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Research article

Long-run operation of a reverse electrodialysis system fed with wastewaters

Javier Luque Di Salvo, Alessandro Cosenza, Alessandro Tamburini*, Giorgio Micale, Andrea Cipollina

Dipartimento dell'Innovazione Industriale e Digitale - Ingegneria Chimica, Gestionale, Informatica, Meccanica (DIID), Università di Palermo (UNIPA) – viale delle Scienze Ed.6, 90128 Palermo, Italy

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ABSTRACT

The performance of a Reverse ElectroDialysis (RED) system fed by unconventional wastewater solutions for long operational periods is analysed for the first time. The experimental campaign was divided in a series of five independent long-runs which combined real wastewater solutions with artificial solutions for at least 10 days. The time evolution of electrical variables, gross power output and net power output, considering also pumping losses, was monitored: power density values obtained during the long-runs are comparable to those found in literature with artificial feed solutions of similar salinity. The increase in pressure drops and the development of membrane fouling were the main detrimental factors of system performance. Pressure drops increase was related to the physical obstruction of the feed channels defined by the spacers, while membrane fouling was related to the adsorption of foulants over the membrane surfaces. In order to manage channels partial clogging and fouling, different kinds of easily implemented *in situ* backwashings (i.e. neutral, acid, alkaline) were adopted, without the need for an abrupt interruption of the RED unit operation. The application of periodic ElectroDialysis (ED) pulses is also tested as fouling prevention strategy. The results collected suggest that RED can be used to produce electric power by unworthy wastewaters, but additional studies are still needed to characterize better membrane fouling and further improve system performance with these solutions.

1. Introduction

Salinity Gradient Power (SGP) is an attractive alternative to produce renewable energy without any environmental issue and with a high potential of power production worldwide (Alvarez-Silva et al., 2016; Daniilidis et al., 2014a; Tedesco et al., 2015b; Veerman et al., 2009). It is based on the simple concept of mixing two waters of different salinity and collecting the free energy that is spontaneously produced during this process. If the mixing process is properly controlled, net energy can be extracted.

There are several technologies designed to control water mixing in different stages of development (Jia et al., 2014), among which Pressure Retarded Osmosis (PRO) (Helfer et al., 2014; Sarp et al., 2016), Reverse ElectroDialysis (RED) (Yip et al., 2014) and Accumulator mixing techniques (Capacitive mixing –CapMix (Rica et al., 2013), and Mixing Entropy Battery –MEB (La Mantia et al., 2011)) deserve mention. Some of these techniques have already been considered for practical applications in site-specific analysis (Emdadi et al., 2016; Helfer and Lemckert, 2015; Tedesco et al., 2017, 2016). In particular, of all current SGP techniques, RED has experienced a sharp growth in terms of understanding and optimization in the last years (Güler et al., 2014; Gurreri et al., 2012; La Cerva et al., 2017; Straub et al., 2016), with the advantage that is able to deal with very high salinity solutions, a challenge that is found in PRO (Schaetzle and Buisman, 2015).

An interesting feature of the RED technology is its flexibility in the feed possibilities available to use. Most studies are devoted to artificial salt solutions (Bevacqua et al., 2017, 2016; Daniilidis et al., 2014b; Tedesco et al., 2015a), some to real waters (D'Angelo et al., 2017; Tedesco et al., 2016; Veerman et al., 2009), while very few studies are devoted to the exploitation via RED of the salinity gradient available in wastewater solutions. This exploitation can give value to an otherwise discard product and can additionally increase the quantity of sources suitable for salinity gradient power technologies.

* Corresponding author.
E-mail address: alessandro.tamburini@unipa.it (A. Tamburini).

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Nomenclature

Acronym Meaning

AEM	Anion Exchange Membrane
CEM	Cation Exchange Membrane
DBL	Double Boundary Layer
ED	Electrodialysis
EPS	Extracellular Polymeric Substances
IEM	Ion Exchange Membrane
RED	Reverse Electrodialysis

Symbol Parameter (units)

A	Active cell-pair area (m^2)
C_{high}	Concentration of high salinity solution ($mol.dm^{-3}$)
C_{low}	Concentration of low salinity solution ($mol.dm^{-3}$)
E_{stack}	RED unit electric potential (V)
I_{stack}	RED unit electric current (A)
N	Number of cell-pairs
OCV_{ideal}	Theoretical Open Circuit Voltage (V)
OCV_{exp}	Measured Open Circuit Voltage (V)
$P_{d,gross}$	Gross power density (W/m^2)
$P_{d,corr}$	Corrected power density (W/m^2)
$P_{d,loss}$	Pumping losses power density (W/m^2)
$P_{d,net}$	Net power density (W/m^2)
$P_{d,corr,net}$	Corrected net power density (W/m^2)
p_{high}	Pressure drops in the high channel (bar)
p_{low}	Pressure drops in the low channel (bar)
R_{AEM}	AEM electrical resistance (Ω)
R_{CEM}	CEM electrical resistance (Ω)
R_{low}	Low salinity compartment electrical resistance (Ω)
R_{high}	High salinity compartment electrical resistance (Ω)
$R_{non\text{-}ohmic}$	Non-ohmic electrical resistance (Ω)
R_{stack}	RED unit electrical resistance (Ω)
v_{high}	Fluid velocity of high feed solution ($cm.s^{-1}$)
v_{low}	Fluid velocity of low feed solution ($cm.s^{-1}$)

