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Assessing CO₂ Capture on Amine Sorbents at Low Vacuum Swing Conditions

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Assessing CO₂ Capture on Amine Sorbents at Low Vacuum Swing Conditions

Honors Research Paper

Brock Haas and Payton Taylor

Spring 2024

ABSTRACT

The urgent need to combat climate change has spurred significant interest in carbon capture technology aimed at reducing the effects of greenhouse gas emissions. Despite previous efforts showing positive progress in carbon capture technology, challenges remain in optimizing their scalability due to economic viability. In this study, the primary objective is to investigate a novel approach to enhance the effectiveness of carbon capture through experimental trials focused on amine sorbents at low vacuum swing conditions. This approach was investigated by first building an experimental reactor comprising of a sealed glass tube connected to gas flow lines. Various sorbents, including TPSENa, pure TiO₂, and a 4:1 ratio of PVA:TiO₂, were tested individually inside the glass reactor. Each trial involved adding sorbent, pulsing electric currents, and analyzing CO₂ capture using an infrared (IR) spectrometer. The reactor setup and experimental procedures were repeated for different sorbents and different configurations, with data collected for analysis. The experimental trials showed that TSPENa and PVA:TiO₂ were capable of CO₂ production, while pure TiO₂ needs to be further studied. All sorbents proved non-thermal plasma is a sufficient avenue that allows energy to be concentrated on bond breaking. The PVA:TiO₂ ratio proved to be the superior sorbent for CO₂ capture. A reactor with a distributed configuration filled with a 4:1 ratio of PVA:TiO₂ sorbent and pulsed with an input of 70 V and 70 kHz for 3 s – 5 s is recommended to maximize CO₂ product. The research confirmed the original hypothesis of the experiment of the distributed copper ring orientation offering a more efficient method for creating non-thermal plasma and enhancing CO₂ capture. The research aims to contribute to the advancement of carbon capture technologies by providing an initial framework for an alternate avenue in scaling carbon capture to an industrial scale.

Key words: CO₂ emissions, amine sorbent, vacuum swing absorption, non-thermal plasma

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1. INTRODUCTION

Carbon dioxide (CO₂) emissions have steadily increased in recent years due to the burning of fossil fuels for energy consumption. The increased concentration of CO₂ in Earth's atmosphere has contributed to global warming and sparked debate over climate change in different regions. The uptick in CO₂ emissions has created an emphasis to find different forms of CO₂ separation technology, as current technologies are not sustainable today due to their high-energy intensity. The proposed research focuses on developing a low-energy CO₂ capture process through the development of low regeneration-energy sorbents and highly energy-efficient vacuum processes. The main research tasks include the creation and testing of gradient amine sorbents in parallel with nonthermal plasma and a VSA unit. The amine sorbent allows CO₂ to be absorbed in the form of weakly adsorbed CO₂ which can then be collected from the non-thermal plasma by applying a vacuum. The generation of non-thermal plasma allows selective bond breaking to occur and eventually increases the overall efficiency of the VSA unit. The amine sorbent allows the vacuum to be operated at ambient temperature without a significant amount of energy demand. The ability of the vacuum to be run at ambient temperature eliminates the energy intensive process of heating and cooling that typically occurs during the temperature swing adsorption process. In addition, ambient temperature operation could extend the lifetime of the amine sorbent and minimize the cost of maintenance. The proposed amine sorbent and VSA technique could revolutionize technology in the CO₂ separation field and provide a cost-effective approach for the removal of CO₂ from the air.

2. OBJECTIVES

The main objective of this research paper is to analyze the feasibility of carbon dioxide capture on amine sorbents at low vacuum swing conditions. The capture of CO₂ at low vacuum

swing conditions is a relatively new area of research but builds off thermal swing adsorption (TSA) research performed at the University of Akron in previous years. The initial research in amine-based thermal swing adsorption had promising results. The results of that research suggested amines could be further modified to enhance the number and fractions of weakly adsorbed CO₂, which will reduce the energy demand for TSA. To effectively apply VSA technology to carbon capture applications, non-thermal plasma must first be studied. The hypothesis proposed through this report suggests that a distributed copper tape orientation will provide a more efficient method for creating non-thermal plasma and, consequently, enhance CO₂ capture. This experiment aims to explore and validate or refute this hypothesis.

3. BACKGROUND

In 2022, Aderinsola Oduntan and Sean Billy at the University of Akron conducted experimental studies on utilizing vacuum for CO₂ capture under the supervision of Dr. Steven S Chuang¹. The overarching aim of the research was to enhance vacuum technology for carbon capture applications. Oduntan and Billy conducted experimental trials that were broken down into three parts¹. The initial phase of the preceding study involved pretreating the sorbent material. The sorbent material utilized in this study was TPSENa, which exhibited the capability to capture significant amounts of CO₂ with low binding energy levels (less than 45 kJ/mol)¹. Low binding energy levels associated with sorbents are critical to the research because they enable the desorption of CO₂ in the subsequent steps of the experiment. The initial stage of the experiment focused on preparing the glass-tube reactor by removing moisture to ensure optimal conditions. The second phase of the study focused on absorbing CO₂ from airflow. Following the absorption of CO₂ by the binding sites of TPSENa, the third phase, desorption, commenced. The desorption phase was focused on a cyclically pulling vacuum to facilitate the release of weakly-

binded CO₂ from TPSENa. The desorbed CO₂ was directed towards an IR machine for analysis via a carrier gas.

The outcomes from the study demonstrated promising results regarding the effectiveness of VSA in facilitating CO₂ capture¹. The study revealed that alongside CO₂ desorption, other gases were present (e.g., nitrogen and oxygen) along with water particulates¹. The previous research served as a foundation for the study discussed in this report, particularly in exploring the avenue of using non-thermal plasma to selectively release CO₂ during the desorption process.

4. NON-THERMAL PLASMA GENERATION TRIALS

The cornerstone of the research discussed in this report revolves around the process of bond formation and bond breaking. Bond formation takes place during the capture of CO₂ in the VSA unit. The key advantage of employing the VSA unit for CO₂ capture lies in its capability to enable higher purity CO₂ capture, devoid of dilution with particulates present in the surrounding environment. Before the VSA unit could facilitate the formation of these high-purity CO₂ bonds, a method to aid in the selective separation of existing CO₂ from an amine sorbent had to be utilized. As discussed in the section above, a non-thermal plasma as the vehicle to facilitate the breaking of bonds between CO₂ and amine sorbents was selected. Previous experimental trials demonstrated the ability of thermal energy to separate CO₂ from amine sorbents. However, its scalability was hindered by its non-energy efficiency. Therefore, non-thermal plasma as the vehicle for aiding the VSA unit was chosen, as it offers both favorable energy efficiency and the ability to selectively break the desired bonds. Prior to evaluating the VSA unit in capturing high-purity CO₂, the effectiveness of non-thermal plasma in the bond-breaking process was initially validated.

4.1 NON-THERMAL PLASMA EXPERIMENTAL SETUP

Before CO₂ capture trials could begin, an experimental reactor was built to house the reaction. The containment structure of the reactor consisted of a cylindrical glass tube with plastic and rubber corks at both ends of the tube. The corks were inserted into the ends of the glass tube in order to seal the reactor and prevent the incoming gas flow from leaking out. A metal connection line was added to both corks that allowed inlet and outlet gas flow lines to be connected to the reactor. The internals of the reactor were comprised of a multitude of different components. The first layer of the reactor internals consisted of glass support balls. The glass support balls were used to support the amine sorbent that would later be added to the inside of the reactor. The second layer inside the reactor was a piece of heat-resistant cloth. The cloth acted as a wall inside the reactor and prevented the amine sorbent from mixing with the glass support balls. After the glass support balls and heat-resistant cloth were added, the amine sorbent was added to the reactor. The type of sorbent used in the reactor was varied throughout the experimental trials. The different sorbents used in the trials included TPSENa, pure TiO₂, and a 4:1 ratio of PVA:TiO₂. A combination of all three sorbents was never used in the reactor, but instead, these respective sorbents were used individually in the reactor during separate trials. The amine sorbent acted as the main component of the reactor. For all experimental trials, 1 g of amine sorbent was added to the inside of the reactor. An additional piece of heat-resistant cloth and a layer of glass support balls were placed on top of the amine sorbent to complete the reactor internals. The sequence of layers on the inside of the reactor were as follows: glass support balls, heat-resistant cloth, amine sorbent (TPSENa, pure TiO₂, or 4:1 ratio of PVA:TiO₂), heat-resistant cloth, and glass support balls. The reactor glass support balls filled approximately 3/5th of the

reactor while the amine sorbent and heat-resistant cloth were located in the center of the reactor between the two layers of support media.

A piece of copper wire was run through the rubber cork and positioned in the reactor so that it came into contact with the amine sorbent. The copper wire was a key component of the reactor structure, as this allowed the amine sorbent to be pulsed with electric currents and acted as a ground electrode. Electrical tape was wrapped around the plastic and rubber corks and acted as an additional safety measure to prevent any gas from escaping the system. The final step in creating the reactor was finding a means to produce a high voltage electrode. This high voltage electrode was created by wrapping a piece of copper tape around the middle of the amine sorbent in the glass tube. The copper tape had a width of approximately 1-cm and was distributed around the reactor in two different manners. The first configuration, the centralized flow, involved wrapping a ring of copper tape around the center of the amine sorbent in the reactor. The second manner, the distributed flow, involved wrapping several evenly distributed rings around the entirety of the amine sorbent in the reactor. Centralized flow was conducted on the TPSENa trials, while distributed flow was performed on the pure TiO_2 experimental trials. A combination of centralized flow and distributed flow was used on the 4:1 ratio of PVA: TiO_2 trials. For both distributions, the piece of copper tape was placed so that the voltage power supply could be connected to the glass tube and transfer the electric current to the reactor. The steps outlined above are shown via a flowchart in **Figure 1** below.

