Mitigation on CO_2 Reduction with Direct Air Capture Technology: Preliminary Investigation to Identify the Gas Flow Behavior in Adsorbent

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Mitigation on CO_2 Reduction with Direct Air Capture Technology: Preliminary Investigation to Identify the Gas Flow Behavior in Adsorbent

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Abstract: The increase of greenhouse gaseous (GHGs) in the atmosphere driving the climate change existence, and now it becomes a global issue. Direct CO_2 capture technology from ambience air is a promising solution to address this issue. This paper promotes a Direct Air Capture (DAC) technology to be a part of solution for capturing CO_2, and describes existing research for identifying the performance of Direct Air Capture CO_2 technology, which has been developed by using selected adsorbent. A comprehensive data-driven analysis and performance evaluation of the adsorption and desorption process has been conducted. The sensors were integrated the measurements of CO_2 concentration in the upstream and downstream of the adsorbent fixed bed, along with on-site field measurements of related parameters such as pressure and temperature, to appraise the efficiency of the Direct Air Capture prototype equipment. Conclusively, the exhaustive data-backed analysis has successfully validated the efficacy of the prototype system in removing historical CO_2.

Keywords: direct air capture; carbon dioxide; adsorbent; fixed bed

1. Introduction

The total of coal proved reserves in the world are about 1,074 billion tonnes, according to BP Statistical Review of the world energy in 2021[1)]. Global coal consumption is expected to rise at an average annual rate of 0.6% between 2012 and 2040, from 6885 million tonnes in 2012 to 8100 million tonnes in 2040[2)]. The International Energy Outlook (IEO) 2016 states that between 2012 and 2040, the global energy-related CO_2 emissions will rise at an average annual rate of 1%. The fossil fuel with the highest carbon content is coal[3,4)]. Nonetheless, the use of coal in energy sector has raised an issue of global warming, since it produces CO_2 emissions as well as other undesirable gases (such CH_4, SOx, and other hydrocarbon products)[5)]

The growth of greenhouse gaseous (GHGs) emissions and the climate change has become a global issue[6–12)]. Carbon dioxide (CO_2) is the most abundant greenhouse gas in the earth atmosphere today; its concentration currently stands at ∼400 ppm by volume, while others (such as N_2O and CH_4) that have higher potency for global warming are in trace amounts[13–15)]. The increase in CO_2 in the atmosphere is mainly caused by fossil fuel combustion within the power plants and industrial activities. The burning of fossil fuels poses a significant threat to the climate by reinforcing the greenhouse effect and exacerbating global warming[16,17)].

In tackling climate change, it is crucial to consider historical greenhouse gas contributions alongside addressing current emissions[18)]. Historical greenhouse gases refer to emissions released into the atmosphere from past industrial activities and human practices. Mainly, carbon dioxide persists in the atmosphere, contributing to the ongoing warming of our earth[18,19)]. Reducing historical greenhouse gas emissions is important since they constitute a prominent portion of the overall greenhouse gas load and influence the climate over extended periods.

CO_2 emission capture and direct air capture (DAC) technologies are effective strategies that seek to diminish existing emissions and actively eliminate historical greenhouse gases, presenting a more inclusive action plan for mitigating the long-term effects of climate change[19,20)]. Several studies have focused on critically reviewing CO_2 capture systems including direct air capture technology[21–32]. With urgent action needed, DAC technology is increasingly recognized as a promising strategy for reducing CO_2 within an ambient air. DAC facilities are designed to extract historical carbon dioxide from the atmosphere and demonstrate a proactive action to tackle the environmental challenges of reducing greenhouse gas. The research and development of technology on reducing current emissions and removing historical carbon dioxide from the atmosphere through DAC application is our aim.

Direct air capture technologies are an effective solution to address the serious problem of global warming and meet the ambitious targets set out in the Paris Agreement. However, there are barriers to the deployment of this technology. The barrier needs to be overcome, and DAC CO_2 technology is expected reach the stage of commercialization. DAC research is more concentrated in certain countries, and developing DAC from research industry scale is challenging[33]. Our study attempts to contribute to the research of DAC by focusing improve the prototype for for experimental facilities. The motivation behind our research lies in establishing a state-of-the-art DAC CO_2 facility capable of conducting in-depth studies of non-isothermal adsorption and desorption phenomena. Establishing such a facility would fill a critical gap in the existing research landscape and provide a platform for testing and improving the prototype. The motivation is rooted in the broader goal of accelerating the progress of DAC technology, with the ultimate aim to develop an effective and a good performance of prototype for mitigating the CO_2 emissions

