# Microwave swing regeneration of aqueous monoethanolamine for post-combustion $CO_2$ capture

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## HIGHLIGHTS

- Microwaves can regenerate $CO_2$ rich MEA solution quickly and at 70–90 °C.
- Microwave regeneration can reduce energy penalty, corrosion, amine degradation.
- Microwaves regeneration presents a special 'non-thermal' effect.
- Fast regeneration can reduce the size of a capture process.

## ARTICLE INFO

## ABSTRACT

Post-combustion carbon capture is a key component of the fight against global warming and climate change. Amine stripping is currently the leading post-combustion technology, and indeed is employed at the World's first and only commercial scale carbon capture project applied to a power plant, at Boundary Dam, Canada. Normally, regeneration of the spent amine solution is achieved by stripping with hot pressurized steam, at around 120–140 °C and 1–2 bar. However, production of these conditions is costly and leads to significant degradation of the amine. Moreover, the size of equipment, and hence capital costs, are also high due to the regeneration timescales involved. Here, we present proof-of-concept laboratory scale experiments to demonstrate the feasibility of regenerating the spent amine solution with microwave irradiation. We show that microwaves can regenerate spent aqueous monoethanolamine solutions quickly and at low temperatures (70–90 °C), potentially reducing overall process costs. By comparing microwave regeneration with conventional thermal regeneration we suggest that, in addition to the usual benefits of microwave heating, microwaves present a special 'non-thermal' effect.

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## 1. Introduction

Anthropogenic greenhouse gas emissions are the leading cause of global warming, with the primary contributor, $CO_2$, surpassing a record 400 ppmv atmospheric concentration in November 2015 [1]. Fossil fuel usage accounts for around 91% of total $CO_2$ emissions from human sources [2], however their continued use remains vital to meet current energy demands [3,4]. Post-combustion $CO_2$ capture (PC-CC) is widely considered as one of the most effective near-term mitigation strategies for combating $CO_2$ emissions [5]. The most matured PC-CC technology is amine scrubbing [6], which is a continuous cyclic process of $CO_2$ absorption and desorption typically performed in two packed columns [7]. Flue gas containing $CO_2$ passes through the bottom of an absorber column and contacts the $CO_2$-lean absorbent between 40 °C and 60 °C at atmospheric pressure [8]. The $CO_2$-rich solvent flows to the stripper column for thermal regeneration using hot steam between 120 °C and 140 °C and 1–2 bar to produce a purified (>99%) outlet $CO_2$ stream [9,10]. The $CO_2$-lean solution exits the bottom of the stripper and recirculates to the absorber column via a crossed heat exchanger ready for the next cycle [8]. The industry benchmark amine is monoethanolamine (MEA), typically employed as a 30 weight percent (wt%) solution in water [4]. $CO_2$ reacts with the solvated MEA to form a stable and soluble carbamate salt, as shown in Reaction 1, which may proceed to higher loading through hydration reactions. Application of heat reverts back to the original amine solution and recovers the free $CO_2$ [11–14].
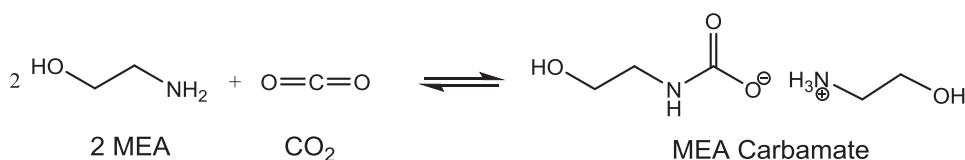
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Reaction 1 – The reaction of MEA with $CO_2$ to form a carbamate.