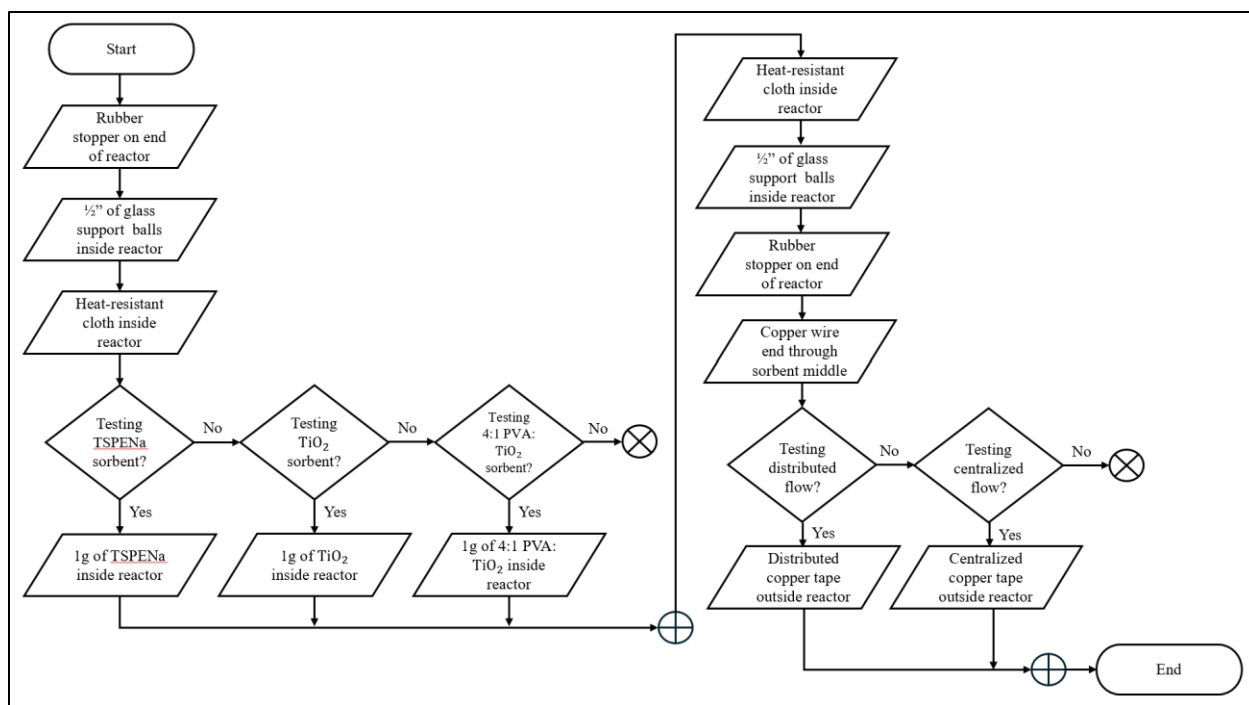


Figure 1 – Schematic of reactor preparation prior to experimental trials.

The reactor was connected to the IR spectrometer machine so the capture of CO₂ could be analyzed. The capture of CO₂ was analyzed using OMNIC software. The OMNIC software was set up for data collection before any experimental trials were conducted and a sample background was collected. The background was collected by adjusting the mirrors on the IR machine until they produced a max wavelength value between 80-100. Once the background was collected, the glass-tube reactor was connected to the IR machine. The gas feed line into the reactor was connected using gas hosing, and the exit flow from the reactor to the spectrometer machine was also connected using gas hosing. A gas line was connected to the exit valve of the spectrometer machine. This exiting gas line from the IR machine was placed in a vial containing water to see if bubbles would form in the water. If bubbles were created, then it signified that gas was successfully flowing through the reactor system.

Once the system setup was complete, the experimental trials for the TPSENa sorbent began by purging the reactor system. The reactor was purged by flowing argon gas through the system for 5 minutes at a rate of 120 mL/min. After the 5-minute period was over, the argon gas flow was closed and the feed line from the argon tank was disconnected from the reactor. An air pump was directly connected to the reactor inlet and air flowed through the system for approximately 20 minutes. After air flowed through the system for 20 minutes, electric voltage was applied to the system. A power source of 120 V was connected to the reactor by attaching electric wire clips to the centralized oriented copper tape on the reactor and the piece of copper wire coming out of the rubber cork. Three trials were conducted on the reactor where voltage and frequency were manipulated. The first trial was conducted at a voltage of 70 V and a frequency of 70 kHz. The second trial was performed at 50 V and 70 kHz, and the final experimental trial was conducted at 70 V and 50 kHz. At each different combination of voltage and frequency, the reactor system was pulsed three times. The electrical pulse was applied for approximately three seconds and the response of the TPSENa sorbent was recorded on the OMNIC software. The values for the power, current, and pulsation time were recorded for each trial. At the conclusion of the three trials, a voltage of 70 V and frequency of 70 kHz was re-applied to the system. A Seek Thermal camera was used to take thermal images of the reactor at the various voltage and frequency values. The thermal camera allowed the reactor temperature to be recorded when the reactor was pulsed. The last step of the experimental trials required flowing CO₂ through the spectrometer to create calibration peaks on the OMNIC graph. CO₂ was sent through the system on four separate occasions. The first two doses of CO₂ were a volume of 1 mL, while the last two doses were reduced to a volume of 0.5 mL. A syringe was used to measure the CO₂ and send it through the IR machine. Once the CO₂ calibration peaks were created, the OMNIC graph was

saved, and the data was collected. A visual representation of the experimental setup described above is pictured in **Figure 2** below.

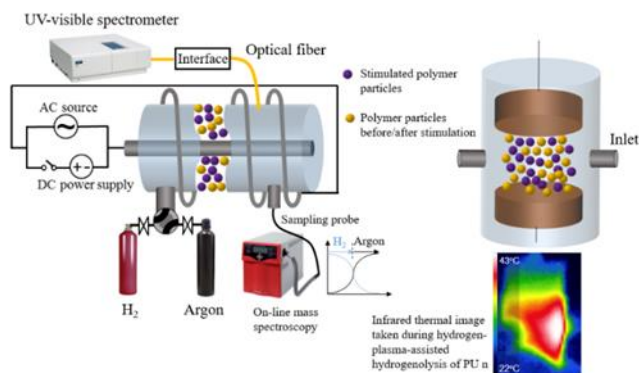


Figure 2 – Representation of experimental setup of the plasma reactor with on-line mass spectrometer and thermal imaging for analysis. Retrieved from Oduntan².

The experimental trials for pure TiO₂ were conducted in a similar manner to the TPSENA experimental trials. Once the background was collected on the OMINIC software, the trials for TiO₂ began by connecting an air pump line directly to the reactor inlet. The air feed line into the reactor was connected using gas hosing, and the reactor exit flow was connected to the IR spectrometer machine by also using gas hosing. A gas line was connected to the exit valve of the spectrometer machine. The air pump was powered on, and flow was sent to the reactor system. The exiting gas line from the IR machine was placed in a vial containing water to ensure flow was exiting from the glass-tube reactor and IR machine. A power source of 120 V was connected to the reactor by attaching electric wire clips to the distributed oriented copper tape on the reactor and the piece of copper wire exiting from rubber cork. Two experimental trials were conducted on the reactor where the voltage and frequency were manipulated. The first trial was conducted at a voltage of 70 V and a frequency of 70 kHz, while the second trial was performed at a voltage of 70 V and a frequency of 50 kHz. At each different voltage and frequency combination, the reactor was pulsed three times. The electrical pulse was applied for roughly 3 s and the response

of the pure TiO₂ sorbent was recorded on the OMNIC software. Values for the current, power, and pulsation time were recorded for each trial. A Seek Thermal camera was used to take thermal images of the reactor at the various voltage and frequency values. The final step of the pure TiO₂ experiment included sending four doses of CO₂ through the reactor to create calibration peaks on the OMINIC graph. The first two doses contained a volume of 1 mL, while the last two doses were a volume of 0.5 mL.

The experimental setup for the 4:1 ratio of PVA:TiO₂ was the same except for the voltages and frequencies sent to the reactor. The voltages and frequencies sent to the reactor and the time of pulsations were varied depending on the orientation of the copper tape. For centralized flow, the first experimental trial was conducted with 70 V and 70 kHz. The rest of the experimental trials included operating parameters of 70 V and 50 kHz, 50 V and 50 kHz, and 50 V and 70 kHz. The final condition tested on the system was once again 70 V and 70 kHz to determine if the system's response had changed after the various pulsations. The various voltages and frequencies were pulsed to the reactor in intervals of 0.5 s, 1 s, 3 s, and 5 s. The only trial that deviated from this trend was the final pulsation of 70 V and 70 kHz, as this was only pulsed at time intervals of 0.5 s and 5 s. Three pulsations were performed at each respective time interval and the response of the PVA:TiO₂ ratio was plotted on the OMINIC software. For distributed flow where the copper tape was spread evenly across the amine sorbent, the first trial was conducted at 70 V and 70 kHz. The trials that followed included pulsing the reactor with 70 V and 50 kHz, 70 V and 40 kHz, 50 V and 70 kHz, and finally 70 V and 70 kHz. The operating condition of 70 V and 70 kHz was repeated to analyze how the response of the amine sorbent had changed after receiving various pulsations. The pulsations were sent to the reactor in time intervals of 1 s, 2 s, and 3 s. The repeated condition of 70 V and 70 kHz was only pulsed for 1 s.

Three pulsations were performed at each respective time interval and the response of the sorbent was recorded on the OMINIC software. For both centralized and distributed flows, values for the pulsation time, current, and power were recorded. A Seek Thermal camera was used to take thermal images of the reactor at the various voltage and frequency trials. The last step in the centralized and distributed trials included performing the appropriate CO₂ calibration steps to create the calibration peaks on the OMINIC graph.