This study provides an extensive investigation of a specific DAC technology. The main objective is to assess the effectiveness of a DAC CO_2 prototype using natural zeolite granules as an adsorbent bed. The use of natural zeolite in this research is due to the fact that it is a natural adsorbent capable of capturing post-combustion CO_2 with excellent CO_2 adsorption capacity and selectivity at low temperatures and pressures and the abundant availability of natural zeolite in Indonesia[34]. However, this study considers only on the performance of DAC within the bed-adsorbent system, other issues related to energy usage, effect of moisture content, and etc., will be developed in future research.

The research seeks to provide detailed and subtle observations on the potential and limitations of the chosen DAC technology. This requires thoroughly examining operational parameters, which function as critical assessment criteria. Through a detailed evaluation of the technology's performance, the investigation aims to offer valuable insights that enrich our comprehension of its possible uses and constraints within the scope of carbon capture. Consequently, the study advances the broader discourse on strategies for mitigating climate change.

This research is also motivated with an aim to fill the research gap with the limitation of the availability of DAC CO_2 facilities. Specifically, this research aims to conduct functionality tests on the constructed DAC CO_2 prototype and evaluate its functionality based on non-isothermal adsorption and desorption phenomena by analyzing the data obtained from the prototype's initial testing. After satisfied results obtained within this work, this research will come into the more extensive and rigorous experiment to determine the significant parameters of the DAC CO_2 technology to optimize the prototype.

2. Theoretical framework

Adsorption is a crucial physicochemical phenomenon with extensive applications in both industrial and scientific fields, primarily related to this research DAC CO_2. Essentially, it pertains to gathering molecules or ions from a fluid phase on the surface of a liquid or solid material. The theoretical underpinning of adsorption lies in comprehending the intermolecular forces that govern the phenomenon. Classical models like the Langmuir and Freundlich isotherms establish a basis for explaining the correlation between adsorbate concentration and the equilibrium adsorbed amount[35]. While the Langmuir model supposes a finite number of identical sites and adsorption in a monolayer, the Freundlich model permits multilayer adsorption on a heterogeneous surface.

In combination with adsorption, desorption represents the inverse process, highlighting the release of adsorbed substances from an adsorbent surface[36]. Theoretical models for desorption incorporate the impact of variables like temperature, pressure, and chemical interactions on the kinetics of desorption. Pressure Swing Adsorption (PSA) and Temperature Swing Adsorption (TSA) are utilized to create systems for effective desorption and regeneration of adsorbents, leveraging theoretical principles. Computational modeling advancements also contribute to the theoretical comprehension of desorption processes, predicting and optimizing desorption behavior under diverse conditions[37]. However, this study more focus on TSA model.

The theoretical frameworks of adsorption and desorption provide the basis for the rational design and engineering of adsorption systems in DAC CO_2. These theoretical frameworks are also used to evaluate the prototype DAC CO_2, which has phenomena that follow the theoretical framework of adsorption and desorption processes. Therefore the understanding of adsorption process and influential factors in dynamic adsorption are essential.

2.1 Adsorption Isotherm

An essential factor in adsorption is the adsorption isotherm. The relationships in adsorption isotherms explain the phenomena and interactions between adsorbate and adsorbent. In general, adsorption performance can be predicted by modelling adsorption isotherm data because adsorption isotherm models can provide information on adsorption capacity, mechanism, and performance evaluation of adsorption processes[38]. There are several adsorption isotherm models; the following isothermal models are most widely applied to evaluate adsorption performance, as shown in Table 1.

Table 1. Factor effect to adsorption capacity relationship.

