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Direct osmosis process for power generation using salinity gradient: FO/PRO pilot plant investigation using hollow fiber modules

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ABSTRACT

The phenomenon of osmosis is known for more than 150 years and involves the contact of a semi-permeable membrane with solutions of different salinity. The osmotic flux that permeates through the membrane can be used for electric power generation as a renewable source of energy. This process can be accomplished by means of the pressure retarded osmosis (PRO). This work consisted of the construction of a demonstrative FO/PRO power pilot plant. Assymetric polymeric cellulose acetate hollow fiber membranes were produced and conditioned in permeation modules. The pilot plant consists of three countercurrent flow hollow fiber modules connected in parallel. According to the modules and fibers dimensions, the membrane area per module can reach 1.5 m^2 that means a packing density of 1500 $m^2\,m^{-3}$. The pilot scale enables the activation of a hydroturbine/generator device coupled to a 9-LEDs panel which can establish the technological and scientific bases for further industrial upscaling. A forward osmosis (FO) test using a $MgSO_4$ solution (0.8 M, π: 22 bar) and an intermittent PRO test using a NaCl solution (0.8 M, π: 37 bar) were performed, where the maximum osmotic flux values were 33 and 8 $L\,m^{-2}\,h^{-1}$, corresponding to an energy performance of 5 and 2 $W\,m^{-2}$, respectively. These values are comparable with most of the latest bench-scale FO membrane investigations.

1. Introduction

With the exponentially growing population and the depletion of fossil fuels, water and energy have become two of the most important global resources. Both water shortages and energy crises have plagued many communities around the world. Less polluting renewable energy sources allow to reduce harmful gases emissions into the environment, promoting greater sustainability. Therefore, the development of renewable energy sources like solar energy, biodiesel, ethanol and wind power becomes a global priority. Meanwhile, attractive and innovative membrane-based technologies options such as forward osmosis (FO) and pressure retarded osmosis (PRO) processes have shown great promise in both water supply and energy production. In these processes, a net water movement occurs through a semi-permeable membrane under osmotic pressure gradient $\Delta\pi$. In PRO mode, this stream can be partially used for electric power generation. The global potential for osmotic power is reported to be 1650 $TW\,h\,y^{-1}$. This is equivalent to about half the current annual hydropower generation, reported to be 3551 $TW\,h\,y^{-1}$ [5,6,7,13]. In regard to its extensive coastline, Brazil shows a great potential for this renewable source.

In the 1980s, Loeb et al. [1–3,14] and then, Baker et al. [4] were the first to investigate the potential viability of osmotic process as a sustainable energy generation. About 30 years later, the Norwegian company STATKRAFT, a pioneer in the development of PRO pilot scale, realised a complete osmotic power plant prototype with 2000 m^2 of membrane installed, aiming to the construction of a 1 MW power plant with approximately 200,000 m^2 of membrane.

Although the osmotic phenomenon has been known for a long time, the PRO process is still not yet widely used. The main reason is the lack of adequate membranes with high flux and good selectivity properties that would make the process economically more competitive [8,25]. The principal requirements for a good FO/PRO membrane are high water flux, together with a low salt permeability, however there are still not enough experimental or theoretical evidences about the best adequate membrane morphology. Actually, FO/PRO membrane development processes involve either integral asymmetric or thin-film composite (TFC) membranes [6,9,13,17,21,24,28,29]. The design of a FO or PRO membrane is not quiet different, however their configuration within the permeation module could vary [12]. In PRO applications, the dense selective layer of the membrane faces the draw solution and the porous support layer faces the feed solution. This

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configuration is necessary to ensure that the membrane can sustain the hydraulic pressure induced on the draw solution side. In FO applications, the selective layer generally faces the feed solution. In this process, the membrane would not withstand any hydraulic pressure. Therefore, it is suggested that the PRO membranes had a higher mechanical resistance in comparison with FO membranes. As a matter of fact, the paradoxical issue in PRO hollow fiber membranes development is combine high water flux and adequate mechanical resistance. However, this point still shows little interest and only few investigation has been achieved [22].

In Brazil, the laboratory of membrane separation processes of COPPE/UFRJ has been working in the synthesis and study of membrane separation processes for more than four decades, being a national and international reference in the area.

This work consists in the production of self-supported anisotropic cellulose acetate hollow fiber membranes that show high permeability to water and reasonable ion selectivity. The membranes are packed in PVC modules that allow the circulation of the different solutions on both sides of the membrane.

Based on the outside diameter of the fibers and the modules dimensions, the maximum effective surface area of membranes per module is approximately 1.5 m^2 that means a packing density of 1500 $m^2\,m^{-3}$. The construction of these modules was also an object of study and innovation, mainly in order to reduce hydraulic losses and to control the mass transfer.