4.2 NON-THERMAL PLASMA TRIAL RESULTS

The amine sorbent experimental trials generated promising results on CO₂ capture. The TPSENa sorbent generated CO₂ under non-thermal plasma conditions. The generation of CO₂ from the amine sorbent was signaled by large peaks on the intensity axis of the IR spectrometer graph. The IR spectrometer graph for the TPSENa sorbent showed that CO₂ was generated at various voltage and frequency combinations when pulsed for 3 s. These combinations include 70 V and 70 kHz, 50 V and 70 kHz, and 70 V and 50 kHz. The graph shows that all tested frequency and voltage combinations produced CO₂ when pulsed for 3 s, but the trial of 70 V and 70 kHz was the most effective in CO₂ production. The combination of 70 V and 70 kHz produced intensity peaks over 0.014, while all other voltage and frequency combinations did not generate peaks over this number. This larger intensity peak value signified more CO₂ was being produced by the sorbent. The conditions of 50 V and 70 kHz produced intensity peaks around 0.013. The combination of 70 V and 50 kHz also produced peaks around 0.013, which is approximately a 7% decrease as compared to the 70 V and 70 kHz condition results for a 3 s pulse time. In addition to the generation of CO₂, another key parameter analyzed during the experimental trials was the reactor temperature. The reactor temperature was monitored to assess the feasibility of creating CO₂ at ambient temperatures. The generation of CO₂ at ambient temperatures is a key

focus, as this will reduce the amount of energy needed to create CO₂ in the process and lower operating costs. The temperature parameter throughout these trials speaks to the scalability of the work produced in this study. During the TPSENa trials, the reactor temperature did not exceed 102°F. The reactor temperature was the highest at 70 V and 70 kHz, and this larger temperature was expected due to the larger voltage and frequency being sent to the reactor. The lowest temperature was recorded at 89°F with operating conditions of 70 V and 50 kHz. The trial at 50 V and 70 kHz produced a reactor temperature of 90°F. The thermal images from the trials containing the reactor temperature are pictured in **Figures 1.F – 3.F** in *Appendix F*. After the electrical pulsations were complete, it was noted that the TPSENa sorbent had changed from a pure white color to a light black color. The TPSENa IR spectrometer graph demonstrating the generation of CO₂ can be found in **Figure 1.H** in *Appendix H*. The recorded values for voltage, frequency, time, power, and current that helped in creating the intensity peaks in **Figure 1.H** can be found in **Table 4.C**. Additional data pertaining to separate TPSENa trials can be found in **Tables 1.C – 3.C**.

Experimental trials for pure TiO₂ were conducted but no results could be concluded. The study was hindered by physical equipment failures, which disrupted the data collection process. Despite the meticulous planning and execution for the TiO₂ trials, the reliability and accuracy of the data were compromised due to issues with the IR machine recording data and producing spectrometer graphs. Due to this, it was not possible to draw accurate and meaningful conclusions or derive significant findings from this sorbent in the study. This demonstrates the importance of robust equipment maintenance, as the results from the TiO₂ sorbent remain inconclusive. Although there were failures with the functionality of the IR machine, the other two portions of data collection that were able to be recorded were the thermal images and the

resulting power and amperages from the 3 s pulse times. **Figure 1.G** in *Appendix G* below displays the resulting thermal image during the pulsation under the conditions of 70 V and 70 kHz, while **Figure 2.G** in *Appendix G* shows the resulting thermal image for the conditions of 70 V and 50 kHz. The resulting temperature changes were consistent with the trials evaluating the TPSENa sorbent, with the temperature for the 70 V and 70 kHz being higher than the 70 V and 50 kHz condition. In addition to the thermal imaging, the resulting values for voltage, frequency, time, power, and current for this portion of the study can be found in **Table 1.D** in *Appendix D* below.

For the PVA:TiO₂ trials, the sorbent was tested with two configurations of copper tape on the exterior of the reactor (i.e., centralized and distributed orientations). As stated in the experimental setup section above, the centralized reactor configuration was tested at four variations of voltage and frequency inputs to the system (i.e., 70 V and 70 kHz, 70 V and 50 kHz, 50 V and 50 kHz, and 50 V and 70 kHz). The resulting values for voltage, frequency, time, power, and current for the centralized reactor configuration for the 4:1 ratio of the PVA:TiO₂ sorbent can be found in **Tables 1.E – 5.E** in *Appendix E* below. In addition to the tabular data, thermal imaging for each 3 s pulsation was taken as well. The thermal images for each input supported the previous narrative, as the higher frequency and voltage settings increased the resulting reactor temperature. It was found the input of 70 V and 70 kHz increased the reactor temperature the most, while the settings of 50 V and 50 kHz raised the reactor temperature the least. The combination of 70 V and 70 kHz with a 3 s pulse produced a reactor temperature of 150°F, while 50 V and 50 kHz with a pulsation time of 3 s led to a reactor temperature of 95°F. These results were as expected and are consistent with the other two sorbents analyzed in this study. The temperature profiles and thermal images of the best case and worst case centralized

scenarios in terms of CO₂ production can be found below in *Appendix H*. The data from the IR spectrometer graph showed that all voltage and frequency combinations were capable of CO₂ capture. The combination of 70 V and 70 kHz was the most successful in CO₂ generation, as they produced a large number of IR bands with high intensity values. These voltages and frequencies produced multiple IR bands with intensity values above 0.40, while other voltage and frequency combinations did not produce as large of a number of high intensity values. The data also showed that a longer pulsation time led to greater CO₂ generation. A pulsation time of 1 s created miniscule intensity values of roughly 0.10, while pulsations between 3 s – 5 s produced intensity values at or above 0.40. The resulting spectrometer graph with the IR band intensities can be found in **Figure 2.H** in *Appendix H*.

The distributed experimental trials of the PVA:TiO₂ sorbent produced similar results compared to the centralized orientation. The distributed orientation for the 4:1 ratio of the PVA:TiO₂ sorbent is pictured in **Figure 3.A** in *Appendix A* below. The distributed reactor configuration was tested at four different voltage and frequency combinations (i.e., 70 V and 70 kHz, 70 V and 50 kHz, 70 V and 40 kHz, 50 V and 70 kHz). The resulting values for time, voltage, frequency, power, and current for the distributed configuration for the 4:1 ratio of PVA:TiO₂ sorbent can be found in **Tables 1.E – 5.E** in *Appendix E* below. Thermal imaging for each 3 s pulsation was taken as well. The thermal images showed that the distributed copper tape configuration produced lower reactor temperatures. The highest reactor temperature for the distributed trials was 117°F which was produced by an input of 70 V and 50 kHz. The lowest temperature of the trials was 81°F, and this was produced by an input of 70 V and 70 kHz. This was the only experimental trial where the combination of 70 V and 70 kHz did not produce the highest reactor temperature, but this can be attributed to the distributed orientation dispersing the

electric current evenly across the sorbent instead of in one centralized spot. The temperature profiles and thermal images of the best case and worst case distributed scenarios in terms of CO₂ production can be found below in *Appendix H*. The data from the IR spectrometer graph showed that all voltages and frequencies were successful in CO₂ capture. All the inputs produced consistent amounts of CO₂ with IR band intensity values spanning from 0.2 – 0.6. The various voltage and frequency inputs produced similar results, but the condition of 70 V and 70 kHz was the best overall producer of CO₂. The smallest IR band produced by 70 V and 70 kHz had an intensity value of 0.2, while the largest intensity value was roughly 0.75. This condition also produced a greater number of high intensity band values than compared to other frequency and voltage inputs. Similar to the centralized orientation results, the data also showed that a longer pulsation time led to greater CO₂ capture. A pulsation time of 1 s created intensity values ranging from 0.1 – 0.2, while pulsations of 3 s – 5s produced intensity values ranging from 0.6 – 0.8. The resulting spectrometer graph with the IR band intensities can be found in **Figure 7.H** in *Appendix H*.

4.3 NON-THERMAL PLASMA TRIAL SIGNIFIGANCE

Several conclusions can be made from the non-thermal plasma experimental trials. A conclusion about CO₂ production could not be drawn from the pure TiO₂ experimental trials, but results showed that TSPENa and the 4:1 ratio of PVA:TiO₂ were both capable of CO₂ capture. The amine sorbent that produced the most CO₂ was the 4:1 ratio of PVA:TiO₂. This sorbent was able to consistently produce IR band intensity values ranging from 0.1 – 0.8 compared to the TSPENa sorbent only producing values spanning from 0.004 – 0.014. These larger IR band intensity values demonstrated that the 4:1 ratio of PVA:TiO₂ was the superior amine sorbent for CO₂ production. The data from the various non-thermal plasma trials proved that longer

pulsation times increased the amount of CO₂ produced. This stayed true for the PVA:TiO₂ trials, as the pulsation times from 3 s – 5 s produced more CO₂ product than pulsation times ranging from 0.5 s – 2 s. The results also showed the configuration of the reactor was a key parameter that affected CO₂ capture. A distributed reactor configuration was more effective in producing CO₂ than a centralized configuration. The distributed reactor produced IR band intensity values from 0.2 – 0.75, while the centralized configuration produced intensity values from 0.1 – 0.4. In addition to producing higher intensity values, the distributed copper tape also lowered the reactor temperature. This is a major benefit, as the distributed configuration allows CO₂ to be created at ambient/lower temperatures. The last parameter that affected the generation of CO₂ was the voltage and frequency sent to the reactor. For the distribution configuration, a voltage and frequency of 70 V and 70 kHz produced the largest amount of CO₂. This input produced IR band intensity values ranging from 0.6 – 0.75, while the lowest intensity value was a respectable 0.2. Based off of this experimental data, it is recommended that a reactor with a distributed configuration be filled with a 4:1 ratio of PVA:TiO₂ sorbent and pulsed with an input of 70 V and 70 kHz for 3 s – 5s to maximize CO₂ capture.

