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Modeling and optimization of a solar forward osmosis pilot plant by response surface methodology

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ABSTRACT

Forward osmosis (FO) is a water treatment/separation technology of emerging interest. Due to its complex nature involving various operating parameters, modeling of this separation process is challenging. A solar thermal and photovoltaic-powered FO pilot plant has been optimized by means of a statistical experimental design and response surface methodology. Predictive models were developed for simulation and optimization of different responses such as the water permeate flux, the reverse solute permeate flux and the FO specific performance index that includes the water and reverse solute permeate fluxes together with the energy consumption. The considered input variables of the FO pilot plant were the feed flow rate, the permeate flow rate and the temperature. The developed response models have been tested using the analysis of variance. A Monte Carlo Simulation method has been conducted to determine the optimum operating conditions of the FO pilot plant. The obtained optimum parameters were confirmed experimentally. Regeneration of the draw solution can be performed by means of an optimized solar powered reverse osmosis (RO) pilot plant with an optimum FO specific performance index ranging from 25.79 to 0.62 L/g kW h achieved under the FO optimal conditions, 0.83 L/min feed flow rate, 0.31 L/min draw solution flow rate and 32.65 °C temperature. The FO energy consumption is only 14.1% the total energy consumption of the FO/RO hybrid system.

1. Introduction

Membrane technologies experienced important developments during last decades allowing significant increases in water production with high quality and low energy consumption. These are attributed mainly to a wide range of available advanced materials, novel and efficient technologies as well as to the well known increasing demand of water supply and sanitation. The worldwide renewed interest in the osmotically driven membrane processes such as forward osmosis (FO) and pressure retarded osmosis (PRO) has increased tremendously in the last few years (Achilli and Childress, 2010; Alsvik and Hägg, 2013; Ge et al., 2013; Gormly, 2014; Helfer et al., 2014; Lutchmiah et al., 2014; Schrier, 2012; Shaffer et al., 2015).

Osmosis is the transport of water across a semi-permeable water selective membrane from a feed solution of higher water chemical potential to a solution of lower water chemical potential (i.e. higher osmotic pressure or higher salt concentration) known as a draw solution. The membrane ideally permits the passage of water rejecting solute(s) molecules or ions. Fig. 1 shows four possible situations that can occur when a semi-permeable water selective membrane is placed in direct contact with pure water and a saline aqueous solution given here as an example. Once water starts moving through the membrane, the hydrostatic pressure at the permeate side of the membrane becomes higher than that of the feed side, resulting in a transmembrane hydrostatic pressure (ΔP) higher than zero. The water flux stops when ΔP equals the osmotic pressure difference ($\Delta\pi$) established between the feed and the permeate. This is the pressure which, if applied to the saline solution, would prevent transport of water across the membrane.

FO occurs when the only transmembrane driving force for water flux is the osmotic pressure difference ($\Delta\pi$) (see Fig. 1). In other words, no transmembrane hydrostatic pressure is applied ($\Delta P = 0$). In this case a high concentration solution (i.e. draw solution) is separated from a low concentration solution by a water selective semi-permeable membrane. The concentration gradient between both the feed and draw solution induces a transmembrane $\Delta\pi$. Consequently, water flows spontaneously through the membrane from the low concentration side to the draw solution

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Nomenclature

A	effective membrane area (m^2)
B	vector of the regression coefficients (β)
C	NaCl salt concentration (g/L)
E	energy consumption (kW h)
F	ratio of variances
N	number of experimental runs
n	number of factors (independent variables)
P	pressure (Pa)
R^2	coefficient of multiple determination
${R_{adj}}^2$	adjusted statistic coefficient
T	temperature (°C)
t	operating time (s)
u	number of significant regression coefficients in the RSM model
V	volume (m^3)
X	($N \times u$) matrix of the independent variables
x_i	coded value of the operating variables
Y	($N \times 1$) vector of the experimental response
$\hat{Y}$	predicted response as a function of the coded variables (x_i)
z	actual value of the operating variable

Subscripts

F	feed
max	maximum
min	minimum
P	permeate or draw solution
S	solute (salt NaCl)
sp	specific
tab	tabulated
W	water