In order to evaluate the performance of the produced membranes in the process of power generation by salinity gradient, a FO/PRO pilot plant was designed and built. The unit consists of three countercurrent flow hollow fiber modules connected in parallel. A low salinity feed stream and a highly concentrated stream, referred to as the draw solution, are pumped through the membranes modules. The best mass transfer efficiency is obtained by the control of the flow rate of the fluids within the modules [16], while the hydraulic pressure difference ΔP across the membrane is used to optimize the conversion of the osmotic flux into electrical power by depressurizing the diluted draw stream in a hydroturbine/generator device. The intermittent pressure retarded osmosis (Int. PRO) operation cycles using a solenoid valve located upstream of an hydroturbine should seem to be a smart alternative and a pioneer adaptation to the PRO process when the total permeation area of the modules is in a pilot scale range. Therefore, this FO/PRO pilot unit could position himself as an ideal intermediate step between bench and industrial scale for the development of viable osmotic power plants.

2. Membrane fabrication

2.1. Material

The polymer used for the fabrication of NF hollow fiber membranes was cellulose acetate (CA) of numerical average molar mass of 50,000 g mol^{-1} provided by Aldrich. A mixture of acetone (AO) and formamide (MA) was used as the solvent. A mixture of *N*-methyl-2-pyrrolidone (NMP) and deionized (DI) water was used as the bore fluid for spinning. Acetone (99.5%), formamide (99.5%) and NMP (99.5%) were all purchased from Vetec, Brazil. The composition of the polymer solution employed was CA/AO/MA (25/45/30% m/m) [9].

2.2. Spinning process

The cellulose acetate powder were dried overnight at 70 °C in a vacuum oven to remove the moisture. The dope solution for spinning was prepared by dissolving a certain amount of the powder into the mixture of acetone and formamide at room temperature. To avoid the evaporation of acetone, the mixing and

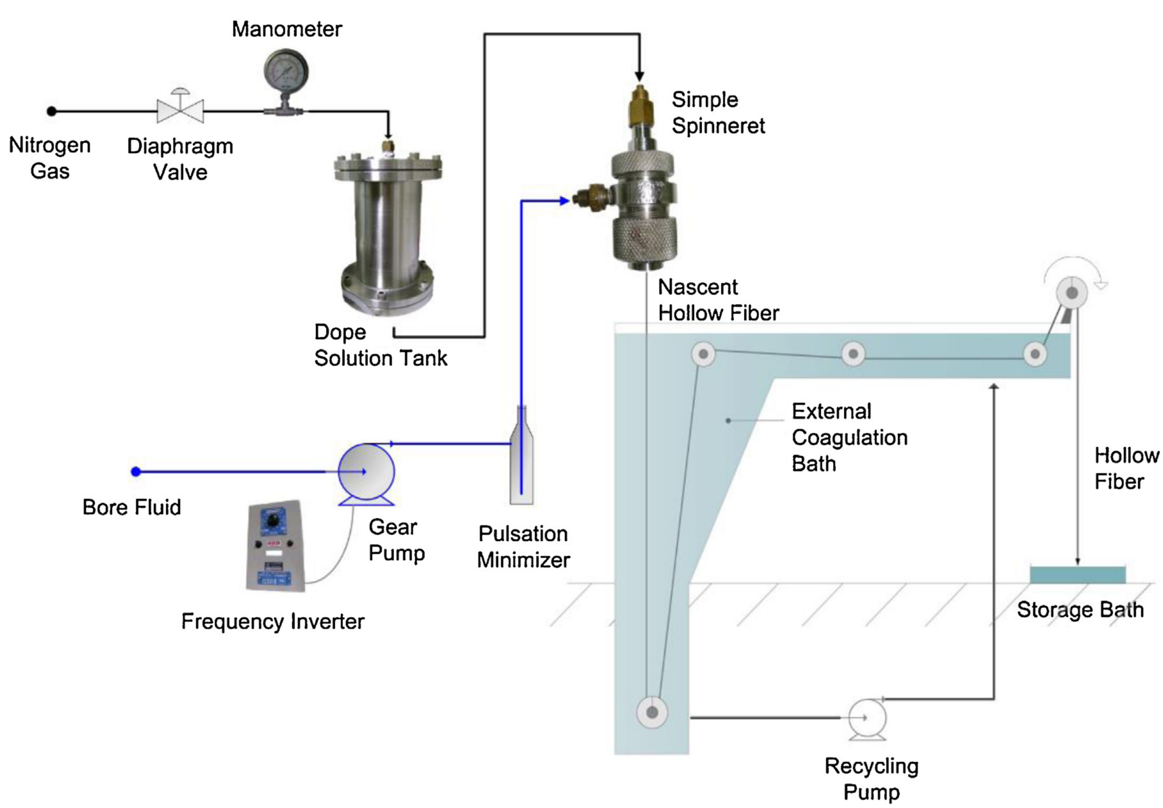

Fig. 1. Schematic of the hollow fiber membranes spinning process.