Equation	Description
Langmuir Isotherm[39] $\frac{1}{Q_e} = \frac{1}{Q_{max}K_L}\frac{1}{C_e} + \frac{1}{Q_{max}}$ (1) $R_L = \frac{1}{1+K_L C_e}$ (2)	The maximum adsorption capacity is achieved due to the presence of a monolayer of the adsorbate on the surface of the adsorbent. Whereas: - Q_e is the number of adsorbate molecules adsorbed per gram of adsorbent (mg/g), - Q_{max} is the single-layer capacity of the adsorbent (mg/g), - C_e is the equilibrium concentration of adsorbate (mg/L), - K_L is the Langmuir adsorption constant. This separation factor (R_L) has the following value: - $R_L > 1$, the adsorption process is unfavorable (allowing the adsorption process to occur, most of the desorption process occurs). - $R_L = 1$, linear adsorption process (depends on the amount and concentration adsorbed). - $R_L = 0$, Irreversible adsorption process (strong adsorption).
Freundlich Isothermal[40] $\ln Q_e = \ln K_f + \frac{1}{n}\ln C_e$ (3)	Describes a type of physisorption where adsorption occurs in several layers and the bond is not strong (multilayer). Whereas: - K_f is the Freundlich constant, - H_e is the adsorbate concentration at equilibrium conditions (mg/L), - Q_e is the amount of adsorbate adsorbed per unit adsorbent (mg/g), - n is a value that indicates the degree of linearity between the adsorbate solution and the adsorption process. The value of n is explained as follows: - n=1, linear adsorption. - n<1, adsorption process with chemical interaction. - n>1, adsorption process with physical interaction. - A favorable adsorption process is expressed when $0 < 1/n < 1$, and a cooperative adsorption process occurs $1/n > 1$.

2.2 Influential factors in dynamic adsorption

Numerous researchers have extensively investigated the factors influencing the adsorption process and the capacity of adsorbents, particularly in the context of DAC systems for CO_2. The correlation between process factors and adsorption capacity is presented in Table 2. The matrix summarizes the relationship between process variables and adsorption capacity.

Table 2. Factor effect to adsorption capacity relationship.

Factor's Effect	Relationship factor's effect on adsorption capacity
Effect Temperature	While the temperature decreases, the adsorption capacity increases[41–44].
Effect Gas Concentration	As the gas concentration increases, so does the adsorption capacity[41–43].
Effect Pressure	As pressure increases, adsorption capacity increases[42,45,46].
Effect Flow Rate	As the flow rate decreases, the adsorption capacity increases[42,44,45].

The temperature of the adsorbate during the adsorption process significantly affects the adsorption capacity of the adsorbent. In each experimental study, the temperature is varied while the flow rate remains constant. Boonchuay, A. et al. conducted an experiment using a CO_2/N_2 gas mixture with a composition of 20/80%vol and a constant flow rate of 2 L/h, varying the temperature at 298 K, 333 K, and 373 K. As a result, the lowest temperature of 298 K exhibited the highest CO_2

breakthrough capacity at 6.43 mmol/g[43]. By manipulating the temperature in intervals of 298 K, 323 K, 343 K, and 363 K while maintaining a constant flow rate of 12 L/min for two conditions of CO_2 concentration of 10%vol and 13.725%vol, Ibrahim and colleagues studied CO_2 adsorption using activated carbon as an adsorbent. Their findings indicate that the temperature of 298 K offered the highest breakthrough capacity at 109.529 and 129.651 mg/g concerning CO2 concentration[41]. The study conducted by Yoro, K. O., et al. aims to investigate the effectiveness of polyaspartamide in the gas mixture CO_2/N_2, with a composition of 15%/85%volum, at a constant flow rate of 1.5 mL/s and a pressure of 200 kPa. The results indicate that the lowest experiment temperature of 403 K produced the maximum adsorption capacity of 5.9 mmol/g[42]. Technical abbreviations have been explained when they are first used. Yavary and colleagues (2019) investigated the adsorption capacity of activated carbon and zeolite 5A on a gas mixture consisting of H_2, CO_2, CO, and CH_4 with a composition of 75.5/16.5/4.5/3.5 %mol, at a pressure equilibrium of 2 Bar and varying temperatures of 25^0C, 35^0C, and 45^0C. The results indicate that the lowest temperature of 25^0C yielded the highest adsorption of CO_2 at 8.08 mmol/g for activated carbon and 7.51 mmol/g for zeolite 5A. Due to limited adsorption capabilities at high temperatures, the process of adsorbate adsorption onto adsorbent is an exothermic reaction influenced by Van der Waals forces on physically adsorbed surfaces. Therefore, it was observed from these experiments that decreasing the adsorption temperature increased the adsorption capacity of the adsorbent.

