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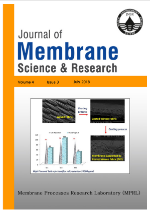

Guest Editorial Note

Reverse Electrodialysis for Salinity Gradient Power Generation: Challenges and Future Perspectives

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Abstract

Salinity gradient energy, which is also known as Blue energy, is a renewable energy form that can be extracted from the mixing of two solutions with different salinities. About 80% of the current global electricity demand could potentially be covered by this energy source. Among several energy extraction technologies, reverse electrodialysis (RED), using anion and cation exchange membranes for ionic transport that is converted into an electrical current at the electrodes, is most promising. This study provides a brief overview of recent advances in RED technology. Furthermore, it discusses future research directions and prospects to expand the true potential of this technology for power generation. Major emphasis should be on the development of task-specific membranes and stacks, the control of fouling and the design of new applications and hybrid processes.

Keywords: Reverse electrodialysis; Salinity gradient energy; Future prospects; Membrane design.

1. Introduction

The use of renewable energy has become a key solution to the global energy problem. Improving energy efficiency and sustainability in renewable energy sources such as wind, solar and hydroelectric is a challenge for the 21st century. Salinity gradient energy (SGE), perhaps a less known source of renewable energy yet, is a type of sustainable energy that can be extracted from the controlled mixing of two solutions with different salinities, such as seawater and river water. About 80% of the current global electricity demand could potentially be covered by this energy source when all discharges of rivers into sea are efficiently utilized [1]. A major advantage of salinity gradient energy is that the process is not dependent on seasonal climate changes like wind and solar-based technologies. Technologies to convert salinity gradient power into electricity are reverse electrodialysis (RED), pressure retarded osmosis and capacitive mixing. During recent years, especially RED has advanced towards larger scale applications using natural river and seawater sources. In RED, ion exchange membranes, i.e. CEMs (cation exchange membranes) and AEMs (anion exchange membranes) are alternatingly piled in a stack allowing the selective transport of ions. Ionic transport is counter-balanced in electrodes by redox reactions creating electron transport in an outer circuit, resulting in electrical power (Figure 1).

Despite the very promising potential of reverse electrodialysis and already successfully ongoing pilot-scale project at the Afsluitdijk in the Netherlands, this technology is not yet fully commercialized and there are a number of challenges to be addressed to further increase the power output obtainable in RED. In this brief research note, we address these. Our discussion centers around the main perspectives of RED in terms of R&D and market opportunities moving from the component level towards the full process.

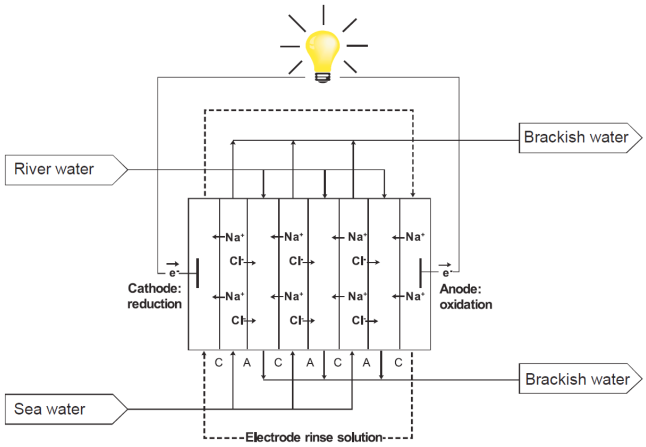

Fig. 1. Principle of reverse electrodialysis. Reprinted with permission from [1].

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2. Research & development perspectives

2.1. Membrane design and development

The application of RED is mostly limited by the lack of membranes specifically designed for RED and the high manufacturing costs and relatively lower power densities produced by currently available ion exchange membranes. Up to date, several attempts to produce specifically designed RED membranes have been made, such as those from polyphenylene oxide (PPO), polyvinylalcohol (PVA) and polyepichlorohydrin (PECH) [2, 3]. In addition to the selection of such polymer materials, preparation of task-specific membranes also appeared in literature, such as modification of membranes to induce antifouling properties [4] or specific selectivity for monovalent ions [4, 5]. To control fouling, membrane surfaces can be modified with for example high molecular mass surfactants that have fixed negative charges that repel large organic anions [6]. Adding a surfactant with a fixed charge opposite to the fixed charge of the membrane or the ions to be retained not only allows fouling control but also creates selectivity for monovalent ions (monovalent ion selective membranes) [7, 8]. The presence of multivalent ions has recently gained attention because of the adverse effects of divalents in feed streams on membrane selectivity, membrane resistance and thus power density. An alternative, versatile approach to mitigate the effects of multivalent ions is the use of supramolecular chemistry creating multivalent permeable membranes as a way to control the ionic membrane transport [5]. Due to the relatively open structure of such membranes, multivalent ions can freely permeate the membranes avoiding resistance increase.