Superscripts

0	center point

Greek letters

α	star or axial point for the orthogonal CCD (= ±1.215 for 3 variables)
β	regression coefficients (in Eq. (10))
ε	statistical error in the RSM model
ϕ	flow rate (L/min)
π	osmotic pressure (Pa)

Abbreviations

ANOVA	analysis of variances
CCD	central composite design
DF	degree of freedom
DoE	design of experiments
RSM	response surface methodology
MS	mean square
SS	sum of squares

side. In FO mode, generally both the feed solution to be treated and the draw solution are circulated tangentially to each side of the membrane module. The used membranes have an asymmetric structure consisting of an active dense or porous layer with pore sizes below 10 nm and a support layer. Various types of osmotic solutions are considered (i.e. sucrose, glucose, $MgCl_2$, $CaCl_2$, NaCl, KCl, etc.) (Cai et al., 2013; Ge et al., 2013). Some advantages of FO are its potential low energy consumption (i.e. electric energy) to run the circulation pumps as well as its high rejection of a wide range of contaminants. One of the problems of FO is the reverse permeate flux of the draw solute, which must be minimal. FO is being applied in various separation processes such as in wastewater treatment, food processing, seawater or brackish water desalination (Gormly, 2014; Lutchmiah et al., 2014; Schrier, 2012; Shaffer et al., 2015).

PRO is an intermediate process between FO and the well known reverse osmosis (RO) technology, where the hydraulic pressure is applied in the opposite direction of the osmotic pressure gradient. In this case, water from a low salinity aqueous solution permeates through a semi-permeable water selective membrane into a pressurized high salinity solution (i.e. seawater). The additional water volume increases the pressure in the permeate side of the PRO membrane module. The power (termed also osmotic power) is then obtained by depressurizing the permeate through, for example, a hydro-turbine. PRO is similar to RO, but in PRO process the applied pressure is maintained below $\Delta\pi$. It must be pointed out that when the applied ΔP is lower than $\Delta\pi$ (Fig. 1), the water permeate flux is still driven by $\Delta\pi$ in the direction of the concentrated draw solution. The interesting application area of PRO is the generation of electricity (Achilli and Childress, 2010; Helfer et al., 2014). When the applied hydrostatic pressure ΔP is greater than $\Delta\pi$ (Fig. 1), the direction of the water flux is reversed leading to the well-known RO separation process used mainly in seawater desalination (Attia, 2012; Delgado-Torres and García-Rodríguez, 2012; Khayet et al., 2010a; Manolakos et al., 2009). Since 1990s the development of low pressure (i.e. high permeability) RO membranes has progressed rapidly (Elimelech and Phillip, 2011; Khayet et al., 2010a).

FO technology is still in continuous improvements trying to overcome the many faced challenges and barriers in order to extend its fields of industrial application. As stated previously, the growing interest of FO is attributed mainly to its lower energy consumption compared to other technologies and to its wider possibility to be coupled to other separation processes including RO for water production and regeneration of the used draw solution (Altaee et al., 2014; Blandin et al., 2015; Choi et al., 2009; Luo et al., 2014; Martinetti et al., 2009; McGovern and Lienhard, 2014; Schrier, 2012; Zhang et al., 2014). It is worth quoting that actual improvements of FO technology, that can contribute to more competitive FO plants achieving significant reductions of energy consumption and water production cost, are focused on the development of FO fouling resistant membranes with low internal concentration polarization coefficients (*ICP*), the design of non-toxic draw solutions with higher osmotic pressures, the combination of FO installation to solar energy systems and the optimization of FO operating factors. As far as we know still there is no published paper on the utilization of renewable energy sources such as wind energy and solar energy systems (i.e. thermal collectors and photovoltaic panels, PV) to run FO plants. Schrier (2012) used solar evaporation for regeneration of the draw solution by removing excess of water using FO for production of fuel-grade ethanol. It is also noted that all the studies reported so far on FO deal with the conventional method of experimentation, in which the effect of an operation variable on the FO system performance is investigated keeping the other variables fixed. This classical or conventional method of experimentation requires many experimental runs, which take a lot of time especially for FO pilot plant tests, ignores the interaction effects between the operating parameters and leads to a low efficiency in optimization resulting in a high energy consumption. These limitations of the classical method of experimentation can be avoided by applying the response surface methodology (RSM)