The gas composition factor influences the adsorption capacity of the adsorbent in mixed gas. An experimental study is conducted by varying its composition to observe the effect of composition on adsorption capacity. Boonchuay and colleagues conducted an experiment investigating the impact of varying CO_2 composition within a CO_2/N_2 gas mixture from 20% to 80% while maintaining consistent operating conditions for each composition. Their results indicate that the amount of CO_2 adsorbed increased proportionally from 6.42 to 7.24 mmol/g as the CO_2 composition increased[43]. The same experimental setup with varying CO_2 compositions was conducted by Ibrahim et al. The CO_2 compositions of 10%vol. and 13.725%vol. were considered, resulting in CO_2 adsorption of 109.529 and 129.651 mg/g at an adsorption temperature of 30°C[41]. Higher CO_2 concentration enhances CO_2 partial pressure and mass transfer, leading to shorter breakthrough times. This suggests that the adsorption process is exothermic and not impacted by nitrogen gas due to the strong links between CO_2 and adsorbent particles. Higher concentrations have been observed to have even greater effects on the links formed between CO_2 and the adsorbent particles.

Another significant factor affecting the adsorption capacity of the adsorbent is the flow rate. The flow rate is altered while keeping the adsorption temperature constant. A study was carried out to investigate the adsorption capacity of CO_2 in a mixed-gas CO2/N_2 with a composition of 20/80%vol. The experiment aimed to vary the flow rate between 1, 2, and 4 L/h at an adsorption temperature of 298 K. The experiment revealed that the highest CO_2 adsorption capacity of 7.42 mmol/g was obtained at 1 L/h, which was the lowest flow rate[43]. The flow rate varied from 0.5 to 1.25 L/min in 0.25 L/min increments for each experiment while using a CO_2 concentration of 12%vol. And a column temperature of 30°C in the experimental study. Altering the flow rate at four different values resulted in a negligible change in the equilibrium dynamic capacity, which remained almost constant at zero. Technical term abbreviations, if used, will be explained when first mentioned. The text conforms to the principles of academic writing quality. The maximum adsorption efficiency was 80% when the contact duration between the mixed gas and the adsorbent was reduced, achieving 49 mmol/g at a flow rate of 0.5 L/min. However, the efficiency dropped to 70% at a flow rate of 1.25 L/min, as stated[45].

3. Material and Methods

This research was conducted experimentally on direct air capture CO_2 prototype that has been made. Natural zeolite granules are being used as an adsorbent bed in this DAC CO2 prototype. The experiment were carried out at ambient conditions. A more thorough description of the materials and methods is provided in the subheading Materials and Experimental Setup.

3.1 Material

The activated zeolite earth in the form of spherical granules from Gunung Kidul is employed for this experiment. The granulated zeolite earth has a sphere diameter of 3-5 mm and is mixed in a 50%-50% ratio with a total mass of 2.62 kg to maintain the void fraction in the fixed adsorbent, allowing air to pass through the fix adsorbent. The zeolite has a specific surface area measured using the BET method of 108.0611 m^2/g.

Based on the results of XRF analysis, it can be seen that alumina and silica compounds are the main constituent components of zeolite. The elements contained in zeolite earth can be seen in Table 3.

Table 3. The element of earth zeolite by using XRF.

Metal Oxide	Concentration (%)
SiO2	73,7384
Al2O3	14,2597
Fe2O3	2,1331
CaO	3,2305
MgO	2,3227

Na2O	0,7140
K2O	2,2307
P2O5	0,4313
SO3	0,1360

3.2 Experimental setup

3.2.1 Prototype Component and System

The DAC prototype has an overall length of 2415 mm and an effective diameter of 10 inches. The main material used in the DAC prototype is stainless steel 304 which has the characteristics of corrosion resistance.

The DAC prototype which has been designed to investigate non-isothermal adsorption, consists of essential components such as Air damper, Bed Duct and Drum Fan, each with a unique role in the adsorption-desorption processes. Please refer to Fig. 1 through 3 for visualization.

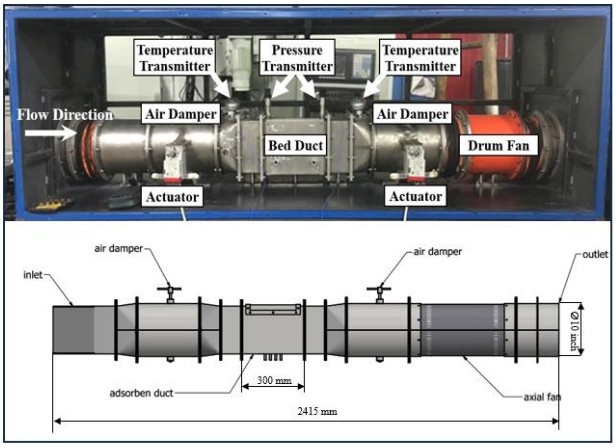

Fig. 1: Front view prototype DAC CO2.

