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MUF-16 for point-source carbon dioxide capture

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Abstract

MUF-16 (MUF = Massey University Framework) is a next generation solid state adsorbent for point source carbon capture that is being commercialised by Captivate Technology. MUF-16 is a metal-organic framework (MOF) that is pelletized and deployed in adsorbent columns. Industrial flue gases and biogas can separated into CO2-rich and CO2-light streams using vacuum pressure-swing adsorption (VPSA) processes.

Following patenting and publication in the scientific literature, Captivate Technology has focused on de-risking the use of MUF-16 for separating CO_2, determining its performance in real-world scenarios, and scaling up to pilot demonstration at industrial sites across New Zealand. De-risking showed that the combination of selectivity, capacity, tolerance to water and impurities and ease of manufacture, and cost, makes MUF-16 an ideal adsorbent for CO_2 capture from flue gas streams. The US Department of Energy targets for purity (95%) and recovery (90%) can be exceeded using simple engineering, with high productivity and low energy consumption.

Solid state adsorbent technology for carbon capture such as that provided by Captivate Technology requires one quarter to one third of the energy required to capture one tonne of CO_2 using chemical absorption, the incumbent process used to separate CO_2 from a mixture of gases [1]. The combination of MUF-16 in a VPSA process provides very low CAPEX and OPEX costs for industrial users as demonstrated by commercial costs of analogous modular carbon capture systems. This opens up carbon capture beyond large scale applications that require economies of scale, significant CAPEX and government support. Captivate Technology provides a pathway for modular carbon capture that can be applied at small scale and large scale, economically.

Keywords: MOF; MUF-16; Captivate Technology; adsorbent, carbon capture; VPSA

1. Introduction

Captivate Technology is a CO_2 capture start-up company based in New Zealand. The company is building carbon capture capability from developing a porous, solid-state material that is a sponge for CO_2, called MUF-16. This novel MOF has the potential to significantly reduce greenhouse gas emissions by selectively sieving CO_2 from waste emissions. The process is continuous and recyclable, generating a steady stream of gaseous CO_2 to be stored or used. Captivate is rapidly moving to demonstration scale in collaboration with industrial partners and end-users.

MOFs are porous, crystalline materials built up using metal ions and organic ligands. MUF-16, shown in Figure 1, is made inexpensively and easily in large quantities using a straightforward process and readily available precursors. Its network of pores trap CO_2 via weak interactions and CO_2 is easily removed once the MUF-16 bed reaches saturation capacity. This regenerates MUF-16, for another round of carbon capture, a process that can be repeated many thousands of times. The rate of CO_2 adsorption is high for MUF-16, which means there are no kinetic limitations on its performance.

Fig. 1. MUF-16 pellets.

In addition, MUF-16 has a low affinity for nitrogen, methane and other gases, which translates into a high purity for the captured CO_2. Its durability and longevity stems from its tolerance of impurities such as water vapour, steam, H_2S, NO_x and SO_x. It is compatible with well established engineering processes such as pressure swing adsorption (PSA) and temperature swing adsorption (TSA). Ideal conditions for adsorption occur at atmospheric pressure and 30 deg C. Upstream compression is therefore not required (unlike for many other solid adsorbents where optimal adsorption occurs at pressure) which results in a very low energy process for CO_2 separation and capture. MUF-16 maintains its performance over multiple adsorption and desorption cycles with real-world flue gases. An investigation has also been conducted into the lifecyle assessment of MUF-16. This includes experimental work that has shown MUF-16 can be easily restored to pristine materials at the end of its life (expected after serval years of continuous use), avoiding landfill or incineration.

The combination of MUF-16 and VPSA provides a process technology for point source CO_2 capture from a wide variety of waste emissions sources. This includes post-combustion emissions from industry (e.g. power generation); commercial, residential and transportation sectors, cement and steel industries, biogas upgrading, geothermal power generation and others.

Captivate Technology has also rapidly grown its capability in the optimization of the adsorption and desorption process through multi-objective computational simulations. This enables process optimization under any given industrial scenario and reduces the cost of capture.

MUF-16 manufacturing has been achieved successfully up until now at the 100kg scale. At the time of writing Captivate is investigating strategies and pathways for manufacturing to occur at the multi-tonne scale.

2. Results

Captivate Technology has worked with several different emitters in New Zealand to demonstrate the ability of MUF-16 in a VPSA process at industrial sites, as shown in Table 1. MUF-16 has been tested at six different industrial locations between 2023 and 2024. Testing has occurred on a demonstration scale with a simple, two-column VPSA unit, each holding 1 kg of MUF-16. The unit receives a small slipstream of the emissions from the flue stack.

Table 1. Captivate Technology MUF-16 demonstration sites and emissions source

Industrial site and emission source	CO_2 %	Impurities in emissions stream
Geothermal power station non-condensable gases	25	N_2, O_2, H_2S, Hg
Fossil fuel power station steam turbine	8	N_2, O_2, NO_x
Sawmill wood waste biomass boiler	10	N_2, O_2, NO_x
Peaker plant natural gas turbine	4	N_2, O_2, NO_x, CO
Food and beverage industry hot water gas fired boiler	8	N_2, O_2, NO_x, CO
Cement plant	25	N_2, O_2, NO_x, SO_x

The mobile 2kg demonstration unit is shown in Figure 2 and an example industrial site location is shown in Figure 3. Straightforward gas pre-conditioning (cooling, dehumidification and particulate removal) occurs before the emission stream enters the VPSA columns containing the MUF-16.

Notably, the adsorbent withstands contaminants such as NO_x, SO_x and H2S, which do not impede the carbon capture process. Results have consistently demonstrated a clean emissions stream that is free of CO_2 with no adverse affects on the MUF-16 and no change in the effectiveness of CO_2 separation over the test period.