The initial hypothesis outlined in the report suggested that arranging the copper ring in a distributed manner would be more efficient for CO₂ capture. The results of this experiment confirm this hypothesis, as the distributed orientation generated a higher amount of product formation depicted in **Figure 7.H** in *Appendix H* below. The higher amount of product in the distributed orientation is denoted by higher peaks in the IR graph, as compared to the peaks generated by the centralized orientation in **Figure 2.H** in *Appendix H* below. In addition to more CO₂ being generated in the distributed orientation, the average power consumption throughout these trials was smaller as compared to the centralized orientation. The power consumption of

the best and worst case scenarios for CO₂ production can be found in *Appendix H*. The combination of a larger amount of product being formed paired with a lower energy consumption indicates the distributed orientation is indeed a more efficient means for carbon capture as compared to a centralized orientation.

Carbon dioxide capture is a crucial process in today's world as it helps combat climate change by reducing the amount of CO₂ released into the atmosphere. CO₂ is a major greenhouse gas that contributes to global warming and its associated impacts such as rising sea levels, extreme weather events, and loss of biodiversity. The idea of amine sorbents at low vacuum swing conditions is a possible solution to the rising CO₂ levels. The research showed various amine sorbents, specifically the 4:1 ratio of PVA:TiO₂, were successful in the capture of CO₂. Non-thermal plasma proved to be a sufficient avenue for bond breaking, as the non-thermal plasma allowed selective bond breaking to occur between CO₂ and the amine sorbent. The non-thermal plasma concentrated energy on bond breaking and increased CO₂ capture efficiency. Although vacuum swing adsorption technologies were not analyzed in depth in this study, it is hypothesized VSA technologies will assist in purifying the generated CO₂. The VSA can be attached to the non-thermal plasma reactor to help remove high-purity CO₂ from the plasma. In addition, the VSA unit can act as an approach to minimize dilution of the CO₂ product. Conventional approaches of CO₂ desorption/regeneration on amine sorbents are often accompanied by high temperatures and pressures, but the utilization of non-thermal plasma and VSA technologies can allow CO₂ capture to occur at lower energy levels, low reactor temperatures, and low pressures. This will eliminate drawbacks such as low energy efficiency, high maintenance and operation cost, and difficulty in integration with renewable energy sources. By capturing and storing CO₂ emissions from industrial processes and power plants,

society's overall carbon footprint can be reduced, and steps can be taken to help achieve global targets for reducing greenhouse gas emissions. The proposed CO₂ capture on amine sorbents at low vacuum swing conditions can play a vital role in enabling a sustainable transition to a low-carbon future while supporting economic growth and innovation in cleaner energy sources.

5. REFERENES

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6. APPENDIX

A. REACTOR CONFIGURATION



Figure 1.A – The built reactor for the TPSENa sorbent experimental trials. The length of the glass tube was 3.25 inches, and the diameter was roughly 0.375 inches. The copper tape was placed on the reactor in a centralized manner for all TPSENa trials. The length of the copper tape was approximately 3.25 inches and the width of the wrapped copper tape around the sorbent was 0.5 inches. The copper tape was wrapped around the reactor multiple times to ensure most of the TPSENa sorbent was covered.



Figure 2.A – The built reactor for the pure TiO_2 sorbent experimental trials. The length of the glass tube was 3.25 inches, and the diameter was roughly 0.375 inches. The copper tape was

placed on the reactor in a distributed manner for all pure TiO_2 trials. The length of the copper tape was approximately 3.25 inches, and the width of the copper tape strands were roughly 1 cm. The width between the copper tape strands were measured to ensure the copper tape was applied evenly. This allowed the electrical pulse to the reactor to be evenly distributed among the sorbent.



Figure 3.A – The built reactor for the 4:1 ratio of PVA: TiO_2 experimental trials. The length of the glass tube was 3.25 inches, and the diameter was roughly 0.375 inches. The copper tape pictured on the reactor above was placed in a distributed manner, but other PVA: TiO_2 trials were conducted with centralized flow. The length of the copper tape for the trials was approximately 3.25 inches, and the width of the copper tape strands were roughly 1 cm for the distributed trials. The width between the copper tape strands were measured to ensure the copper tape was applied evenly. This allowed the electrical pulse to the reactor to be evenly distributed among the sorbent. For the centralized trials, the width of the wrapped copper tape around the sorbent was roughly 0.5 inches. The black discoloration in the PVA: TiO_2 sorbent was caused by the large number of electrical pulsations that were sent to the reactor.

B. EXPERIMENTAL SETUP

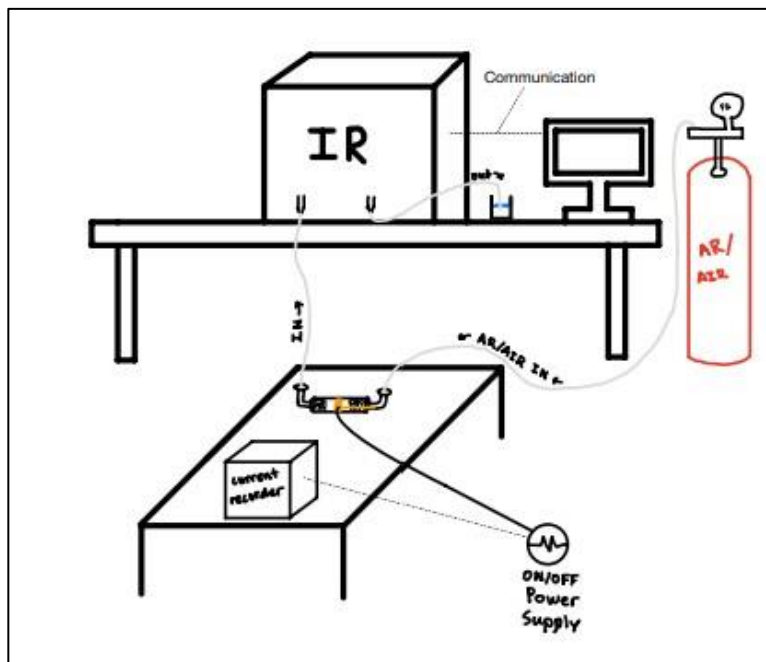


Figure 1.B – The experimental setup for all the non-thermal plasma trials. The image shows the reactor connected to the power supply and the IR spectrometer. The reactor (pictured on the top of the table) was connected to a power supply via electrical cords that supplied an electrical pulse to the reactor. Gas hosing was used to connect the outlet of the reactor to the IR spectrometer. The IR machine was used to analyze the effectiveness of CO₂ capture in the reactor. The IR spectrometer was sealed with plastic film and tape to ensure that flow to the system was not lost.

C. TPSENa SORBENT EXPERIMENTAL RESULTS

The values for the voltage, frequency, time, power, and current from the TPSENa experimental trials are summarized in the tables below.

Table 1.C – The TPSENa experimental results for a voltage of 70 V and a frequency of 70 kHz.

The results below correspond to the 70 V & 70 kHz section of the IR spectrometer graph in

Figure 1.H in *Appendix H* below.

Trial	Volts (V)	Frequency (kHz)	Time (s)	Power (W)	Current (Amp)
1	70	70	4.06	110.3	1.1
2	70	70	3.74	76.4	1.2
3	70	70	3.86	85.2	1.4
4	70	70	3.82	98.6	1.3
5	70	70	3.76	82.1	1.3
6	70	70	3.58	88.2	1.4
7	70	70	3.42	74.5	1.5
8	70	70	3.35	40.1	1.3
9	70	70	3.38	61.8	1.3
10	70	70	3.00	60.8	1.3
11	70	70	3.48	67.5	1.3
12	70	70	3.40	62.1	1.2
13	70	70	3.45	60.5	1.2
14	70	70	3.33	57.5	1.2
15	70	70	3.30	57.5	1.2

Table 2.C – The TPSENa experimental results for a voltage of 50 V and a frequency of 70 kHz.

The results below correspond to the 50 V & 70 kHz section of the IR spectrometer graph in

Figure 1.H in *Appendix H* below.

Trial	Volts (V)	Frequency (kHz)	Time (s)	Power (W)	Current (Amp)
1	50	70	3.95	58.1	0.9
2	50	70	3.96	41.4	1.0
3	50	70	3.77	52.8	0.9
4	50	70	3.45	47.8	1.0
5	50	70	3.42	49.1	0.9
6	50	70	3.32	45.8	0.9
7	50	70	3.45	26.4	0.8
8	50	70	3.41	40.1	0.8
9	50	70	3.43	41.1	0.8

Table 3.C – The TPSENa experimental results for a voltage of 70 V and a frequency of 50 kHz.

The results below correspond to the 70 V & 50 kHz section of the IR spectrometer graph in

Figure 1.H in *Appendix H* below.

Trial	Volts (V)	Frequency (kHz)	Time (s)	Power (W)	Current (Amp)
1	70	50	3.88	50.8	0.8
2	70	50	3.98	52.4	0.8
3	70	50	3.62	44.8	0.8
4	70	50	3.45	36.4	1.3
5	70	50	3.38	63.1	1.3
6	70	50	3.31	59.8	1.2
7	70	50	3.46	55.8	1.1
8	70	50	3.26	32.7	1.1
9	70	50	3.21	40.5	1.1

Table 4.C – The TPSENa experimental results for a range of voltages spanning from 50-70 V

and a range of frequencies ranging from 50-70 kHz.

Trial	Volts (V)	Frequency (kHz)	Time (s)	Power (W)	Current (Amp)
1	70	70	3.48	67.5	1.3
2	70	70	3.40	62.1	1.2
3	70	70	3.45	60.5	1.2
4	50	70	3.45	26.4	0.8
5	50	70	3.41	40.1	0.8
6	50	70	3.43	41.1	0.8
7	70	50	3.46	55.8	1.1
8	70	50	3.26	32.7	1.1
9	70	50	3.21	40.5	1.1
10	70	70	3.33	57.5	1.2
11	70	70	3.30	57.5	1.2

D. PURE TiO₂ SORBENT EXPERIMENTAL RESULTS

The values for the voltage, frequency, time, power, and current from the pure TiO₂ experimental trials are summarized in the table below.

