

Direct Air Capture Technology and Its Application

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Abstract: Direct air capture technology (DAC) is integral to achieving carbon emission targets. This paper briefly analyses the application of DAC technology in indoor CO₂ removal and CO₂ mineralisation. Thanks to the elevated concentration of CO₂ in the air (1000ppm) and the integrated DAC unit and air conditioning unit, the indoor CO₂ removal system significantly reduces energy consumption. CO₂ mineralisation, combined with DAC technology, offers a safe solution for permanent carbon storage and the possibility of obtaining a valuable end product by selecting the right mineralised feedstock. Future research should continue to focus on the development of adsorbent materials and the integration of CO₂ capture with subsequent applications to achieve sustainability.

Keywords: Direct air capture, Indoor CO₂ removal, CO₂ mineralisation.

1. Introduction

Massive emissions of greenhouse gases have led to large-scale global climate change, including frequent bad weather, ocean acidification, biodiversity decline, etc., which have a great impact on human life and the earth's environment. In order to meet the 2°C target set out in the 2015 Paris Agreement and strive to limit the temperature rise to 1.5°C, we need to reduce CO₂ emissions on the one hand and capture and store or use existing CO₂ on the other. In this case, Direct air capture (DAC) from the environment to compensate for carbon dioxide emissions in production and life that are difficult to decarbonise is a necessary means to achieve net zero emissions or even negative emissions. DAC was proposed in 1999 and currently has a relatively high level of technical readiness (TRL6). Compared with other carbon capture technologies, DAC has no geographical restrictions, can be located close to the CO₂ utilisation or storage site to avoid transportation needs, and can solve the emission problems of many CO₂ distribution sources such as transportation and construction industries, so DAC is considered to be a promising technology. The International Energy Agency estimates that DAC's capture capacity will reach 90 million tonnes of CO₂ per year by 2030, rising significantly to 980 million tonnes of CO₂ per year (13% of total CO₂ emissions) by 2050.

Direct air capture, which removes carbon dioxide directly from the atmosphere, is an energy-intensive process due to the high energy consumption of separation and the high cost of capture (US \$27 to US \$1,000 / tonne CO₂) compared to capture costs of US \$20 to US \$100 / tonne CO₂ from large CO₂ exhaust sources^[1,2]. The combination of DAC and CO₂ utilisation technology is the fundamental way to reduce its life cycle cost and achieve low emissions. Hepburn et al. (2019) analysed the potential scale and cost of ten CO₂ use pathways involving chemicals, fuels, microalgae, building materials, and land use. The findings suggest that the total CO₂ utilisation of each path could exceed 500 million tonnes per year by 2050 and provide a direction for CO₂ application, taking into account technical and economic barriers^[3]. This paper mainly introduces two application scenarios of DAC, briefly introduces the application of DAC in indoor CO₂ removal and CO₂ mineralisation, including adsorbent

materials, coupling of DAC with other technologies and systems, and finally looks forward to the future development of this technology.

2. Indoor CO₂ Removal

Because people spend 80 to 90% of their lives indoors, the average indoor CO₂ concentration is higher than that of outdoor air. Previous studies have reported that indoor CO₂ concentrations are related to occupancy and activity types, such as 1,850 PPM for offices, 2,800 PPM for schools, 3,000 to 8,000 PPM for spacecraft, 13,672 PPM for bedrooms, and 21,836 PPM for kitchens^[4]. Residents may suffer headaches, drowsiness and dizziness associated with high levels of carbon dioxide. China, Japan, Singapore and the World Health Organization (WHO) prescribe 1000ppm as a limit value, while the United States considers 600ppm as a high comfort level^[5]. Therefore, DAC's use in indoor environments is promising from the point of view of CO₂ concentrations and human health concerns.

In 2001, Sunita et al. (2001) realised the amine-modified porous scaffold for carbon dioxide capture on the space shuttle for the first time. Because the space station is small, high concentration of CO₂ is easy to cause, which may pose a threat to the health of astronauts. The use of materials capable of absorbing CO₂ to maintain indoor CO₂ concentration while producing O₂ to maintain the basic conditions for survival. Indoor air conditioning system mainly relies on air treatment equipment. In summer, to ensure the indoor temperature is lower than the outdoor, it needs to transfer indoor heat. Winter to ensure that the indoor temperature is higher than the outdoor requires heat input; the heat exchange can be coupled with direct air treatment equipment. Since then, amine functionalised materials have received a great deal of attention as adsorbents for the removal of indoor CO₂. Zhao et al. (2019) synthesised polyethylenimine-modified silica (PEI_x-silica) for indoor CO₂ concentration control. The results show that under the conditions of drying and 90% relative humidity, the CO₂ adsorption capacity of PEI10000-silica is 58.5 and 100.4mg/g, respectively^[6]. The adsorption capacity of 10 cycles is reduced by 7% and has long-term stability. Due to the limitations of the indoor environment, the regeneration temperature is generally controlled within 70°C,