The following sectors and applications are targets for MUF-16 and Captivate Technology;

Biogas capture
VPSA systems for biogas upgrading to renewable natural gas (RNG) are commercially available. Captivate has conducted process calculations and written bespoke software to identify processes that deliver optimal purity, recovery, productivity and lowest energy consumption, when using MUF-16. For example, a simple four step process can deliver methane with up to 99% recovery and up to 99% purity from raw biogas.

Analysis has also been conducted to capture methane from upgraded tail gas which has CH_4/CO_2 ratio = 6/94. A two-step VPSA process can recover high quality methane from this tail gas.

Biomass combustion capture
Biomass boilers burning wood waste are commonly found in New Zealand at commercial greenhouse complexes and sawmills. Waste CO_2 can be captured using a Captivate carbon capture unit with CO_2 used for example, to enhance growth in greenhouses.

Natural gas post-combustion capture
Natural gas engines, boilers and turbines are abundant in industry for power and electricity generation and process

heat. MUF-16 as show in Table 1 has been demonstrated to be effective in capturing CO_2 from these emissions. The CO_2 concentration in the emission stream can vary from 3% in gas turbines to close to 10% in boilers. With its favourable properties, MUF-16 can be used for economic projects at small to medium scale (individual engine capture) and at low concentration.

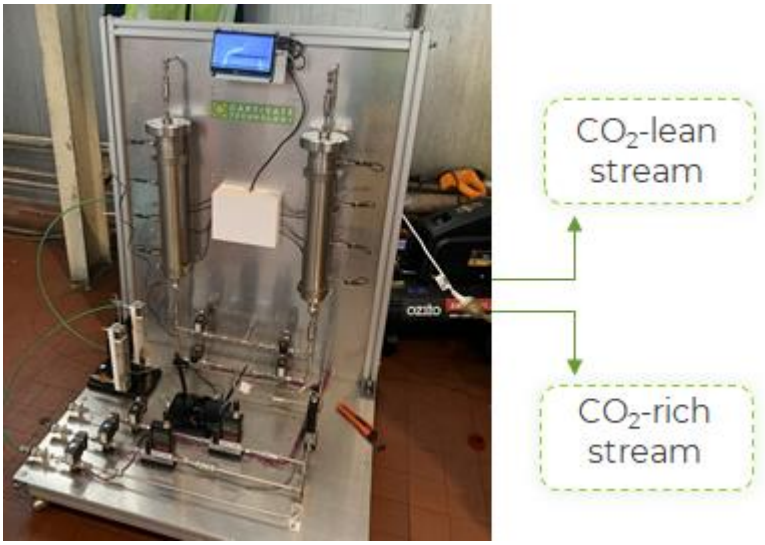

Fig. 2. Captivate Technology "2 kg" pilot demonstration unit

Fig. 3. Peaker Plant Captivate Technology demonstration site and 100MW gas turbine

Cement process emissions capture

The cement industry accounts for approximately 8% of global CO_2 emissions. Emissions occur in the manufacture of clinker which is an initial step to making cement. CO_2 emissions occur from the kiln combustion of fuel and limestone

($CaCO_{3)}$ which liberates $CO_{2.}$ The $CO_{2.}$ stream to be captured is therefore at relatively high concentration (>20%) which provides favourable economics.

Geothermal applications

Some geothermal sites emit non-condensable gases containing CO_2. MUF-16 has been demonstrated to successfully capture CO_2 amongst a mix of gases containing H_2S and mercury vapour. This challenging gas mixture has provided significant confidence about the potential longevity of MUF-16. Captivate conservatively estimates that MUF-16 can remain in commercial carbon capture equipment for 4 years before it is required to be replaced and recycled.

Syngas

CO_2 is found in raw syngas that is produced by the steam reformation of methane. As such there is significant opportunity for the inclusion of economic carbon capture units in syngas operations.

3. Financial analysis

Discounted cashflow economics using capital costs and energy consumption from commercially available small and medium scale PSA carbon capture systems has been conducted. Low energy requirements lead to low operating costs and attractive internal rates of return, even at small scale and low concentration carbon capture. While not essential for compelling business cases, where available, tax credits, carbon taxes and emission trading schemes can contribute to the revenue side of the equation.

4. Future plans

Captivate is now scaling up demonstration units that have the ability to capture up to several hundred tonnes of CO_2 per annum. These will provide the technical de-risking required to springboard into full commercial scale operations. The small footprint and flexible engineering of MUF-16 capture units makes the process ideal for both brownfield applications and greenfield sites. By stacking modular units, the capacity can be increased to meet the emissions reduction requirements of any industrial emitter or biogas operation of any size. Once captured and separated, the CO_2 can be stored or utilized.

Captivate's business model is to sell or license MUF-16 and provide CO_2 capture equipment as a turnkey solution or as a service. Captivate can tailor the process to the ultimate end use of CO_2, whether that be for underground sequestration or for the manufacture of synthetic fuels, which will depend on the local market for CO_2 and access to underground sequestration.

5. Conclusions

With its next generation MUF-16 adsorbent, Captivate Technology is positioned to be a market leader in CCUS. Carbon capture processes have historically used chemical absorption by solvents such as amines, a process that has many drawbacks. It is expensive, high in CAPEX and OPEX, requires significant operating manpower and significant energy and physical footprint to implement and maintain.

Solid-state carbon capture technology using MUF-16 expedites the role out of carbon capture by providing a cheaper, more flexible and lower energy option that is attractive for emitters and project developers. This opens up a broad market for carbon capture across all scales.

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