



Innovative reverse-electrodialysis power generation system for carbon capture and utilization



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ABSTRACT

Global warming has become a serious threat biosphere and effective measures are required to mitigate its intensification. To this end, carbon capture and sequestration (CCS) is a promising technology, while post-combustion capture (PCC) has been developed from CCS. However, an energy penalty during the regeneration step of the CO₂ absorbent has remained a critical problem. In the present study, a lab-scale test was conducted on carbon capture with reverse-electrodialysis (CCRED) to evaluate its potential to overcome the technical and economic drawbacks of CCS and RED. The results show that a normalized peak power density of 1 W/m², equal to 328.6 kJ/kgCO₂, could be obtained. The peak power density was 2000-fold higher than that in previous studies. By utilizing CO₂ as an energy source in CCRED, this novel process can compensate for the energy penalty in conventional CCS.

1. Introduction

Global energy demand is increasing annually and fossil fuels continue to play a key role in energy supply [1,2]. Given the current inadequacy of successful substitutes for fossil fuels in existing industries, carbon capture and sequestration (CCS) is a realistic solution to energy supply and demand, as well as the reduction of CO₂ emissions [1–3]. The Intergovernmental Panel on Climate Change (IPCC) has categorized the capture of CO₂ into three types: (1) post-combustion; (2) pre-combustion; and (3) oxy-fuel combustion [4].

In post-combustion capture (PCC), CO₂ is separated from flue gases with a chemical sorbent instead of being emitted to the atmosphere directly [4]. It has been the most widely studied of the three types because of the intuitive retrofitting of point CO₂ sources [1,2,5–11]. For CO₂ separation from flue gases, technologies involving not only chemical absorption, but also physical absorption, adsorption using solid sorbents, and membrane separations have emerged as potential candidate technologies for efficient PCC [7]. Among these, the amine-based absorption (amine scrubbing) unit is the most developed and economical technology of PCC [7].

Fig. 1 is a schematic of a typical PCC process with amine scrubbing. Although amine scrubbing is the most economical of the available candidate technologies, it requires the CO₂ desorption unit to

regenerate amine absorbents, which requires a large amount of heat energy (operates at 100–120 °C). Consequently, it imposes an energy penalty on the original system [1,12–14]. Among generic amine-absorbents, *N*-methyldiethanolamine (MDEA) is the representative tertiary amine species, and it has low vapor pressure and high resistance to degradation [15]. Due to the characteristics of tertiary amines, CO₂ reacts with MDEA and leads to the formation of bicarbonate species instead of carbamate species [16]. Moreover, tertiary amines have lower regeneration energy than primary (e.g. monoethanolamine: MEA) or secondary (e.g. diethanolamine: DEA) amine groups [16].

Going beyond CCS, carbon capture and utilization (CCU) has been a hot topic as an active response to climate change [17]. In CCU, high-quality CO₂ is not required and the captured carbon can be used in physical applications (e.g. enhanced oil recovery: EOR), biological applications (e.g. photosynthesis), and chemical synthesis [14,18–20].

Salinity gradient power is the energy available from the salinity difference between high and low salt concentrations. The global energy potential between seawater and fresh water (or river water) is up to 2.4 TW [27]. In addition to seawater and fresh water, the thermolytic solution (e.g. ammonium bicarbonate) was introduced to obtain salinity gradient energy and hydrogen [21–23]. Among the competitive candidate technologies, reverse-electrodialysis (RED) is the most matured technology for harnessing salinity gradient energy. Further, RED is a

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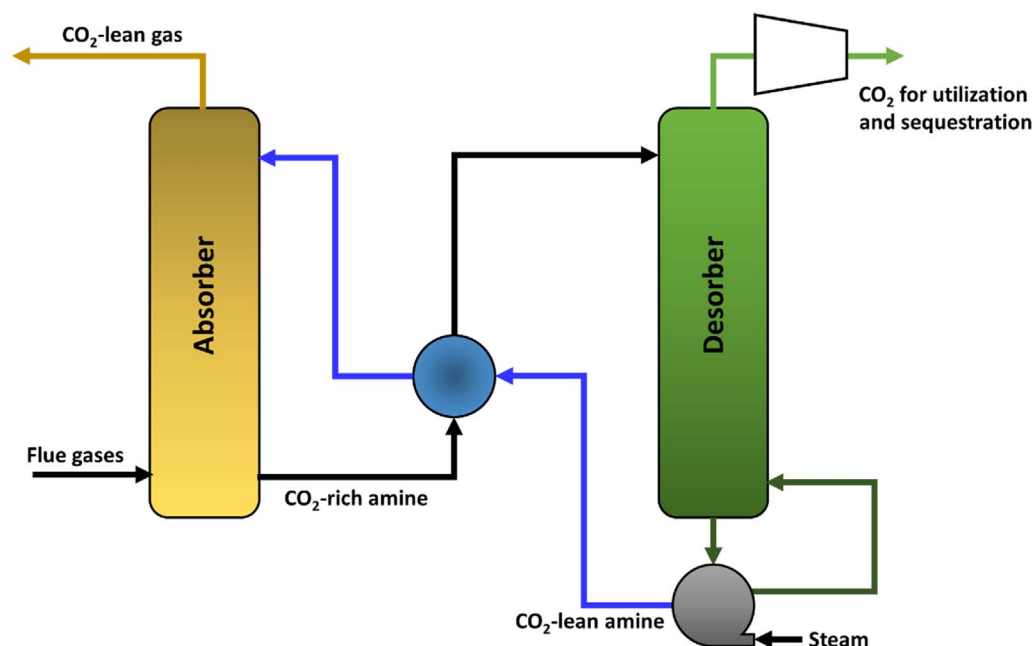