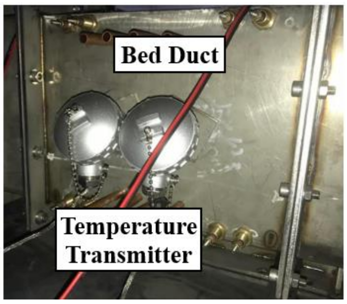

Fig. 2: Back view of bed duct where pressure transmitter is located inside the fixed bed adsorbent.

Fig. 3: Fix bed adsorbent with aluminum plate and thermowell located inside the bed duct.

Air damper serves to regulate and control air flow into the DAC system. Bed duct containing zeolite serves as a place for adsorption and desorption, while the drum fan serves to draw air flow into the system.

The adsorption chamber or bed duct functions as the system's central component, housing the fixed adsorbent bed and maintaining a regulated atmosphere for the cyclic processes. During the desorption process, four electric heaters are employed as heat sources to release CO_2 captured in this study. While the sorbent material used in this phase is a placeholder for future testing, integrating these components in the prototype provides a solid foundation for exploring the complexities of non-isothermal adsorption.

In this functional test, the air flap driven by the motorized actuator operates only in the on/off mode. During the adsorption process, the air flap is fully open. In contrast, during the desorption process, it must be closed to allow the bed channel to be evacuated by a modified air compressor acting as a vacuum pump.

3.2.2 Prototype DAC CO_2 testing setup

Carbon dioxide capture through DAC technology involves chemical and physical processes directly extracting it from the atmosphere[22,47] Fig. 4 and Fig. 5 present a general illustration of how this mechanism can occur.

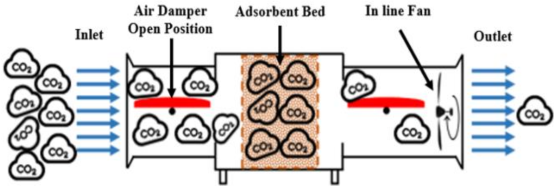

Fig. 4: Illustration adsorption process.

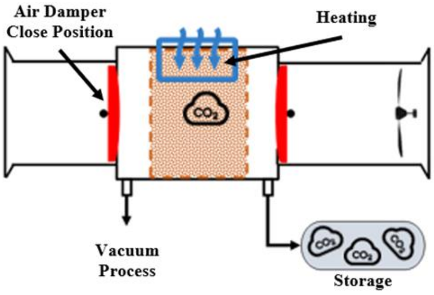

Fig. 5: Illustration desorption process.

As illustrated in Fig. 4, the adsorption process begins with using a motor fan to draw in predetermined amounts of adsorbate from the surrounding air, either through an induced draft intake mechanism or a forced draft. The adsorption process was occurred in ambient temperature. Once the adsorbate has been collected, it passes through a sorbent substance which selectively adsorbs CO_2 from the adsorbate. The choice of sorbent material depends on the specific DAC system in use. The activated zeolite allowing air to pass through the fix adsorbent, after capturing CO_2, the sorbent material requires separation via a desorption process illustrated in Fig. 5, desorption can be achieved via several techniques, such as temperature swing, pressure swing, or chemical reactions. The desorption process was run for eight hours. The four electric heaters were used to heat the adsorbent bed's top and bottom sides. Each location had two heaters, each with a wattage of 500 and 1500 respectively. During the desorption process, the temperature should be maintained in the range of 90-110°C. And to degas, the adsorbent bed should maintain a temperature above 110°C.

Following this, the trapped CO_2 is generally discharged from the sorbent material through adjustments in pressure or temperature. This step permits the recycling of the sorbent material for future use in the DAC system. The concentrated stream of CO_2 that is released is collected for subsequent processing or storage for various purposes. It can be employed in carbon utilization initiatives such as generating synthetic fuels or chemicals. Alternatively, it can be confined in subsurface geological structures or utilized in industrial procedures.

The DAC prototype's functional test setup is meticulously designed to enable a comprehensive evaluation of its performance and functionality in capturing CO_2 from the atmosphere. Figure 6 and Fig. 4 show the picture of the prototype and the schematic diagram of its measurement plan. The fundamental component of the experimental setup is the DAC apparatus, which consists of a sequence of linked reaction chambers, sorbent matter, and an advanced gas flow system. The precision-built reaction chambers are crucial in facilitating the sorption and desorption procedures that underpin CO_2 capture. Accurately calibrated sensors, analyzers, and measurement instruments are strategically positioned within the setup to ensure precise data collection. This controlled setting enables the systematic execution of the test plan, which yields valuable data on the DAC prototype's performance under diverse conditions and contributes to iterative refinements.