and the performance is also affected by relative humidity^[7]. Wang et al. (2020) studied the adsorption and regeneration properties of PEI-impregnated resin (PEI-MR10) at CO₂ concentrations of 500-2000 ppm and relative humidity of 0-50%. Their experimental results showed that increasing relative humidity and CO₂ concentration both promoted the amount of CO₂ adsorbed^[8]. Ji et al. (2022) used the evaporation/condensation heat of steam compression refrigeration cycle of building air conditioning system to carry out the adsorption/desorption process for DAC, analysed the effects of adsorbent type and adsorption/desorption temperature on system performance (COP), and optimised adsorbent and refrigerant considering

CO₂ working adsorption capacity and COP. The results show that Mg-MOF-74 as adsorbent and R134a as refrigerant are the better choices. Due to indoor environmental restrictions, the desorption temperature of CO₂ needs to be limited to 70°C. At 70°C, the actual working adsorption capacity of Mg-MOF-74 is two times that of zeolite 13X, which is 0.38mol/kg. At 35°C, zeolite 13X was the adsorbent, and R134a was the refrigerant. As a result, the exergetic efficiency and COP of zeolite 13X are 81.9% and 7.21, respectively, showing the best system performance^[9]. Therefore, the development of adsorbents for indoor CO₂ removal requires attention to the effects of temperature and humidity on adsorption properties.

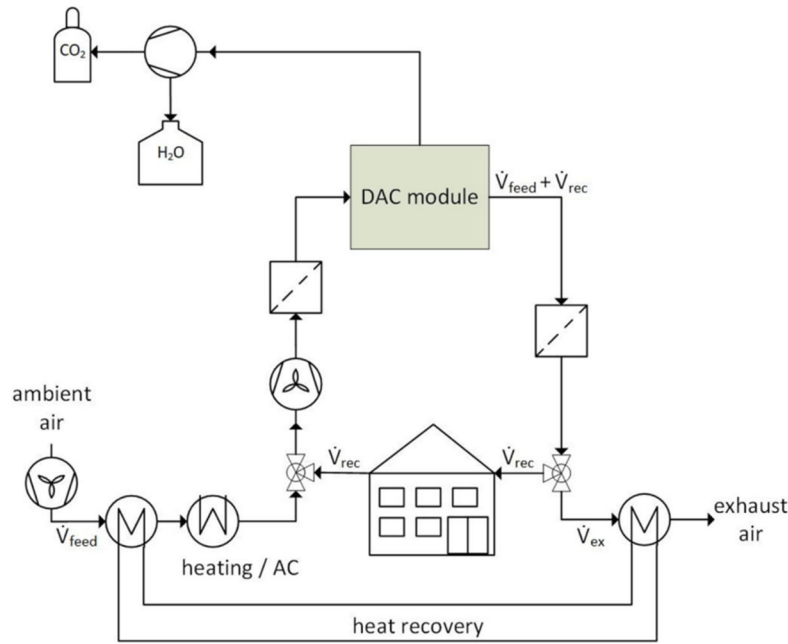


Figure 1. Schematic diagram of HVAC/DAC coupling system [10]

The thermal integration of air handling units (AHU) and Dacs is an attractive way to save energy. Kim et al. (2020) propose an integrated AHU with a CO₂ capture device that removes both CO₂ and moisture to maintain a healthy indoor environment. They note that the coupling strategy reduces the building's heat load and air dehumidification energy load^[11]. In addition, Baus et al. (2022) propose to address the tradeoff between energy-efficient building operations and a healthy indoor environment by combining heating, ventilation, and air handling systems with DAC technology^[10]. As shown in Figure 1, ambient air is first heated and then mixed with indoor air to enter the DAC unit, where CO₂ is captured and subsequently recycled for storage, and CO₂-free air enters the building interior. The results show that in a simulated 3500m³ building with 100 people inside, the coupled system with heat recovery saves 37% of energy compared to a traditional HVAC system. Although the overall energy consumption can be effectively reduced through the coupling of DAC technology and air handling equipment, it still requires a large amount of electricity to drive the system operation, and the use of new energy sources (solar, wind) can help reduce the carbon emission requirements of the process and improve the economic efficiency. Shen et al. (2022) first developed an integrated solar-powered indoor air CO₂ capture system, revealing a dynamic mass and energy balance while considering multivariate optimisation, with overall system performance indicators including CO₂ capture capacity, air