Moreover, the geometry of the RED membranes has been modified as well in order to mainly reduce the stack resistance. From that perspective, relatively thinner membranes are aimed to be used, and profiled (also named corrugated or microstructured) membranes have been fabricated to eliminate the use of non-conductive spacers in RED stack [9, 10]. Such profiled membranes integrate the membrane and spacer functionality making the use of non-woven spacers obsolete, which is very beneficial in terms of performance as spacers are very sensitive to fouling thus reducing power densities [11].

Above described approaches for tailor-made RED membranes aimed to provide low resistance, high permselectivity, adequate chemical and mechanical stability and simple and environmentally benign fabrication routes. Additionally, feasibility of RED requires a very low membrane price of preferably less than 5 €/m^2 [12]. The ongoing challenge is thus to prepare low-cost membranes specifically designed for RED. It is estimated that upcoming research in membrane design and development will be in the direction of task-specific membranes having properties such as improved monovalent selectivity, antifouling properties, and target-ion-selectivity for non-sodium chloride ions.

2.2. Conversion of ionic charge into electrical charge

Traditionally, at both ends of the membrane pile, the ionic current is converted into electrical current using redox reactions. Often hexacyano ferrate is used for that being a less environmentally friendly solution. To overcome this issue, capacitive electrodes were applied [13]. To store ions and charge, capacitive electrodes use activated carbon on a support of Ti/Pt mesh. To prevent saturation of the electrodes, feed waters and electrical current are periodically switched. Power densities are close to or even better than similar RED stacks with conventional redox based electrode systems, but operation is more complex. Further research should expand in the direction of redox reaction free systems, with major focus on environmental friendliness and ease of operation.

2.3. Fouling control

RED application under practical conditions using natural water streams inevitably copes with fouling. One way to address this is to tailor membrane chemistry (as discussed). According to recent studies, it is shown that fouled RED stack can exhibit even more than 50% lower power densities, already during the first day of operation [11]. Recent studies on antifouling strategies therefore also include using finer prefiltration, increasing the intermembrane distance and the application of specific anti-fouling strategies, among which air sparging, periodic switching of the feed waters or the use of CO_2 saturated feed water as two-phase flow cleaning for fouling mitigation [14–16]. In addition to several fouling tests, analytical tools such as fluorescence spectroscopy that allows to monitor regional fouling in membranes were developed by a research group [17]. The challenge for practical applications is to apply these fouling control strategies in a cost-effective way. Thus, strategies, which consume less energy and produce more power, are required to obtain an optimal RED performance.

2.4. Stack design and upscaling

Design of a RED stack is vital for the efficiency of practical RED applications as it includes many components having direct impact on the performance, such as cell dimensions, feed water flow paths, manifolds, electrodes and feed water compartments. Up to now application of large industrial scale stacks is limited, and most research data reported are based on laboratory-scale RED stacks. Several attempts and ideas have been developed in terms of stack design, such as asymmetric stacks (i.e. river water compartment is thinner and seawater compartment is thicker), a breathing cell geometry (i.e. compartment thicknesses are variable during operation), and fractal and radial flow RED designs [15, 18]. Pressure drop analysis in individual components of a RED system also helped gaining insights in the most adequate stack-design [19]. Moreover, in order to make the transition to large RED power plants, upscaling of the stack and system is an absolute prerequisite. Today, it is a known reality that limited power density in RED is a key holdup in practice. Thus, an interesting research option in stack design is to scale-down the dimensions where the cell length is shorter because this provides a significant reduction in pumping power thus increasing the net power density. In micro/nano-scale RED systems were already studied by several research groups [20–23]. Although the nanofluidic channels or nanopores in these systems seem to overcome the bottleneck of limited power density, the practical application of such small designs for large scale power production is questionable though. Further studies including the validation of cost-effectiveness of those systems are needed to scale up the technology.

2.5. New process applications

Recent articles on RED do not solely focus on the conventional operation using river and seawater to harvest SGE but also on new or hybrid applications using the principle of RED. Such processes mainly include energy recovery from waste streams [24], energy storage in for example acid-base batteries [25], and hybrids with desalination processes and redox reactions [15, 26]. These research directions show that RED is rather flexible and compatible to create symbioses with other processes. Moreover, new applications of RED with ionic solutions other than sodium chloride might be further developed as these non-sodium chloride systems have not been fully examined yet.

3. Conclusions

As a promising sustainable energy technology, RED has attracted worldwide attention recently. Although great progress has been achieved by several research groups during recent years, there is still plenty of room for further development to increase power densities and to substantially enhance the widespread application of RED. Further development of RED technology may focus on, but is not limited to the following: 1) design of tailored, task-specific RED membranes, electrodes and stacks; 2) development of antifouling strategies for a more efficient process with higher power output; 3) creation of new market opportunities and new applications of RED.

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