In this experimental setup (Fig. 6), TT01, TT02, TT03, and TT04 are temperature transmitters. They are all resistance temperature detectors (RTDs). TT01 and TT02 are in the chamber to measure intake and outtake temperatures, respectively. TT03 and TT04 are located within the fixed bed adsorbent. Two three-wire pressure transmitters, labelled PT01 and PT02, are in the chamber to measure intake and outtake pressure. These instruments, along with the temperature and pressure transmitters, serve as vital tools for precisely measuring and transmitting temperature and pressure data, providing crucial insights into the thermal dynamics of the system in this experiment. Simultaneously, the CO_2 sensor at the intake (S1) and outtake (S2) areas, which is specifically designed for accurate CO_2 concentration measurements, contributes to a comprehensive understanding of the experimental requirements. The CO_2 sensor used in this experiment is Greystone Infrared CO_2 Sensor. This integrated approach enhances the accuracy of the measurements and ensures a comprehensive characterization of the chamber environment. These capabilities are crucial for the accuracy of research endeavors. The entire data will be recorded using DAQ 9174 - NI.

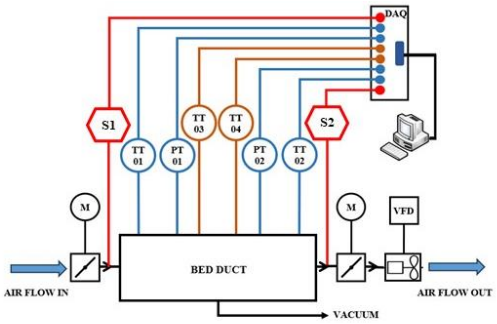

Fig. 6: Schematic Diagram DAC CO_2.

3.3 Criteria evaluation

Central to the evaluation of the DAC prototype are the critical criteria of adsorption and desorption, two core processes that define the system's efficacy in capturing and releasing carbon dioxide (CO_2). The prototype's adsorption efficiency will be rigorously assessed, measuring the percentage of CO_2 effectively captured from ambient air by the sorbent material within the defined reaction chambers. This criterion is a crucial performance indicator, reflecting the system's efficacy in efficiently adsorbing CO_2 molecules. At the same time, desorption, the controlled release of captured CO_2 from the sorbent material, is equally important. The assessment will concentrate on the thoroughness and expediency of the desorption process, guaranteeing that the DAC prototype can regenerate the sorbent material effectively for subsequent cycles, it shows the criteria in Table 4.

Table 4. Factor effect to adsorption capacity relationship.

Process	Criteria evaluation
Desorption	Pressure before and after the adsorbent bed should be below ambient pressure, showing the vacuum process's functionality. Pressure before and after the adsorbent bed should increase gradually and reach an equilibrium point between two points, showing the captured CO_2 is released.
Adsorption	The temperature of the adsorbent bed is higher than that of the chamber since it shows the exothermic process. Pressure before and after adsorbent bed should be equal, reflecting the mass transfer of adsorbate. CO_2 concentration before and after the adsorbent bed should show an increased

	amount of captured CO_2 in a certain period of time.

4. Result and Discussion

4.1 Desorption test result

The preliminary testing results for the desorption process are presented in Fig. 7 and Fig. 8.

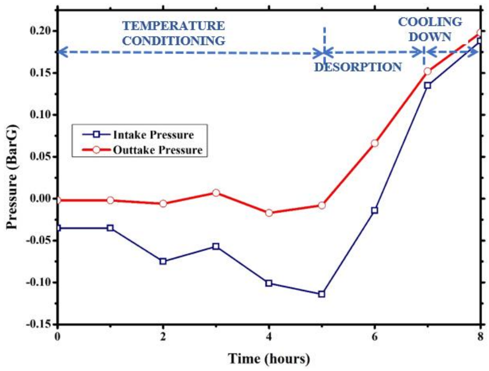

Fig. 7: Pressure chamber during the desorption process.