Table 1.D – The pure TiO₂ experimental results for a voltage of 70 V and frequencies of 70 kHz and 50 kHz.

Trial	Volts (V)	Frequency (kHz)	Time (s)	Power (W)	Current (Amp)
1	70	70	3.32	42.4	0.8
2	70	70	3.55	47.1	0.9
3	70	70	3.62	48.1	0.8
4	70	70	3.53	68.8	1.3
5	70	70	3.53	69.2	1.2
6	70	70	3.47	69.2	1.3
7	70	50	3.47	57.5	1.1
8	70	50	3.36	56.8	1.1
9	70	50	3.62	38.7	1.1
10	70	50	3.25	35.8	0.6
11	70	50	3.60	36.4	0.7
12	70	50	3.68	38.1	0.7

E. CENTRALIZED AND DISTRIBUTED 4:1 PVA:TiO₂ EXPERIMENTAL RESULTS

The values for the voltage, frequency, time, power, and current from the 4:1 ratio of PVA:TiO₂ experimental trials are summarized in the tables below. **Tables 1.E – 5.E** are the results comparing centralized and distributed flow.

Table 1.E – The experimental results from the 4:1 ratio of PVA:TiO₂ sorbent. This set of data was collected under operating conditions of 70 V and 70 kHz and compares the results of both centralized and distributed flow. This condition for the respective copper tape orientations was the best performing in terms of CO₂ product generation. The results in the ‘Centralized’ column below correspond to the first 70 V & 70 kHz section of the IR spectrometer graph in **Figure 2.H** in *Appendix H* below. The results in the ‘Distributed’ column below correspond to the first 70 V & 70 kHz section of the IR spectrometer graph in **Figure 7.H** in *Appendix H* below.


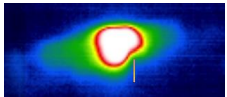

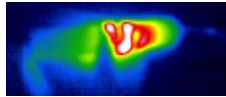
Centralized				Distributed			
70 V & 70 kHz							
Optical Pic		Thermal Pic		Optical Pic		Thermal Pic	
							
Trial	Time	Power	Current	Trial	Time	Power	Current
1	0.50	N/A	1.3	1	1.28	N/A	0.5
2	0.60	N/A	1.3	2	1.31	N/A	0.9
3	0.52	N/A	1.3	3	1.26	N/A	0.9
4	1.11	N/A	1.3	4	2.09	N/A	0.9
5	0.97	N/A	1.3	5	2.01	N/A	0.9
6	1.08	N/A	1.3	6	2.24	N/A	0.9
7	3.47	67.8	1.3	7	3.26	36.9	1.00
8	3.49	40.7	1.2	8	3.41	48.4	1.00
9	3.56	63.5	1.1	9	3.48	27.4	0.9
10	5.34	125.3	1.1	10	-	-	-
11	5.05	123.7	1.1	11	-	-	-
12	5.09	122.0	1.1	12	-	-	-

Table 2.E – The experimental results from the 4:1 ratio of PVA:TiO₂ sorbent. This set of data was collected under operating conditions of 70 V and 50 kHz and compares the results of both centralized and distributed flow. The results in the ‘Centralized’ column below correspond to the 70 V & 50 kHz section of the IR spectrometer graph in **Figure 2.H** in *Appendix H* below. The results in the ‘Distributed’ column below correspond to the 70 V & 50 kHz section of the IR spectrometer graph in **Figure 7.H** in *Appendix H* below.


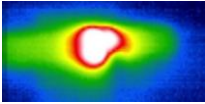

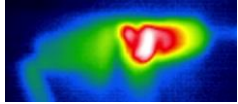
Centralized				Distributed			
70 V & 50 kHz							
Optical Pic		Thermal Pic		Optical Pic		Thermal Pic	
							
Trial	Time	Power	Current	Trial	Time	Power	Current
1	0.75	N/A	0.8	1	1.28	N/A	0.9
2	0.69	N/A	0.8	2	1.29	N/A	0.7
3	0.72	N/A	0.8	3	1.28	N/A	0.7
4	1.15	N/A	0.8	4	2.21	N/A	0.8
5	1.07	N/A	0.8	5	2.33	N/A	0.7
6	1.19	N/A	0.8	6	2.23	N/A	0.7
7	3.45	41.7	0.8	7	3.44	42.1	0.7
8	3.28	38.1	0.8	8	3.27	41.8	0.7
9	3.45	41.1	0.8	9	3.58	42.4	0.7
10	4.95	90.2	0.8	10	-	-	-
11	5.01	90.2	0.8	11	-	-	-
12	4.92	90.1	0.8	12	-	-	-

Table 3.E – The experimental results from the 4:1 ratio of PVA:TiO₂ sorbent. This set of data was collected under operating conditions of 50 V and 70 kHz and compares the results of both centralized and distributed flow. The results in the ‘Centralized’ column below correspond to the 50 V & 70 kHz section of the IR spectrometer graph in **Figure 2.H** in *Appendix H* below. The results in the ‘Distributed’ column below correspond to the 50 V & 70 kHz section of the IR spectrometer graph in **Figure 7.H** in *Appendix H* below.

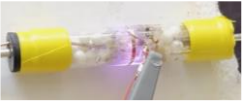
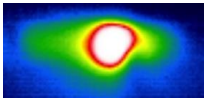


Centralized				Distributed			
50 V & 70 kHz							
Optical Pic		Thermal Pic		Optical Pic		Thermal Pic	
							
Trial	Time	Power	Current	Trial	Time	Power	Current
1	0.70	N/A	0.6	1	1.21	N/A	0.6
2	0.72	N/A	0.7	2	1.29	N/A	0.6
3	0.69	N/A	0.7	3	1.34	N/A	0.6
4	1.20	N/A	0.6	4	2.34	N/A	0.6
5	1.09	N/A	0.7	5	2.35	N/A	0.6
6	1.09	N/A	0.7	6	2.26	N/A	0.6
7	3.44	38.1	0.7	7	3.41	41.3	0.6
8	3.42	37.1	0.7	8	3.44	40.1	0.6
9	3.37	35.7	0.7	9	3.42	42.7	0.6
10	5.24	65.1	0.6	10	-	-	-
11	5.39	65.8	0.7	11	-	-	-
12	5.29	66.5	0.7	12	-	-	-

Table 4.E – The experimental results from the 4:1 ratio of PVA:TiO₂ sorbent. This set of data was collected under operating conditions of 50 V and 50 kHz with centralized flow and 70 V and 40 kHz for distributed flow. These conditions for the respective copper tape orientations were the worst performing in terms of CO₂ product generation. The results in the ‘Centralized’ column below correspond to the 50 V & 50 kHz section of the IR spectrometer graph in **Figure 2.H** in *Appendix H* below. The results in the ‘Distributed’ column below correspond to the 70 V & 40 kHz section of the IR spectrometer graph in **Figure 7.H** in *Appendix H* below.


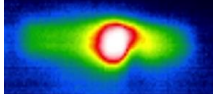

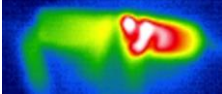

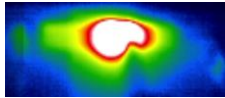


Centralized				Distributed			
50 V & 50 kHz				70 V & 40 kHz			
Optical Pic		Thermal Pic		Optical Pic		Thermal Pic	
							
Trial	Time	Power	Current	Trial	Time	Power	Current
1	0.60	N/A	0.5	1	1.31	N/A	0.6
2	0.72	N/A	0.5	2	1.26	N/A	0.7
3	0.66	N/A	0.5	3	1.30	N/A	0.7
4	0.99	N/A	0.5	4	2.23	N/A	0.7
5	0.90	N/A	0.5	5	2.27	N/A	0.7
6	1.07	N/A	0.5	6	2.35	N/A	0.7
7	3.31	24.2	0.5	7	3.49	37.1	0.7
8	3.38	13.3	0.5	8	3.58	38.7	0.7
9	3.36	25.4	0.5	9	3.35	35.7	0.7
10	4.97	42.4	0.5	10	-	-	-
11	4.90	41.7	0.5	11	-	-	-
12	5.34	46.4	0.5	12	-	-	-

Table 5.E – The experimental results from the 4:1 ratio of PVA:TiO₂ sorbent. This set of data was collected under operating conditions of 70 V and 70 kHz with centralized and distributed flow. This set of conditions was repeated at the end of the experimental trials to analyze how the response of the amine sorbent had changed after receiving numerous pulsations. The results in the ‘Centralized’ column below correspond to the second 70 V & 70 kHz section of the IR spectrometer graph in **Figure 2.H** in *Appendix H* below. The results in the ‘Distributed’ column below correspond to the second 70 V & 70 kHz section of the IR spectrometer graph in **Figure 7.H** in *Appendix H* below.

Centralized				Distributed			
70 V & 70 kHz							
Optical Pic		Thermal Pic		Optical Pic		Thermal Pic	
							
Trial	Time	Power	Current	Trial	Time	Power	Current
1	0.62	N/A	1.2	1	1.31	N/A	0.6
2	0.55	N/A	1.2	2	1.22	N/A	0.8
3	0.81	N/A	1.2	3	1.07	N/A	0.9
4	5.35	123.7	1.1	4	-	-	-
5	5.30	122.0	1.1	5	-	-	-
6	5.35	122.0	1.0	6	-	-	-

F. TPSENa THERMAL IMAGES

The thermal images from the TPSENa non-thermal plasma experiments can be found below.

