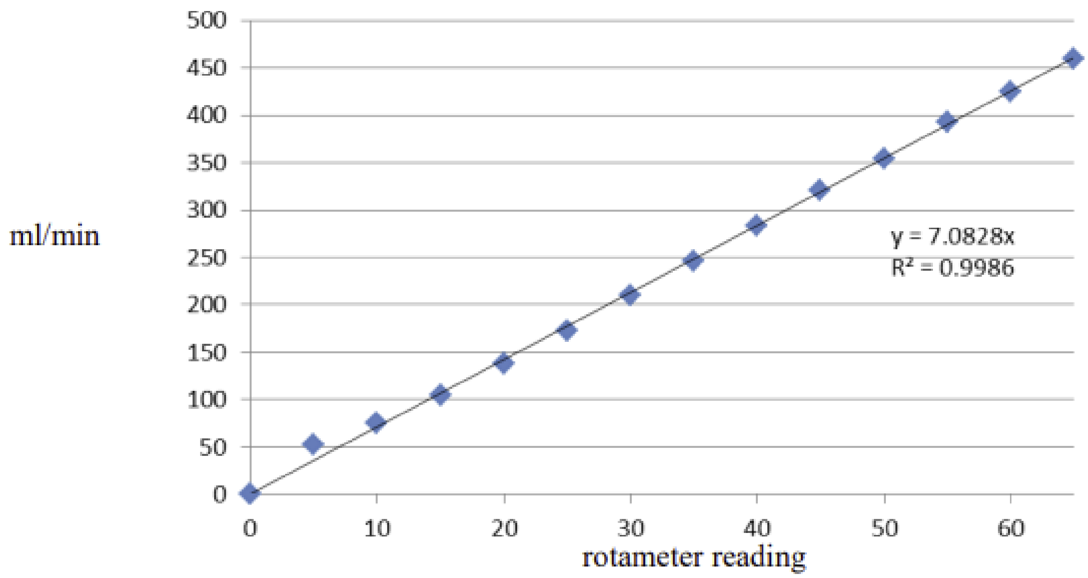


Figure 10. CO_2 rotameter calibration curve.

"The Political Ecology of Mangrove Forest Restoration in Thailand: Institutional Arrangements and Power Dynamics"

By: Benjamin S. Thompson

Abstract:
Mangrove forest restoration is practiced across the (sub)tropics to suppress ongoing deforestation and degradation of coastal ecosystem services and biodiversity. This article critically assesses mangrove restoration policies and initiatives in Thailand, using a political ecology lens focussed on institutional arrangements and power dynamics. Analysis based on interviews with 44 respondents shows how formal and informal institutions created by weak actor relations can inhibit long-term success. Revealed are inconsistencies between national mangrove restoration policies and the financial capacity of the government agency tasked with policy implementation. This can create a reliance on private-sector funding via corporate social responsibility (CSR), which centres decision-making power with firms regarding how, where, and when mangrove rehabilitation is implemented. Loosely-defined national targets lead stakeholders to report 'false successes' based on the spatial area planted, rather than on the long-term survival rate of afforested or reforested mangroves. This creates a cycle of failure' with little institutional learning (i.e., feedbacks on the ecological reasons for failure), and duplicated rehabilitation efforts. The strong institution of corporate philanthropy in Thailand makes subsequent CSR money readily available, while coinciding restoration events with public holidays associated with the Thai Royal Family motivates local participants to try again. Contemporary narratives from two progressive mangrove rehabilitation projects – with long-term collaboration, cooperation, and monitoring – help identify recommendations for overcoming these long-standing institutional challenges. The article demonstrates how weak and unequal actor relations – resulting from capacity limitations, power asymmetries, and cultural ideologies – creates gaps between policy design and implementation, thus leading to ineffective environmental governance.

Link to full document:
https://www.zsl.org/sites/default/files/media/2018-08/Political%20Ecology%20-%20Mangrove%20Restoration%20in%20Thailand.pdf

Important Organizations in Mangrove Remediation

- Mangrove Action Project
    - https://mangroveactionproject.org/mangrove-restoration/
    - Community-Based Ecological Mangrove Remediation
    - Restoring The Natural Mangrove Forest
- Mikoko Pamoja, The Global Mangrove Alliance
    - https://www.mangrovealliance.org/initiatives/
    - Promoting restoration of mangroves, research in climate remediation, and policy change in favor of ecological protection
    - Roots of Hope
- United Nations: Communities of Ocean Action
    - https://sdgs.un.org/topics/oceans-and-seas/coas
    - The UN has identified 7 marine communities, including mangroves, in dire need of protection and restoration
    - Save the ocean — protect the future
- One Child One Tree
    - https://onechildonetree.wordpress.com/project/
    - Natalia Sali's initiative to get young students involved in the restoration of their local ecosystem in the Philippines, including replanting mangrove trees

Educational Videos about Mangroves

Mangroves and Their Benefits

https://app.animaker.com/video/U1RVURNHKAFDMCT1

Mangroves are in Trouble?

https://app.animaker.com/video/XYN4DPAHBB2H29YL