

# Power production from coal-mine brine utilizing reversed electro dialysis

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## Abstract

The present work was aimed at electric energy obtaining by mixing coal-mine brine with low-salinity water utilizing reversed electro dialysis (RED). The electro dialytic unit equipped with alternatively arranged cation and anion exchange membranes, was mounted in-between two Pt-coated electrodes. The number of the anion and cation-exchange membranes was set to achieve 4 brine and 4 low-salinity water compartments. The relatively thin, of 0.19 mm thickness, ED stack spacer enabled low membrane to membrane distance and resulted in relatively low ohmic voltage loss. The electro dialytic system was fed with brine, containing 111 g NaCl/L, simulating coal-mine brine and low-salinity water of 0.56 g/L NaCl content, as a fresh water.

In order to estimate the possible electric charge and electric power produced in the proposed system, the current–voltage curves were analyzed at different linear flow velocities. Also the cost estimation based on the electric resistances was done. Thus the feasibility of electric energy obtaining in the considered way was discussed.

*Keywords:* Renewable energy; Reversed electro dialysis

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## 1. Introduction

Coal mines in Poland discharge ca. 550,000 m<sup>3</sup>/d of water containing 4000 t/d of chlorides and sulphates into the Vistula and Odra river basins, which makes ca. 2.4 million tons of salt load yearly (as sodium chloride) [1,2] and poses a substantial ecological problem. About 50%

of salt occur in water with very high salinity (so-called coal-mine brines, with the sum of Cl<sup>−</sup> and SO<sub>4</sub><sup>2−</sup> concentration > 42 g/L). These coal-mine brines may be applied for energy generation in a so-called reverse electro dialysis (RED) which is the reverse of the well known desalination method [3,4]. When a concentrated brine and a fresh water flows through alternating cells of an ED unit, a voltage is generated across each compartment. Thus a concentration cell is formed,

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a cell which generates voltage as a result of differing concentrations. When the number of cells is high enough, the sum of cell-pairs voltage drops, exceeds the electrode reactions potentials and electric power may be produced.

Lacey [3] made a comprehensive survey of previous research on RED. In his opinion, for reverse electrolysis to be economically feasible, the internal resistance of the cells should be minimized and net output power maximized by using large concentration ratios between the brine and the dilute solution. This requirement is fulfilled in the case of mixing coal-mine water with fresh water, which is the objective of the present work.

S. Loeb [5] described method and apparatus for power generation utilizing reverse electro-dialysis, this technique appears to be capable of producing low cost energy, particularly when highly concentrated brines are applied.

## 2. Experimental

Previously in Ref. [4] we considered the use of reversed electro-dialysis (RED) to derive energy by mixing seawater and the fresh water. It was found, that investment cost is as high as \$6.79/kWh at peak power of 460 mW/m<sup>2</sup> and 0.54 cm/s linear flow velocity. This was caused by relatively low salinity of seawater and large amount of energy required for pumping.

In the present work we consider power generation in the reversed electro-dialysis process using much more concentrated, than seawater previously applied, coal-mine brines of salinity ca. 110 g NaCl/L. The four-compartment electro-dialyser was used. Each compartment consisted of cation and anion exchange membrane arranged alternately. CMX and AMX Neosepta (Tokuyama Co.) normal grade membranes were used. Spacers of 0.19 mm thickness were mounted in-between membranes. This enabled low membrane to membrane distance and resulted in relatively low ohmic voltage loss.

The electro-dialytic system was fed with brine, containing 111 g NaCl/L and low-salinity water of 0.56 g/L NaCl content. The working length of each membrane was 3 cm, working area 4 cm<sup>2</sup> and linear flow velocity ranged from 0.12 to 1.32 cm/s. The whole electro-dialytic unit was mounted in-between two Pt-coated electrodes. The RED process was carried out in continuous flow operation. Electro-dialyser applied was described with more details in Ref. [4].

Because the sum of cell-pairs voltages in our experiment did not exceed the one required for the electrode reactions (oxygen and hydrogen evolution) to take part, the electrodes were supplied by the rectifier that simulated an energy consumer (resistor). The voltage drop at the extremities of the RED stack was monitored by SS probes [4].

The current–voltage curves collected at different linear flow velocities are presented in Fig. 1. There the straight line between output voltage and current density suggest that the concentration cell internal resistance is constant and follows Ohm's law at every flow velocity (Table 1). Moreover, since the slopes of the curves in Fig. 1 collected at 0.12, 0.22 and 0.58 cm/s are statistically not different, the cell internal resistance was found to be flow velocity independent in this range. The slight difference in absolute values of voltage drop at given current density seems to be

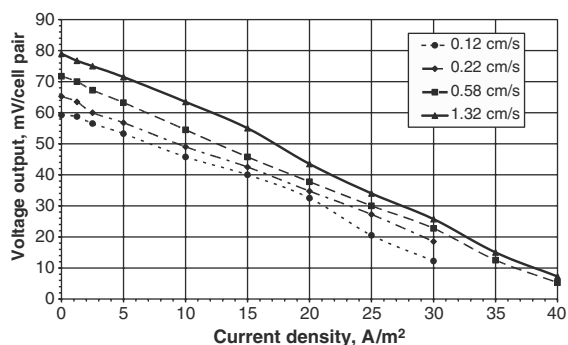


Fig. 1. Relationship between the current density and voltage output per cell pair; 111/0.56 g/L solutions.