Fig. 1. Schematic diagram of amine scrubbing units for carbon capture.

very attractive candidate for the CCS system. It consists of several ion-exchange membranes, and the salinity gradients across these ion-exchange membranes develop an electrochemical potential, which is called a Donnan or liquid junction, or Nernst potential [24–26]. In RED, several pairs of cation and anion-exchange membranes are arrayed alternately between electrodes, and dissolved ions in a concentrated solution are moved to a diluted solution through the ion-exchange membranes. Eventually, ionic transfer is converted to electrical current on the electrode with proper redox reactions. Even though the electrochemical potential developed on a single pair of ion-exchange membranes is very small, the total electric potential and power can be enhanced by integrating the membrane pairs [27,28]. By utilizing the CO₂-rich absorbents from amine scrubbing in CCS as a concentrated source in RED, chronic problems of RED (e.g. geographical limitations to water use, contamination caused by supplied water) and CCS (e.g. energy penalty on regeneration of absorbents) can be solved simultaneously [28–30].

Previous studies introduced high concentrations of gaseous CO₂ as a concentrated source for salinity gradient power to generate electricity with capacitive electrodes [31–33]. However, these studies did not fully take into account each technology as a potential renewable energy source in the CCS system. Here, we introduce a convergent system of RED and CCS to overcome technological and economic problems in both RED and CCS, and as such, the proposed system has been named carbon capture with reverse-electrodialysis (CCRED).

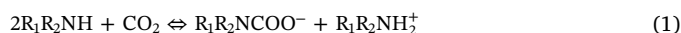
2. Theory

2.1. Amine scrubbing

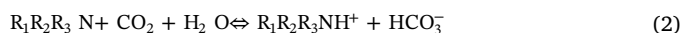
Amine scrubbing for CO₂ capture was first evaluated by Rochelle in 1991 [10]. To date, amine scrubbing has been the most developed technology for carbon capture [7,34]. Conventional amine scrubbing systems consist of absorbers and desorbers (Fig. 1), and use a single or blended aqueous alkanolamine solutions to capture CO₂. Typically, aqueous alkanolamines for CO₂ capture are classified into three groups: primary, secondary, and tertiary amines. Generally, primary and secondary or unhindered amines have a similar chemical structure and the leading mechanism is a zwitterion intermediated reaction to produce carbamates [16,35]. However, tertiary or hindered amines have bulky groups and in contrast produce bicarbonates [9,12,16]. Unhindered

amines have fast reaction rates, and two moles of amine species can capture one mole of CO₂ (Eq. (1)) [9,12]. On the other hand, hindered (or tertiary) amines capture CO₂ and react with water to produce bicarbonate species (Eq. (2)) [9]. Overall, hindered amines have a larger capacity than unhindered amines and less of an energy penalty for regeneration, even though hindered amines exhibit lower absorption kinetics than unhindered amines [9,16].

- Primary and secondary (unhindered) amines:



- Tertiary (hindered) amines:



2.1.1. Concept of CCRED

Fig. 2 shows a comparison of the power generation mechanisms of a typical RED system and the conceptual power generation mechanisms of CCRED. Generally, on the both systems, the fixed charge on the ion-exchange membrane allows the transfer of oppositely charged mobile ions (counter-ions) through ion-exchange membranes. In a typical RED unit, electrochemical potential is developed by selective mono-valent ion transfer (i.e. Na⁺, Cl⁻) through ion-exchange membranes after mixing of seawater and fresh water [28]. On the contrary, in the CCRED unit, bicarbonate species and conjugated cations participate in the development of electrochemical potential. Hence, increasing the concentrations of bicarbonate species is essential in CCRED. This is the main reason for using MDEA as the CO₂ absorbent. Furthermore, MDEA has less regeneration energy than typical unhindered amines [16]. In the CCRED cell, concentrated bicarbonate species (HCO₃⁻) are selectively moved through anion exchange membranes (AEMs) and counter cations (H⁺) are moved through cation exchange membranes (CEMs). If primary or secondary amines are introduced into the CCRED cell, loss of carbamate species may occur and amine absorbents cannot be returned to the absorber unit. In addition, certain protonated absorbents may be disturbed during operations because of size exclusion and electrostatic repulsion. Thus, the CCRED unit is more suitable for carbonate species than for carbamate species.

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