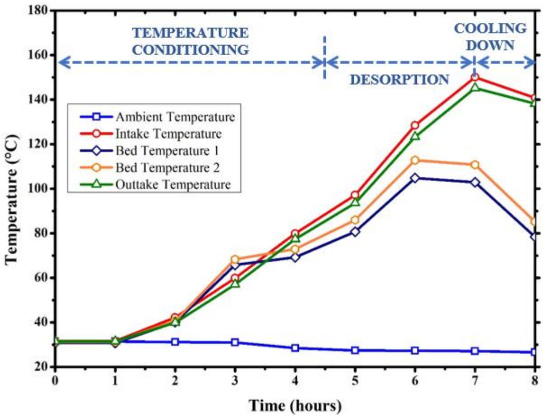

Fig 8: Temperature change profile during desorption process.

The electric heaters can heat the whole chamber, as shown in Fig. 8. The adsorbent material inside the bed is also heated, as shown by the temperature sensors TT01 and TT02. Intake bed temperature can achieve 140^0C from initially about 32°C within 8 hours. Some references$^{48)}$ indicate desorption temperature arranged about 80-130°C for Temperature Vacuum Swing Adsorber (TVSA) method. However, this information in line with the actual condition occurred in this experimental. This temperature was set in order to make sure CO2 and other gaseous release from the adsorbent. At the same time, excess heat transferred to the top surface of the bed ducting chamber was almost the same as the target temperature both in the chamber and adsorbent material. It happened because the electric heater at the top side transfers more considerable heat to the top side than to the chamber or even the sorbent material.

Figure 7 and Fig. 8 show that in the first five hours, when the temperature increasing, the pressure at the intake tends to be constant. This is due to the energy provided to the system (in this case the addition of heat) used to heat the adsorber bed up so that it reaches a temperature that results in the desorption process (the process of releasing CO_2 gas from the adsorber). When the temperature reaches above 100^0C, the pressure increases, both on the intake and outtake sides from vacuum conditions (under ambient pressure) to positive pressure, as shown in Fig. 7. This phenomenon occurred due to some CO_2 coming out of the adsorber so that the counter space pressure becomes positive pressure, which means that the CO_2 molecules captured by the adsorbent material have been released due to sufficient heat. Furthermore, when the intake and outtake temperatures continue to increase, on the opposite side, the temperature in the adsorber bed tends to be constant or even tends to decrease slightly. This is caused by the CO_2 trapped in the adsorber has been reduced and almost completely released from the adsorber. And when the intake temperature reaches 140°C, the bed temperature goes down so that the adsorber can be reused in the next cycle. Therefore, the graph in Fig. 7 and Fig. 8 above shows that the desorption process goes according to the hypothesis.

4.2. Adsorption test result

Air dampers were set on fully open, and the fan motor speed was set at 60 Hz. Two adsorbent beds are put inside a bed duct chamber with granulated zeolite earth inside that has a mass of 1.9 kg in total. The adsorption process runs at ambient temperature, and the testing results are shown in Fig. 9 to Fig. 11.

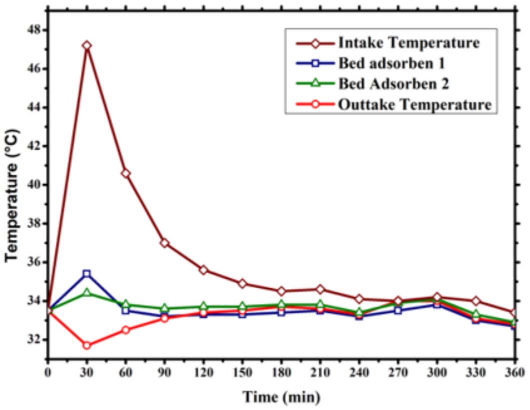

Fig. 9: Temperature change Profile during adsorption process.

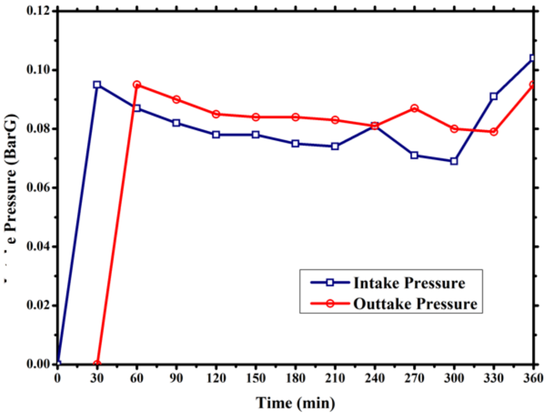

Fig. 10: Pressure change profile during adsorption process.