Table 1  
Cell internal resistances

Flow velocity (cm/s)	Cell internal resistance ( $\Omega/\text{m}^2$ )	Standard deviation (%)	Correlation coeff.
0.12	0.00156	4	>0.99
0.22	0.00152	2	>0.995
0.58	0.00166	8	>0.999
1.32	0.00182	2	>0.998

the result of varying amount of salt transferred, this however should be examined separately.

In order to identify maximum power possible, the unit power produced as function of current density was calculated for 111/0.56 g/L solutions. The results are presented in Fig. 2. There the maximum power produced of  $0.870 \text{ W}/\text{m}^2$  was observed at the electric current density of  $20 \text{ A}/\text{m}^2$  and flow velocity of  $1.32 \text{ cm}/\text{s}$ .

As the electric resistance of AMX and CMX membranes applied in laboratory experiments are relatively high ( $2\text{--}3.5 \Omega/\text{cm}^2$ ) an estimation of unit power produced when applying low resistance membranes ( $1 \Omega/\text{cm}^2$ ) was made. The results are presented in Fig. 3. It can be clearly seen there that the replacement of the AMX and CMX membranes with the low resistance ones result in the increase in maximum power produced and its corresponding current density.

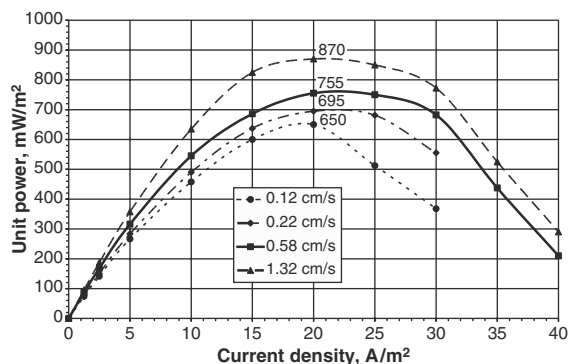


Fig. 2. The effect of current density on cell unit power; 111/0.56 g/L solutions; AMX, CMX membranes.

The optimum values found were  $1.18 \text{ W}/\text{m}^2$  at  $30 \text{ A}/\text{m}^2$  and flow velocity of  $1.32 \text{ cm}/\text{s}$ .

The effective power, defined as previously found cell power produced diminished by pumping energy was then calculated. The value of pumping energy was estimated for industrial RED unit assuming effective membrane length equal to  $0.5 \text{ m}$ , the entrance and exit passageway lengths equal to  $3 \text{ cm}$ , the velocity of solution in the entrance and exit passageway 3 times higher than in the current-passing section. The pressure drop for  $0.19 \text{ mm}$  spacer applied was measured in laboratory, as a function of linear velocity, using a mercury manometer. The pressure drop affected by the spacer and membrane walls only was thus measured. It was found that the pressure drop was a linear function of flow velocity and was equal to  $2550 \text{ Pa}$  for  $1 \text{ cm}/\text{s}$  flow velocity and  $10 \text{ cm}$  channel length. The estimated values of pumping power were then found to be equal

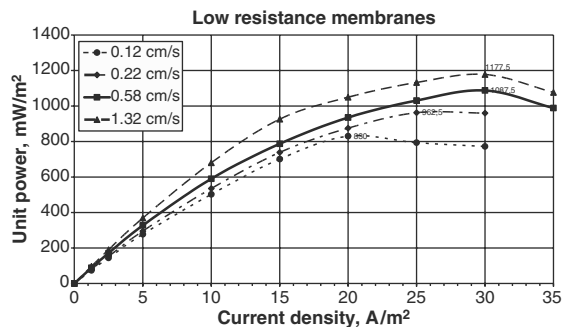


Fig. 3. The effect of current density on cell unit power; 111/0.56 g/L solutions; low resistance membranes.

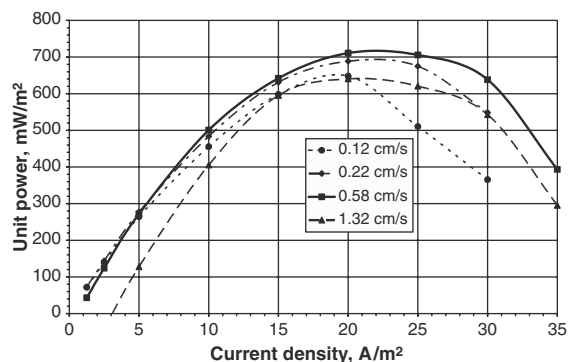


Fig. 4. The influence of current density on RED effective unit power for 111/0.56 g/L system using AMX and CMX membranes.

to 2.0, 6.4, 44.3 and 229.6 mW/m<sup>2</sup> for 0.12, 0.22, 0.58 and 1.32 cm/s flow velocity, respectively.