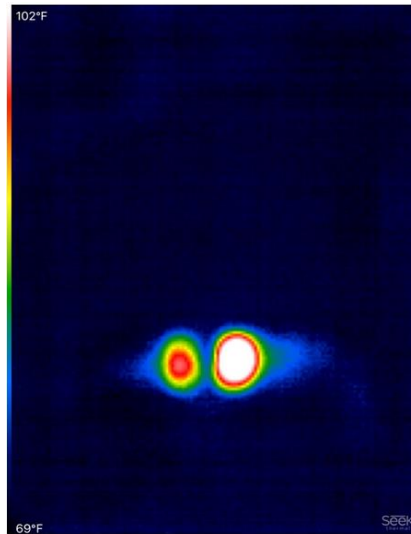


Figure 1.F – A thermal image of the TPSENa sorbent at a voltage of 70 V and a frequency of 70 kHz with a pulsation time of 3s. The experiment was performed with centralized flow.

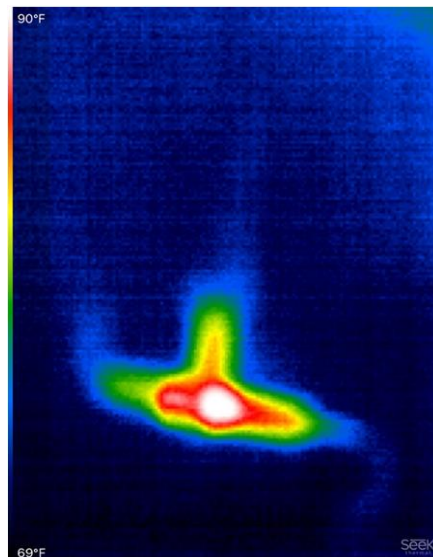


Figure 2.F – A thermal image of the TPSENa sorbent at a voltage of 50 V and a frequency of 70 kHz with a pulsation time of 3s. The experiment was performed with centralized flow.

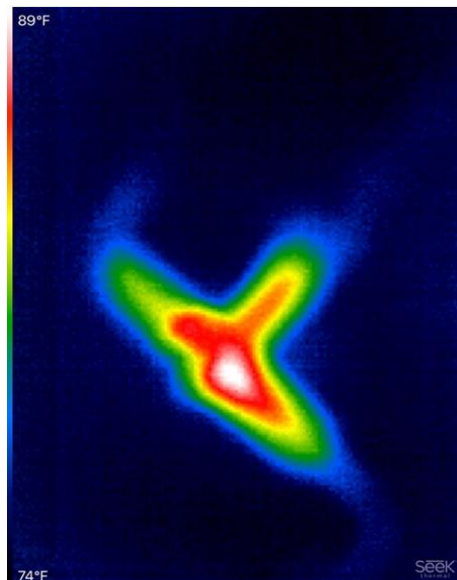


Figure 3.F – A thermal image of the TPSENa sorbent at a voltage of 70 V and a frequency of 50 kHz with a pulsation time of 3s. The experiment was performed with centralized flow.

G. PURE TiO₂ THERMAL IMAGES

The thermal images from the pure TiO₂ non-thermal plasma experiments can be found below.

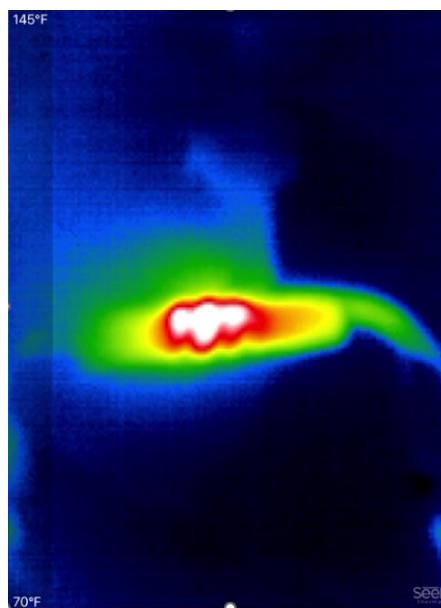


Figure 1.G – A thermal image of the pure TiO₂ sorbent at a voltage of 70 V and a frequency of 70 kHz with a pulsation time of 3s. The experiment was performed with distributed flow.

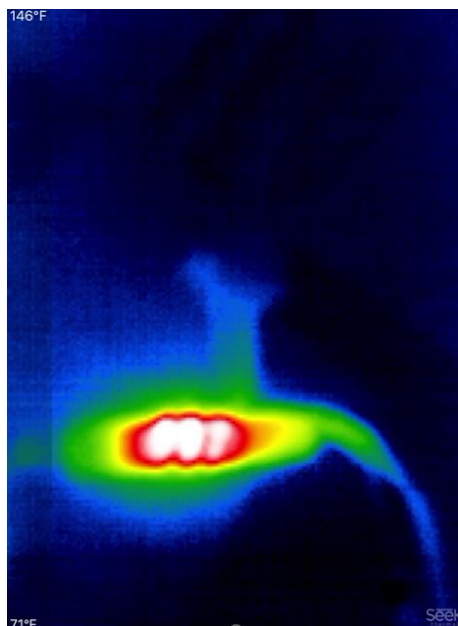


Figure 2.G – A thermal image of the pure TiO_2 sorbent at a voltage of 70 V and a frequency of 50 kHz with a pulsation time of 3s. The experiment was performed with distributed flow.

H. IR SPECTROMETER ANALYSIS & TEMPERATURE PROFILES

The following IR spectrometer graphs were created for the TPSENa and PVA: TiO_2 experimental trials to analyze the capture of CO_2 . A graph was not created for the pure TiO_2 experimental trials due to an IR spectrometer equipment failure. The figures below allowed a comparison between centralized versus distributed reactor configuration to be made. The comparison analyzes the best and worst case scenarios of the trials in terms of CO_2 production. The best case scenario for the centralized configuration was a voltage and frequency of 70 V and 70 kHz, while the worst case scenario was an input of 70 V and 50 kHz. The best case scenario for the distributed reactor configuration was an input of 70 V and 70 kHz, while the worst case scenario was determined to be 70 V and 40 kHz.

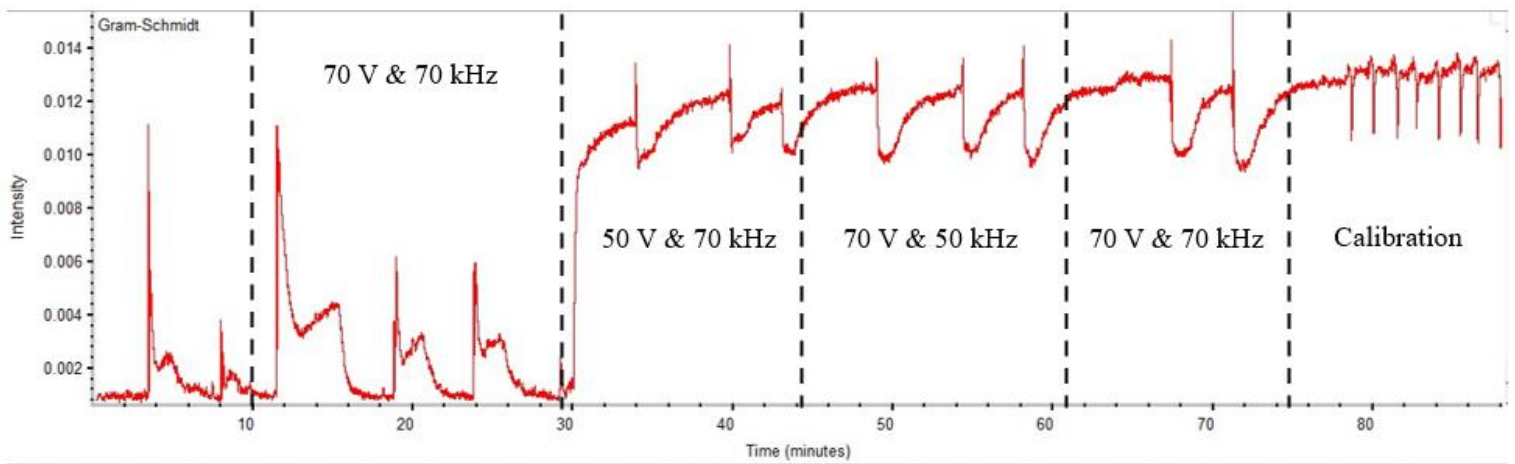


Figure 1.H – The IR spectrometer results for the TPSENa sorbent. The graph was created using the operating conditions shown in **Table 4.C**. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trial. The first two peaks on the graph can be ignored, as these were due to an operating error. The last eight peaks, beginning around 79 minutes and ending at approximately 88 minutes, were CO₂ calibration peaks. These peaks were not generated from electrically pulsing the reactor. The results shown above correspond to the respective table in **Table 1-4.C** in *Appendix C* above.

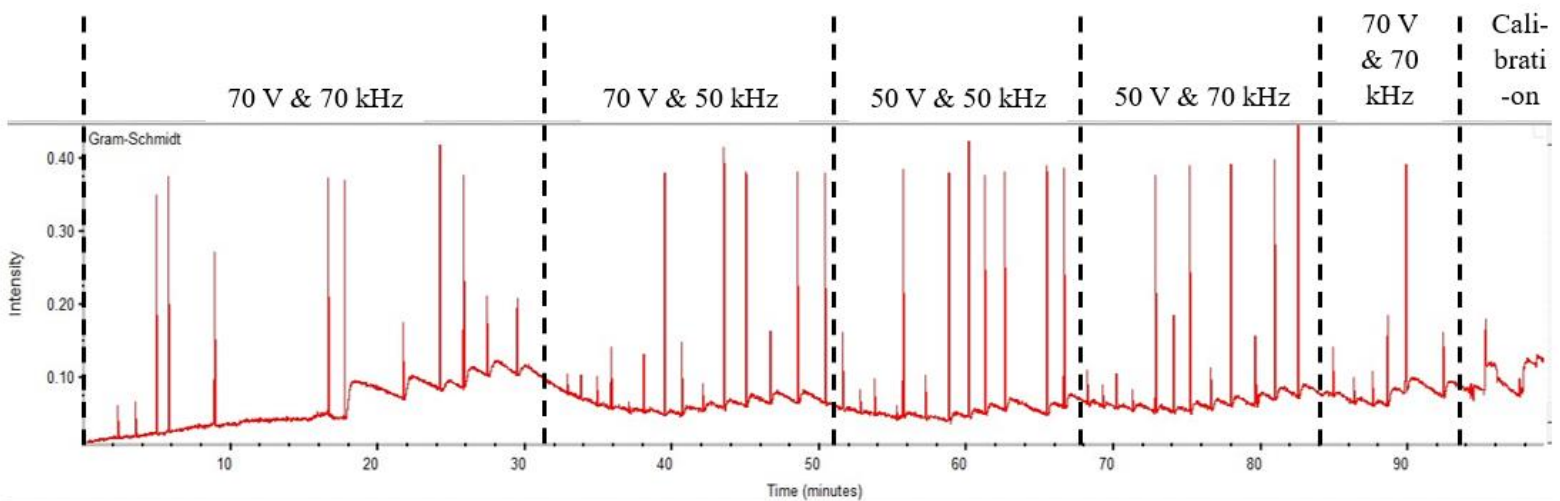


Figure 2.H – The IR spectrometer results for PVA:TiO₂ ratio with centralized flow. The graph was created using the centralized operating conditions shown in **Tables 1.E – 5.E**. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trials. The small peaks shown at the end of the graph are CO₂ calibration

peaks. Results show that IR band intensity increased as voltage and frequency increased. The results displayed in the IR spectrometer graph above correspond to the ‘Centralized’ column in **Table 1-3.E** in *Appendix E* above.