quality enhancement, and energy saving potential. In a 40m² room with 39 people and a control room concentration of less than 800 ppm, the system captured 40.655 kg CO₂ per day, reducing cooling energy consumption by 24.083 kWh (38.18%)^[12]. This study provides an important reference for the combination of indoor CO₂ capture and renewable energy.

Although CO₂ capture materials remain a technical bottleneck for DAC, DAC modules suitable for indoor operation have not yet been commercialised. However, due to higher CO₂ concentrations than outdoor environments, DAC combined with indoor CO₂ removal can achieve higher capture efficiency and provide a clean indoor environment, which makes DAC materials easier to enter the market.

3. CO₂ Mineralisation

Carbon capture and storage (CCS) is considered one of the most promising options for controlling the CO₂ footprint, and it involves three steps: capture (point source or air), transport (pipeline, ocean, etc.), and storage. CO₂ storage technologies are essential to achieve greenhouse gas reductions of up to 1200 Gt by 2100, equivalent to 15.4 Gt/a by 2050^[13]. Carbon dioxide mineralisation is a process that uses basic oxides (MgO, CaO) to solidify carbon dioxide into inorganic carbonate for permanent storage and has attracted wide attention due to its flexible location and stable product. Natural mineralisation processes are generally slow, so optimising operating conditions (temperature, pressure, etc.)

is critical to accelerate carbonisation^[14]. There are two types of CO₂ mineralisation methods: in situ and in situ^[15].

In situ carbon mineralisation refers to the direct injection of carbon dioxide into suitable formations (basalt, ultrabasic rocks, etc.) to achieve permanent carbon storage. There are two ways to inject CO₂; the first is to inject supercritical CO₂ as a separate buoyant phase into porous rock strata at depths greater than 800 meters. Alternatively, high-purity carbon dioxide at a depth of 350 meters is dissolved by water during injection, which has a lower risk of leakage because carbon dioxide has no buoyancy^[16]. CarbFix has set up a CO₂ mineralisation demonstration project in Iceland where CO₂ and H₂S from the Hellisheidi power plant are completely dissolved in the plant's condensate water and then injected into basalt^[17]. Water containing CO₂ and H₂S accelerates the leaching of metal ions due to acidity, and more than 95% of CO₂ is mineralised by isotope detection within two years.

Off-site carbon mineralisation refers to the process of transporting natural minerals or industrial wastes rich in

magnesium and calcium to carbon capture points for above-ground carbonisation^[18]. Olivine (Mg₂SiO₄), serpentine (Mg₃Si₂O₅(OH)₄) and wollastonite (CaSiO₄) are abundant in reserves and are considered promising natural minerals for carbon mineralisation. The theoretical storage capacity of Mg₂SiO₄ is estimated to be sufficient to accommodate all the carbon dioxide released on earth from the burning of fossil fuels^[19]. Alkaline paper mill waste, steel slag, fly ash and other industrial wastes are cheap and have economic and environmental advantages. In addition, the process produces a valuable product, which reduces the total cost. Katsuyama et al. (2005) used carbon dioxide from cement waste and flue gas as raw materials for carbon dioxide mineralisation to produce CaCO₃ with a purity of about 98%. The results show that the production cost (\$136/t) is significantly lower than the market price (\$200-350/t)^[20]. However, with a further increase in purity, the cost (\$323 /m³) will increase significantly.

