Pressure drop in Reverse Electrodialysis: Analysis using CFD

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Salinity gradient energy–SGE is probably the less studied form of energy available in marine systems. Even though it is known since 1954, SGE started to gain some attention about 13 years ago [1], [2]. When two water bodies of different salinity (i.e. concentration) are mixed, free energy is released in the form of heat, therefore, it is a spontaneous process, which occurs naturally in several systems like estuaries and coastal lagoons. Recent studies conclude that SGE may supply 3% of global energy consumption, being the Mediterranean Sea, the Caribbean Sea, and the Gulf of Mexico the zones with higher potential for its harnessing [3].

The driving force in the mixing process is a chemical potential (associated with concentration) difference. The aim of SG technologies is to change the process path by which the chemical potential gradient between the two waters of different salinity is reduced.

Regarding technologies to convert SGE into electricity, Reverse Electrodialysis – RED is one of the most promising. It is analogous to Electrodialysis, which has been widely studied in desalination [4]. RED is a direct conversion method based in electrochemistry and ion exchange membranes. Theoretical analyses suggest that it is suitable for applications with salinity gradients in nature (e.g. river and seawater) and for small generation systems in coastal communities through modular devices [5]. RED study is at pilot unit stage in Europe, mainly, with plants in the Netherlands and Italy operating since 2014; the first one uses seawater and river water as feed solutions, while the second one harness salinity gradient between brine and brackish water. Both having an installed capacity of about 50 and 1 kW, respectively [2], [6].

The concept of RED is based on the arrangement of two types of ion exchange membranes (IEM): cation exchange membranes (CEM) and anion exchange membranes (AEM); CEM has negative fixed charge, hence ions charged positively (Cations, e.g. Na+) can pass across them while negatively charged ions (Anions, e.g. Cl-) are rejected; conversely, AEM allows the passage of anions rejecting the cations. When IEM are placed in an alternating arrangement, compartments (HCC for high concentration solution i.e. seawater and LCC for low concentration solution i.e. fresh water) are formed, where feed solutions may flow without being brought into contact with each other, following the chemical potential gradient direction, ions will tend to diffuse/migrate from the HCC to the LCC, the latter, coupled to perm selectivity of IEM, generates an ionic current where anions will move in a certain direction, meanwhile the cations do the same in the opposite direction, see Fig 1. If two electrodes are placed at the end of the arrangement of the membranes, the energy of the electric field formed by the movement of the ions can be converted into an electronic current by redox reactions.

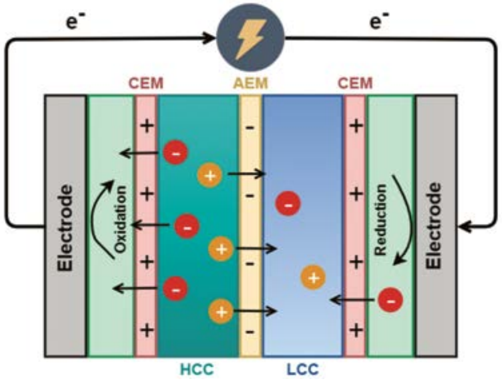

Fig. 1 Schematic representation of RED

Although RED has been studied worldwide, there still some limitations to overcome in terms of net power density and energy efficiency, thus, lowering costs, ensuring long-term stable operation, and increasing its reliability under natural conditions, are necessary for RED to be competitive with other renewable sources of energy, even with the marine ones. For the latter, research in anti-fouling strategies, membranes development, process design, redox couple, and suitable operation conditions are being conducted all over the world [7], [8].

Stack design in reverse electrodialysis has been a major concern in the technology development. Operating conditions, fluid distribution and pressure drop along the channels are some of the most critical aspects in RED since they are directly related to the net power output. For that reason, comprehensive research involving such aspects and their coupled effects has been addressed in the literature []. For the latter, key parameters such as flow velocities, flow configuration, compartment dimensions and geometries, interphase phenomena, ion migration, and ion diffusion must be considered.

A recent approach for RED stack design based on computational fluid dynamics (CFD) has been used to study of channel geometry and spacer effects on the fluid behavior, mass transfer, and pressure drops [9]– [12]. So far, CFD analysis has been mainly focused on stacks with inert turbulence promoters (spacer-filled channels). However, spacers have a major drawback under natural conditions, due to higher pressure drops, scaling, and biofouling, promoted by the spacers. Accordingly, spacer-less stacks should be considered if the technology is to be scaled up.

The aim of this work is to perform CFD simulations of several channel geometries for a RED stack and to consider the pressure drop in empty channels. It is combined with a phenomenological model to obtain adequate stack dimensions and operating conditions, which may lead to a higher net power density output.

So far, two different geometries have been studied, both varying in the inlets and outlets shape. The first comprises sudden expansions and contractions of 90° at the inlets and outlets, respectively, while the other is designed with 45°

expansion and contractions. The 2D laminar flow distribution and for 1 cm/s inlet velocity simulated using ANSYS Fluent® version 19.0 are shown in Fig 2.