Greek Symbol

α_{app}	IEMs apparent perm-selectivity
γ_{high}	NaCl activity coefficient of the high salinity feed
γ_{low}	NaCl activity coefficient of the low salinity feed
Λ	Electrical conductivity ($mS.cm^{-1}$)
τ	Response time when switching from RED to ED operation (s)

In this sense, several industrial processes require high amounts of salt, generating effluents with high salinity levels, similar to those found in seawater, or even higher, as the case of food processing, textile dyeing, petroleum derivatives and tanneries (Lefebvre and Moletta, 2006; Sivaprakasam et al., 2008; Xiao and Roberts, 2010). One of the issues to solve for these kind of wastewaters is the high-salinity of the effluents, which needs to be diluted before discard to minimize environmental impact (Cambridge et al., 2017; Roberts et al., 2010), a process that can be accomplished (at least partially) by RED technology. On the other hand, low salinity effluents are more readily available, like those coming from urban waste disposals (Raffin et al., 2013). This opens a wide spectrum of new feed sources for salinity gradient power still to be explored.

To the date there are not much studies dealing with wastewater re-use to produce energy from SGP technologies. D'Angelo et al. demonstrated the possibility of using RED in wastewater treatment by successfully removing Acid orange 7, while operating the first RED pilot plant fed with real brine and brackish water in a long duration experimental campaign (D'Angelo et al., 2017). Wang et al. used a phenol-containing wastewater to feed a RED unit with the objective of recovering phenol derivatives, proving the possibility of coupling RED with ED in the wastewater treatment process (Wang et al., 2017). Very recently, Kingsbury et al. studied the response of a RED unit fed with five different pairs of real waters and wastewaters and remarked the role of organic fouling in the severe detriment of power density (Kingsbury et al., 2017). However, to the authors' knowledge there are still no studies in literature related to the long-term effects that these kinds of feeds may produce on the overall RED unit performance and on the possible strategies to prevent or reverse their potential damage. Thus, in order to understand whether RED is capable to benefit from these otherwise unworthy wastewaters, we performed long duration experiments and evaluated the system time-evolution. The so-called long-runs can also give light into the feasibility of an enduring energy production via a RED unit continuously fed by wastewaters for a realistic period of operational time. In particular, wastewater originated in a fish canning factory, and wastewater coming from urban water disposal, were used as high and low salinity feeds, respectively.

When using feeds from wastewater treatment plants, the time-dependent behaviour of ion exchange membranes in long-run operations is subjected to fouling phenomena (Kingsbury et al., 2017; Vaselbehagh et al., 2017; Vermaas et al., 2013). Fouling mechanisms consist in the attachment, adsorption and accumulation of pollutants over the surface or inside the membrane, leading to an alteration of the membrane material and/or to pores obstruction that hinders transport of permeates thus reducing the process performance (Guo et al., 2012).

The anti-fouling techniques to be applied will depend on the type of fouling that is produced, which can be classified as inorganic (scaling), organic or colloidal fouling, and biofouling (Mikhaylin and Bazinet, 2016). In the case of (Reverse) ElectroDialysis systems, AEMs are mainly affected by organic fouling (Lee et al., 2009) and/or biofouling (Vaselbehagh et al., 2017), while scaling by inorganic species (Ca^{2+}, Mg^{2+}) can be quite common on CEMs (Mikhaylin and Bazinet, 2016; Vermaas et al., 2013). An easy and suitable strategy to prevent and control fouling in RED systems consists in periodic (back) washing techniques with deionized water and/or chemical cleaning agents (Garcia-Vasquez et al., 2016; Mikhaylin and Bazinet, 2016). In particular, alkaline solutions should be more effective in order to treat organic fouling, while the use of acid reagents should be more effective in removing scaling produced by inorganic species.

It is worth to mention that besides fouling, clogging of channels may also occur, especially if the channels are thin and filled with meshed-spacers. The obstruction is physical rather than physical-chemical like the stronger interactions established in fouling processes, so if the backwashing is proven effective in reversing fouling is expected to also unclog the spacer-filled channels. Channel clogging can be very important in RED as it can also contribute to an increase of pressure drops and thus affect the net power density generated (Gurreri et al., 2016, 2012; La Cerva et al., 2017).

The objective of this work is that of analysing for the first time the performance during long-run tests of a RED unit operated with real feed solutions of different origin and salinity, but both coming from a biological wastewater treatment plant. As a first step, system was operated with artificial solutions to determine the best