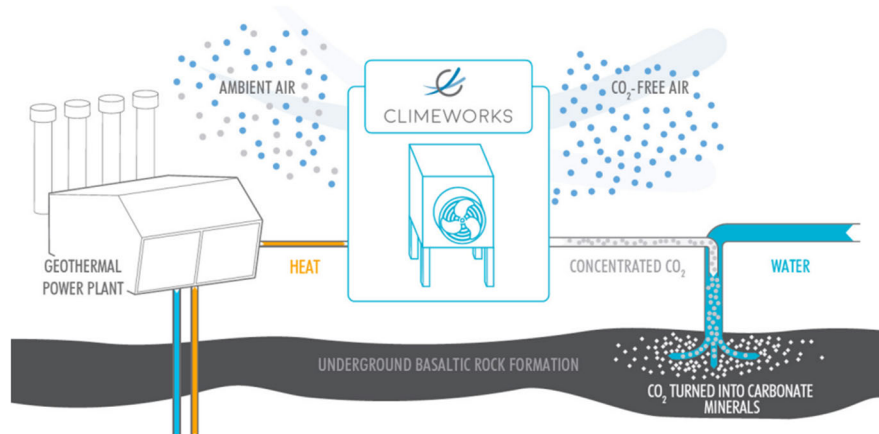


Figure 2. Schematic diagram of Climeworks-CarbFix project combining DAC and mineralised storage^[17]

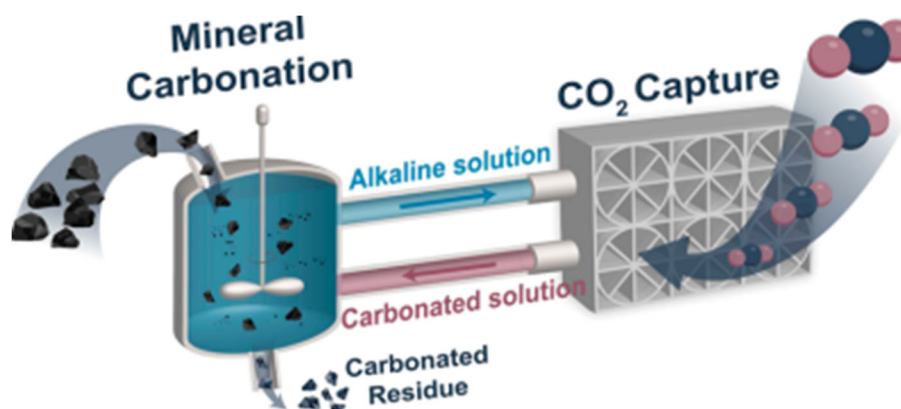


Figure 3. Schematic diagram of the integration process of DAC and mineral carbonisation^[21]

Compared to point source CO₂ capture, combining DAC with sequestration technology, regardless of geographical restrictions, can achieve negative emissions and reduce transportation costs. Climeworks and CarbFix have collaborated for the first time to develop a carbon-negative permanent storage system that includes DAC, and CO₂ mineralised storage with heat from a geothermal power plant (Figure 2). Ragipani et al. (2022) developed a DAC-coupled mineral carbonisation process using alkaline solution and fly ash as the collector and mineral feedstock, respectively (Figure 3). The results show that the carbonation efficiency is the highest under alkaline conditions, and the conversion rate

of CaCO₃ in Na₂CO₃ solution (1.9M) can reach ~80% within 1 hour, and its levelized cost is 116~133 US dollars /tCO₂, including capital and operating costs^[21].

DAC technology combined with CO₂ mineralisation has several significant advantages, including flexible DAC cells, permanent storage, low risk of leakage, and a valuable end product. CO₂ mineralisation efficiency depends on operating parameters and feedstock type. It is essential to find suitable mineralising feedstock and to study the effects of temperature, pressure and PH. In addition, mineralisation is a spontaneous exothermic process, and good heat management is beneficial to the system economy.

4. Conclusions

Under the condition that it is impossible to completely abandon fossil energy, CCUS, as an indispensable part of the carbon-neutral technology portfolio, is an important technical means and underpinning technical guarantee to achieve the temperature control goals of the Paris Agreement. DAC technology is a negative emission technology developed on the basis of traditional CCUS technology. DAC can reduce the concentration of CO₂ in the atmosphere, and it is a technical means to truly realise "negative emission". Although adsorbent materials remain a technical bottleneck in current research, CO₂ capture combined with subsequent applications could theoretically reduce overall energy consumption and achieve sustainability.

The combination of indoor CO₂ removal and DAC can promote human health and make carbon capture easier to market. Optimising the equipment of AHU-coupled DAC devices and developing adsorbents suitable for indoor environments are the focus of future research. CO₂ mineralisation, combined with DAC technology, provides a secure solution for permanent carbon storage. In addition, by selecting the right mineralised feedstock, it is possible to obtain a valuable end product.

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