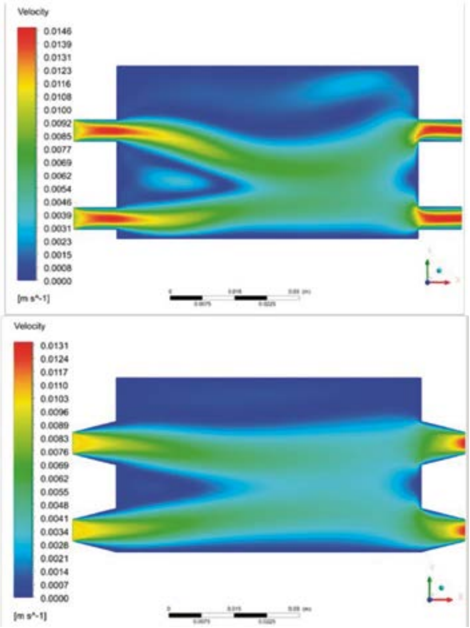

Fig. 2 Flow velocity distribution. 90° Expansion/Contraction (Top). 45° Expansion/Contraction (Bottom).

The flow field shows stagnation zones for both geometries; however, this effect is more visible for the 90° sudden expansion and contraction geometry. On the other hand, dead zones are more evident in the gradual expansion and reduction geometry.

Regarding the velocity profile, higher velocities are achieved in the inlet and outlet of the 90° expansion and reduction geometry. The pressure drop between the inlet and outlet of each geometry is presented in Table 1.

Table 1. Pressure drop for two type of inlet/outlet configuration.

Degree of Expansion and Contraction	ΔP (Outlet–Inlet) [Pa]
90°	0.2087
45°	0.0861

According to the results, the pressure drop in the 90° geometry is around 2.5 times higher than the pressure drop in the 45° geometry, showing that small changes in channel geometries could lead to lower pressure drops and, hence, to higher net power output, providing insights about hydrodynamic losses in this kind of geometries.

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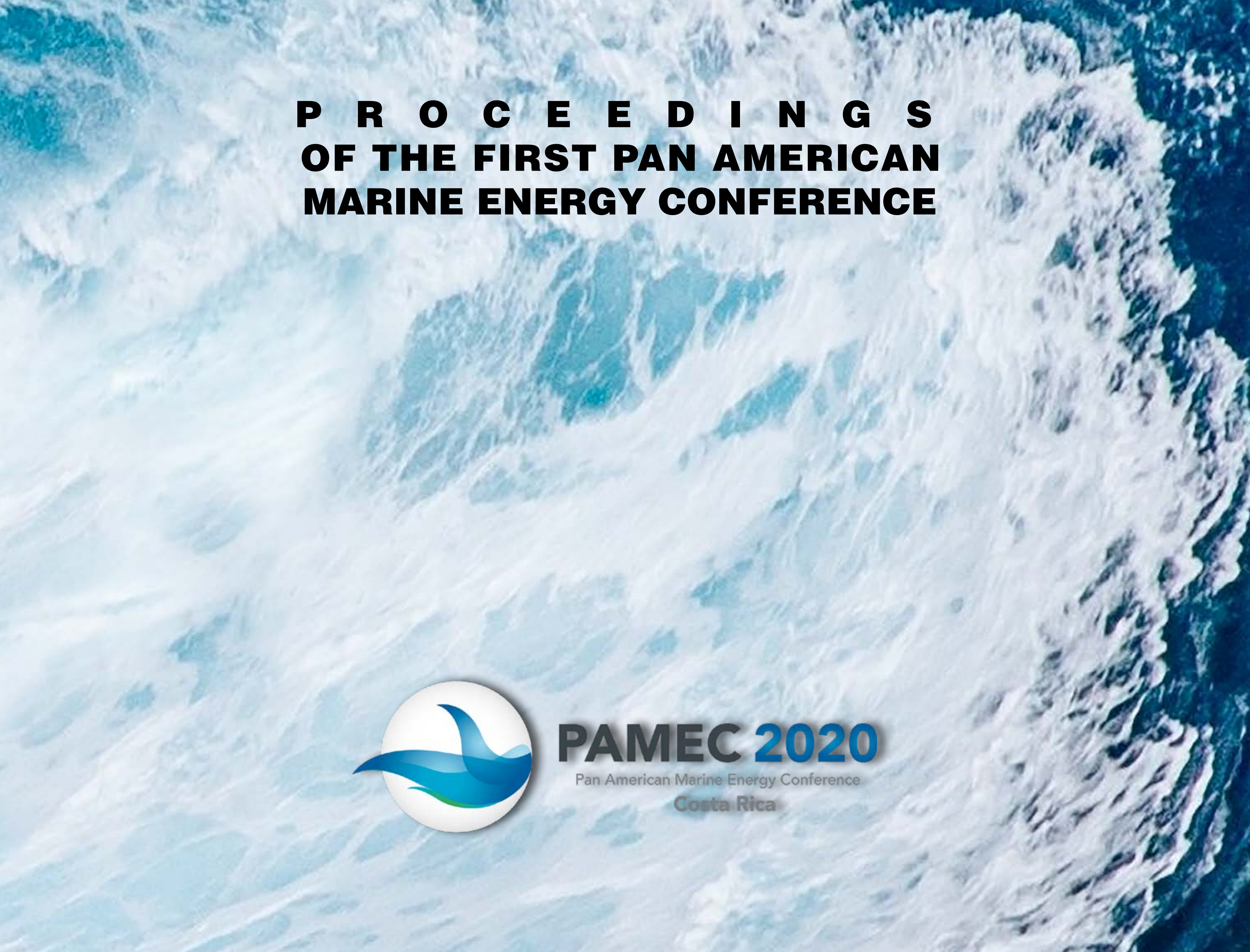

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