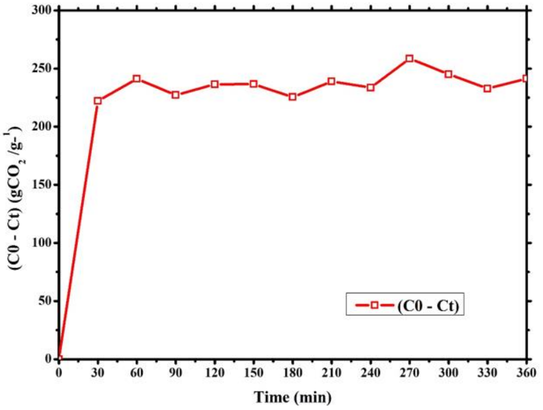

Fig. 11: CO_2 adsorbed quantity during test run.

Figure 9 illustrates the changing of temperature during the adsorption process. In the first 30 minutes, the intake temperature increases rapidly from the ambient temperature to reach about 47^0C. It is caused by air hitting the adsorber bed space. It is occurred at the intake position before entering the bed and some particles were absorbed in the adsorber. This condition occurred as a result of the accumulated air in the intake position, and it causes a rapid increase of temperature and pressure. Similarly, the bed temperature also experienced an increase in temperature although not as drastic as in the intake. The adsorbent bed temperature increases from ambient temperature to reach temperature about of 35^0C. After passing the initial stage of 30 minutes, the retained air has successfully passed through the adsorber bed so that the air temperature at the intake decreases until it reaches equilibrium toward the temperature of ambient.

Figure 10 shows the changing of pressure at intake and outtake condition. The first 30 minutes indicates that the intake pressure increases rapidly. During this condition, the gas stream propagates through the adsorbent. After the gas stream passed the adsorbent and reach the outtake (after 30 minutes), it can be seen that the pressure of outtake increases. Finally they both reach the steady state condition of pressure.

In the meantime, the Fig. 11 shows that air particles (in this case CO_2) propagation. It begins to be absorbed by the sorbent with an exothermic process. It causes the temperature of the adsorbent bed also decreasing due to the release of heat from the exothermic process. At the same time, CO_2 adsorption can also be seen in the CO_2 sensor results, whereas the CO_2 concentration after the adsorbent bed is lower than before the adsorbent bed. The difference of these condition also can be seen in Fig. 11. The amount of CO_2 adsorbed on the sorbent ranges from 225 gCO_2/g to 250 gCO_2/g with an average of 234 gCO_2/g.

From the description of Fig. 9 to Fig. 11, as aforementioned, It indicates that CO_2 clearly absorbed within the adsorbent.

5. Conclusion

The DAC prototype has been developed in this research, and initial test has been conducted. The results obtained from the test have clearly indicated the occurred of process adsorption and desorption within the DAC-prototype. The phenomenon of temperature and pressure changing within the bed, as well as CO_2 measurement from the sensor were described the process of adsorbing and releasing the CO_2 from the zeolite. In the desorption process, the pressure chamber from negative pressure becomes positive pressure, and both sensors are shooed equally when the desorption finishes. This phenomenon shows that gas molecules captured by an adsorbent bed are released during this process. Meanwhile, in the adsorption process, the temperature of the sorbent material inside the adsorbent bed captures molecules from the adsorbate from value indicators given by the CO_2 sensors

However, some improvement potentially developed for further research by using this prototype of DAC. In conclusion, the prototype of DAC CO_2 is ready and could be run further for the significance parameter test.

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Nomenclature

DAC	*Direct Air Capture*
Qe	*number of adsorbate molecules adsorbed per gram of adsorbent (mg/g)*
Qmax	*single-layer capacity of the adsorbent (mg/g)*
Ce	*equilibrium concentration of adsorbate (mg/L)*
KL	*Langmuir adsorption constant*
RL	*separation factor*
Kf	*Freundlich constant,*
Ce	*the adsorbate concentration at equilibrium conditions (mg/L)*

Qe	*amount of adsorbate adsorbed per unit adsorbent (mg/g)*
n	*a value that indicates the degree of linearity between the adsorbate solution and the adsorption process*
PFO	*Pseudo-First Order*
PSO	*Pseudo-Second Order*
ΔH	*enthalpy*
ΔS	*entropy*
ΔG	*Gibbs Free Energy*
K	*equilibrium constant*
R	*universal gas constant (8.314J/mol/K)*
T	*temperature (Kelvin)*

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