The influence of current density on cell the effective RED power for 111/0.56 g/L systems using AMX and CMX membranes is presented in Fig. 4. In this case, unlike unit cell power, the effective RED power was found to be maximum when 0.58 cm/s flow velocity was considered. This was because higher flow velocity, namely 1.32 cm/s, consumes additional energy related to the pressure drop that have to be exceeded. The magnitude of this additional (required to pump electrolytes at high velocities) energy consumption is not compensated by an increase in cell unit

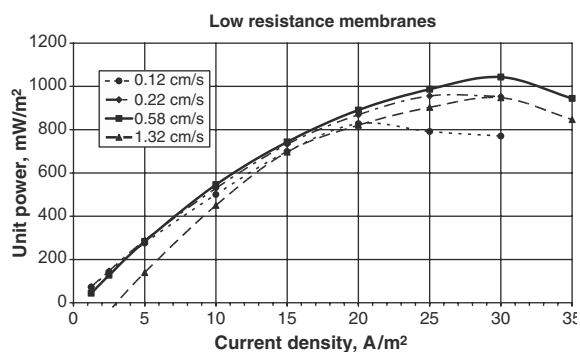


Fig. 5. The influence of current density on RED effective unit power for 111/0.56 g/L system using low resistance membranes.

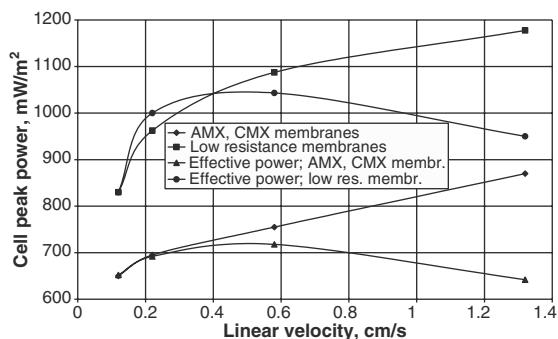


Fig. 6. The effect of the solutions' velocity on the cell peak (optimum) power.

power and optimum RED effective unit power was found to be ca. 0.710 W/m<sup>2</sup> at 20 A/m<sup>2</sup> and flow velocity of 0.58 cm/s.

The influence of current density on RED effective unit power for 111/0.56 g/L system using low resistance membranes is presented in Fig. 5. As for AMX and CMX membranes, the RED effective unit power was found to be maximum for the intermediate flow velocity of 0.58 cm/s. The RED effective unit power value reached 1.040 W/m<sup>2</sup> at 30 A/m<sup>2</sup> and linear flow velocity of 0.58 cm/s. The existence of the optimum flow velocity at which maximum RED effective unit power is observed may be also clearly seen in Fig. 6.

The cost of energy produced by RED was then estimated for industrial unit. The effective working membrane area was assumed as equal 80% of total membrane area, the membranes life 10 years (80,000 h) and the total investment cost equal to \$100 per 1 m<sup>2</sup> of installed membrane. Assuming 1.040 W/m<sup>2</sup> peak energy power (Fig. 6, low resistance membranes, 0.58 cm/s) the share of investment cost in energy production is equal to \$3.0/kWh.

### 3. Conclusions

Utilizing reversed electro dialysis (RED) to generate electric energy by mixing coal-mine

brine with low-salinity water in electro dialysis stack was examined in laboratory.

The relatively thin, of 0.19 mm thickness, ED stack spacer enabled low membrane to membrane distance and resulted in relatively low ohmic voltage loss, that was desired.

The electro dialytic system was fed with brine, containing 111 g NaCl/L, which was stimulating coal-mine brine and low-salinity water of 0.56 g/L NaCl content, as a fresh water.

Analysis of our experiments results indicated that the maximum effective unit power depends on: electric current density, flow velocity and membrane resistance (type). The maximum effective unit power of 0.72 W/m<sup>2</sup> was observed for AMX and CMX membranes at 20 A/m<sup>2</sup> and 0.58 cm/s flow velocity and 1.040 W/m<sup>2</sup> for low resistance membranes at 30 A/m<sup>2</sup> and 0.58 cm/s linear flow velocity.

The detailed cost estimation showed that the minimum energy obtaining investment cost, of \$3.0/kWh may be achieved using low resistance membranes. High unit price of low-resistance membrane, however, increase the energy obtaining cost to a great extent.

We also concluded that high energy obtaining investment cost seems to prevent the application of RED technique at a large scale. Cost of equipment (e.g. pumps, pipes), and high cost of low resistance ion-exchange membranes are the

origins of the above shortage in RED application. Since the membrane cost is the major component of the RED energy production cost, one may also conclude that approx. a hundred time decrease in the membrane price would make the considered technology economically feasible.

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