Amine scrubbing is a proven, if expensive, technology. The dominant process costs arise from the large equipment size, the-heat required during regeneration and thermal degradation of the solvent at the high processing temperatures [4,15]. Solutions to these problems have tended to focus on development of better solvents and optimization of the process configuration [16–19]. Here, we outline proof-of-concept laboratory scale experiments to test the feasibility of microwave swing regeneration (MSR) as an alternative approach to the conventional thermal recovery of $CO_2$ from a rich MEA solution. This is motivated by recent literature highlighting microwave heating as an effect means of regenerating solid adsorbents for $CO_2$ capture and storage [20–23]. Microwave, or dielectric, heating refers to the direct heating of a sample through interaction with electromagnetic radiation. As such, microwaves offer instantaneous and volumetric heating without [24] heat transfer restrictions associated with conventional conductive or convective heating [25]. For polar solvents, such as water or MEA, microwave heating primarily takes place via reorientation of molecular dipoles in the presence of the rapidly oscillating electric field [24,25]. A phase lag between the molecular motion and the electric field causes friction between neighbouring molecules, which ultimately leads to dissipation of the electromagnetic energy into heat [26,27]. Other important loss mechanisms occur through ion conduction in ionic solutions and Maxwell-Wagner polarization, resulting from interfacial phenomena, in inhomogeneous media [27].

The susceptibility of a substance to microwave heating is governed by its frequency-dependent complex permittivity [24]:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \tag{1}$$

where the real part, $\varepsilon'(\omega)$, is a measure of the polarizability of the dielectric by an external field and the imaginary part, $\varepsilon''(\omega)$ is the dielectric loss factor, which represents the ability to convert absorbed microwave energy into heat [24]. The average power per unit volume absorbed by a sample during microwave heating, $P_{abs}$ (W), is proportional to its dielectric response and also affected by microwave field properties, specifically the angular frequency, $\omega$ (Hz), and the average electric field strength, $E$ (V/m), which is determined by the inlet power and local electric field distribution [28]:

$$P_{abs} = \omega\varepsilon_0\varepsilon''(\omega)|E|^2 V \tag{2}$$

where $\varepsilon_0$ is the permittivity of free-space ($8.854 \times 10^{-12}$ F/m) and $V$ is the sample volume ($m^3$).

Microwave technology has long been acknowledged as an effective means to intensify chemical processes [24]. Applications have traditionally centred around microwave-assisted organic synthesis and solid adsorption-desorption systems for desiccant dehydration, volatile organic compound (VOC) recovery, air separation and water purification [24,25,27]. Many studies have reported more efficient chemical productivity and economic performance with MSR compared to conventional regeneration techniques, owing to the direct and rapid nature of microwave heating. Cherbański et al. compared the desorption kinetics of MSR to conventional temperature swing regeneration (TSR) for acetone and toluene removal from zeolite 13X molecular sieves [29]. They revealed more efficient desorption with MSR due to the direct and instantaneous heating of the adsorbent by microwave radiation, becoming more pronounced for the more polar adsorbate [29]. Hashisho and co-workers developed an MSR system for the adsorptive separation of organic vapours and binary gas mixtures, including $CO_2/CH_4$, with activated carbons and titanosilicate Na-ETS-10. Microwave desorption was found to be up to 40 times faster than conductive thermal heating and more energy efficient over multiple regeneration cycles [30–36]. Ania et al. illustrated the effects of microwave and conventional thermal regeneration on the structure and adsorptive capacity of activated carbons. An inverted temperature gradient during microwave heating encouraged diffusion of the desorbing molecules from the core of the carbon bed towards the surface leading to shorter regeneration times [37]. Polaert and co-workers have made extensive use of MSR for a broad range of solid adsorbents for water and VOC recovery [38,39]. The absorbed microwave power and dielectric properties were concluded to be the most important parameters in ensuring a favourable economic performance. Optimization of the experimental design lead to important energy savings compared to conventional TSR [38,39]. Turner et al. investigated the influence of microwave radiation on sorption and competitive sorption of polar and non-polar adsorbates in high-silica zeolites [40]. The microwaves permitted greater sorption selectivity, and also generated interesting surface temperature effects. Due to the extremely low dielectric response of silica, the bulk zeolite couples negligibly to the microwaves, however the surface silanol (hydroxyl) groups possess significant dielectric loss parameters and couple strongly