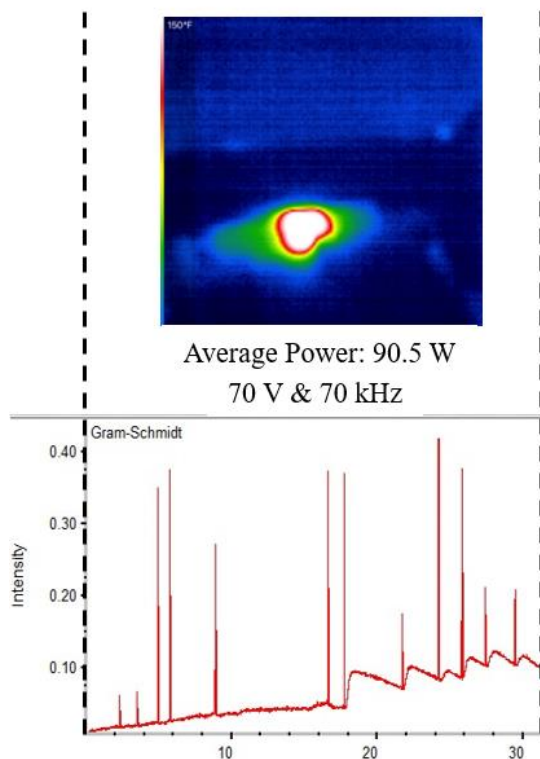


Figure 3.H – The IR spectrometer graph for 70 V and 70 kHz with centralized flow. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trial. The voltage and frequency input of 70 V and 70 kHz was the best producer of CO₂, as it generated the largest number of high intensity IR band peaks. The average power for the 70 V and 70 kHz centralized trials was 90.5 W.

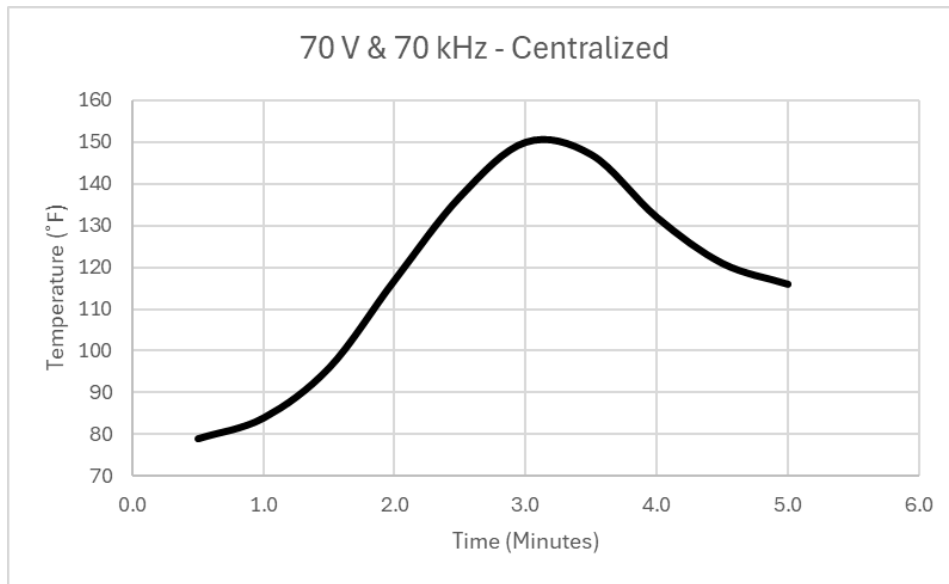


Figure 4.H – The temperature profile for the voltage and frequency combination of 70 V and 70 kHz with centralized flow at a pulsation time of 3 s. The highest temperature during the best case trial was 150°F, while the lowest temperature was 116°F.

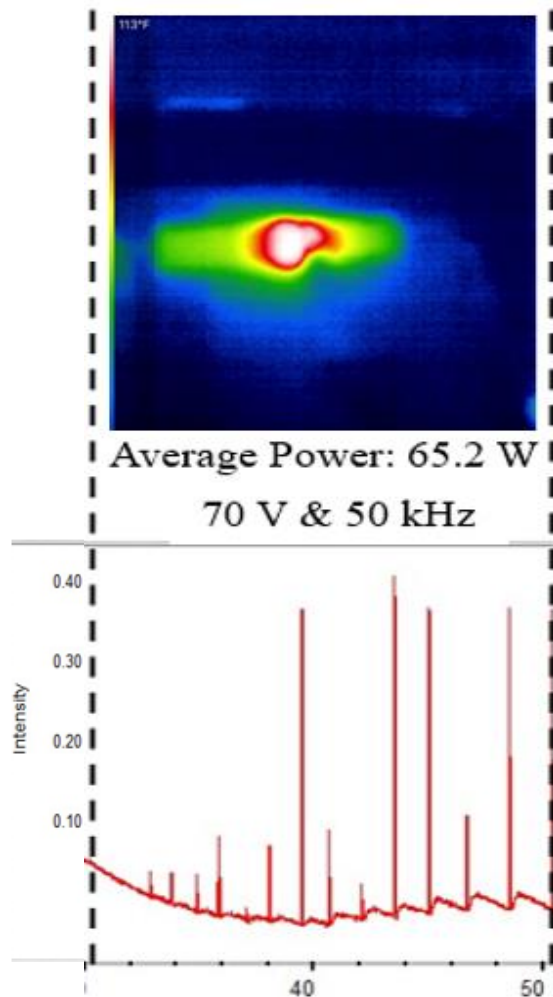


Figure 5.H – The IR spectrometer graph for 70 V and 50 kHz with centralized flow. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trial. The voltage and frequency input of 70 V and 50 kHz was the worst producer of CO₂, as it generated the lowest number of high intensity IR band peaks. The average power for the 70 V and 50 kHz centralized trials was 65.2 W.

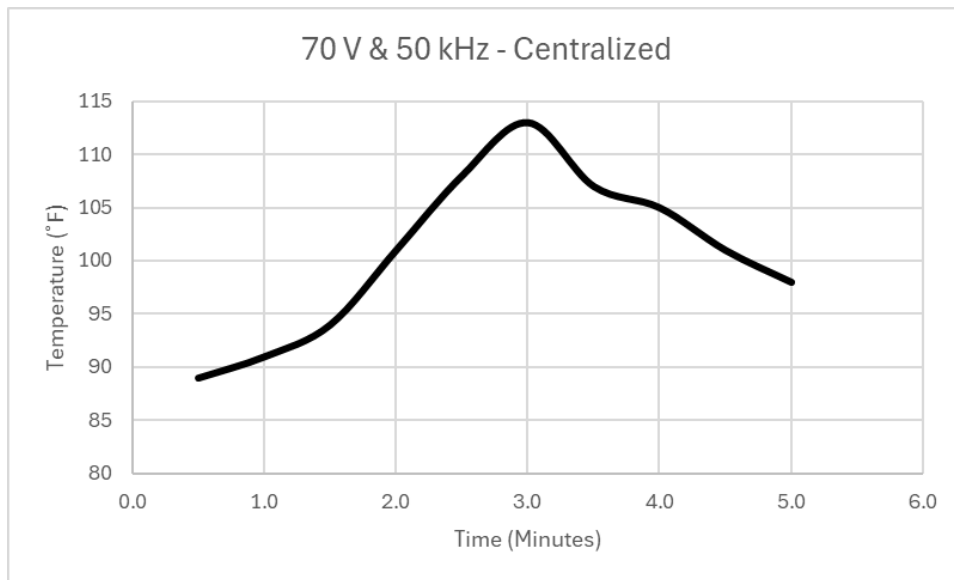


Figure 6.H – The temperature profile for the voltage and frequency combination of 70 V and 50 kHz with centralized flow at a pulsation time of 3 s. The highest temperature during the worst case trial was 113°F, while the lowest temperature was 89°F.

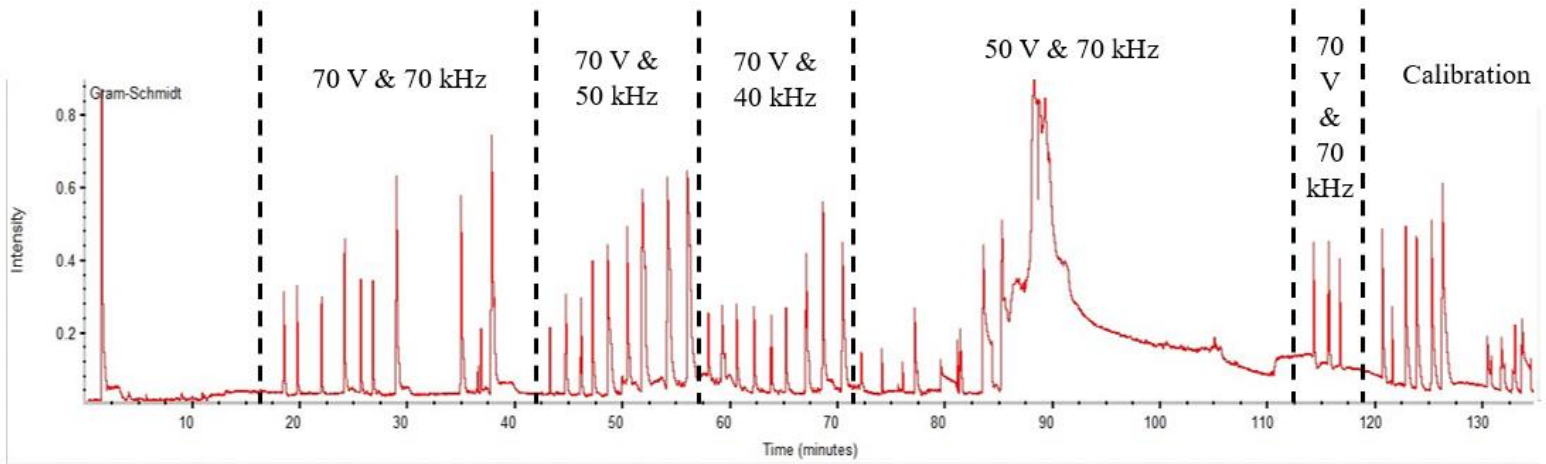


Figure 7.H – The IR spectrometer results for PVA:TiO₂ ratio with distributed flow. The graph was created using the distributed operating conditions shown in **Tables 1.E – 5.E**. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trials. The first peak on the graph can be ignored, as this peak was created by a test pulsation before the experimental trials began. Results show that IR band intensity increased as voltage and frequency increased. In addition, the results show that distributed flow created higher IR band intensity peaks than centralized flow. The results displayed in the IR spectrometer graphs above correspond to the ‘Distributed’ column in **Table 1-3.E** in *Appendix E* above.

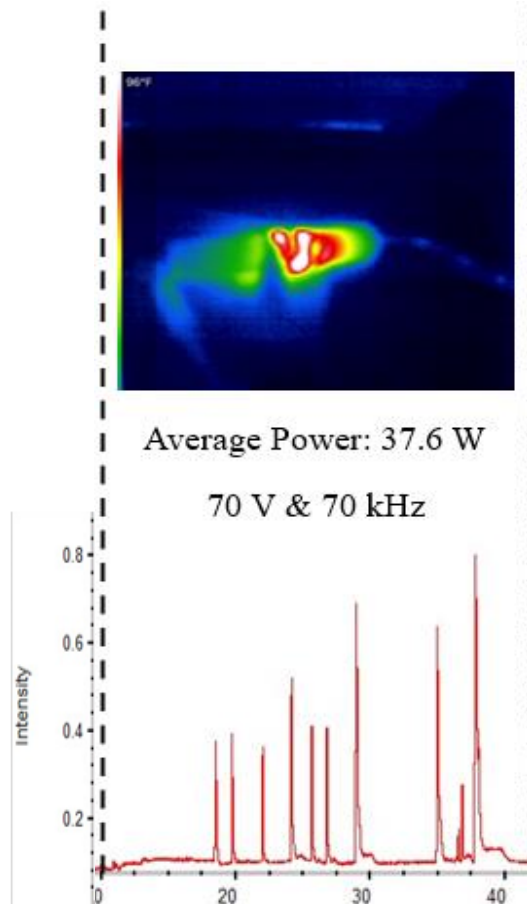


Figure 8.H – The IR spectrometer graph for 70 V and 70 kHz with distributed flow. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trial. The voltage and frequency input of 70 V and 70 kHz was the best producer of CO₂, as it generated the largest number of high intensity IR band peaks. The average power for the 70 V and 70 kHz distributed trials was 37.6 W.

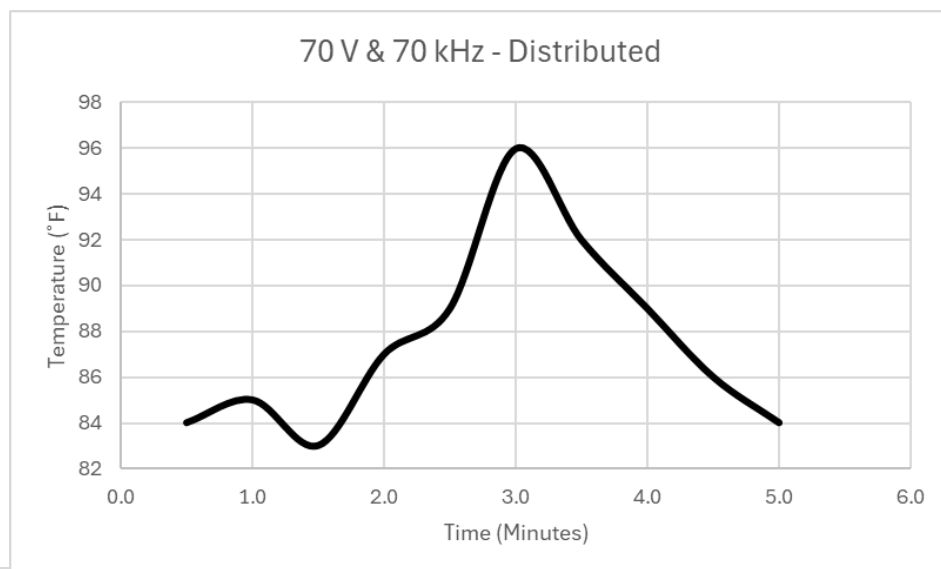


Figure 9.H – The temperature profile for the voltage and frequency combination of 70 V and 70 kHz with centralized flow at a pulsation time of 3 s. The highest temperature during the best case trial was 96°F, while the lowest temperature was 83°F. The distributed reactor temperature was lower than the centralized reactor temperature.

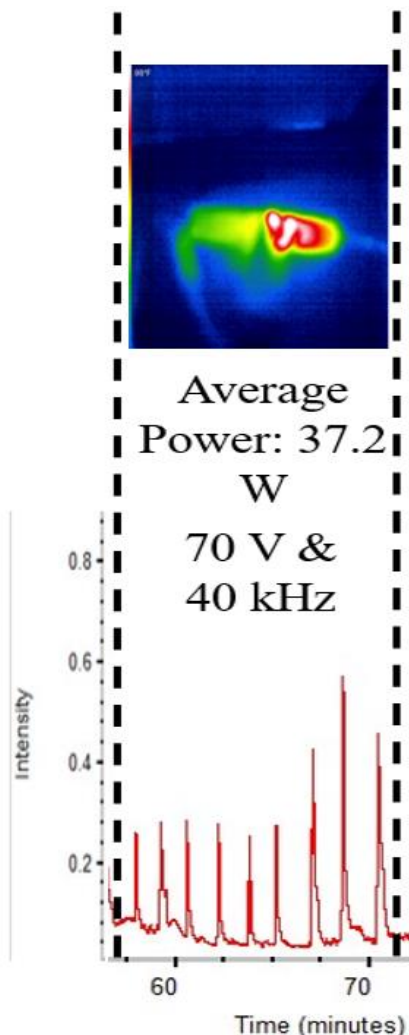


Figure 10.H – The IR spectrometer graph for 70 V and 40 kHz with distributed flow. The graph analyzes IR band intensity versus time (minutes). The peaks on the graph represent CO₂ that was generated during the trial. The voltage and frequency input of 70 V and 40 kHz was the worst

producer of CO₂, as it generated the lowest number of high intensity IR band peaks. The average power for the 70 V and 40 kHz distributed trials was 37.2 W.

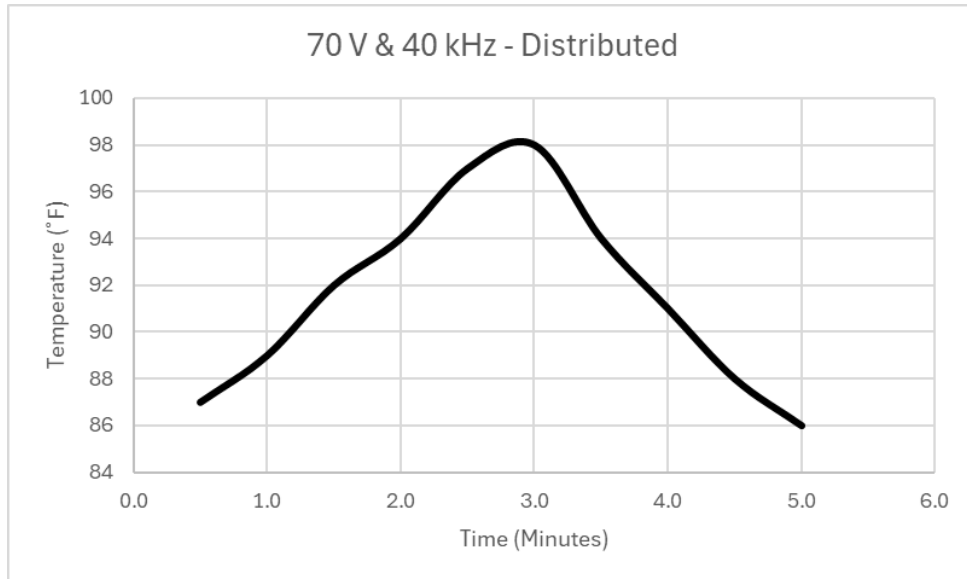


Figure 11.H – The temperature profile for the voltage and frequency combination of 70 V and 40 kHz with centralized flow at a pulsation time of 3 s. The highest temperature during the worst case trial was 98°F, while the lowest temperature was 86°F.