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Analysis of specific energy consumption in reverse osmosis desalination processes

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ABSTRACT

This paper aims to quantify the contribution of the various factors to energy consumption in reverse osmosis (RO) desalination processes and to identify those with the greatest potential for reduction. Specific energy consumption (SEC), in kWh per m^3 of permeate production, is due to the retentate osmotic pressure, the resistance to fluid permeation through the membrane, the friction losses in the retentate and permeate channels of the spiral wound membrane (SWM) modules and the non-ideal operation of high pressure pumps and energy recovery devices (ERD). Taking advantage of a recently developed SWM-module performance simulator, the aforementioned individual contributions to SEC are determined for two case studies, typical of seawater and brackish water desalination processes, for steady state operation. Detailed results are obtained with SEC itemized per SWM element in a typical 7-element pressure vessel. Comparative assessment of the results is enlightening, showing that the greatest margin for the desirable SEC reduction is related to improvements of membrane permeability and efficiency of pumps and ERD. The indirect, yet significant, effect of other key design and operating process parameters is also discussed.

1. Introduction

The specific energy consumption (SEC), in kWh per m^3 of product water, is the single most important parameter characterizing the performance of the desalination process [1], particularly from the standpoint of overall process sustainability [2]. SEC is comprised of contributions from the operation of the various sections of an entire membrane desalination plant; i.e. (1) the feed-water intake facility, (2) the pre-treatment section, (3) the main desalination section (that includes high-pressure pumps, RO membrane trains and energy recovery devices [ERD]), (4) the product post-treatment section and (5) the brine treatment/disposal facility [3]. The largest contribution to SEC, usually varying between 60% and 80% (depending on feed-water type, local conditions, technology employed) is due to the *main section* where the membrane desalination process is carried out [4,5]. This section, on which this paper is focused, also exhibits the greatest potential for SEC reduction, as will be discussed in the following.

In the typical desalination process considered here (including pumps, RO membrane trains and ERDs), energy is consumed to overcome the retentate osmotic pressure, the resistance to fluid permeation through the membrane, the friction losses in the retentate and permeate channels of the spiral wound membrane (SWM) modules as well as loses due to the non-ideal operation of high pressure pumps and energy recovery devices (ERD). With the exception of the thermodynamically imposed minimum SEC [6], related to the feed-fluid osmotic pressure, the contribution to SEC from other factors can be controlled (at least to some extent) and minimized through improvements in equipment and process design and operation [3–5]. Therefore, it is of great interest to comparatively assess these contributions and to identify those factors with the greatest potential for SEC minimization through appropriate improvements, mainly in equipment and process design. Such information is most useful for techno-economic design studies of RO plants, for prioritization of related R & D activities as well as for environmental-impact and overall sustainability studies of desalination projects [2]. Regarding the latter studies, it is needless to stress the direct relation of SEC with the environmental burden due to the desalination plant operation.

There are quite a few published studies dealing with the contributions to SEC in RO plants which are summarized in recent papers. Two types of such papers can be identified; i.e. those based on data from operating plants (e.g. [1,7,8]) and other employing theoretical analysis [9–13]. Although the former type of data are useful, they usually provide itemized energy consumption values averaged in operating time (over an undefined range of process conditions), often with incomplete supporting data on process design and operating conditions. The existing theoretical-type studies, to the best of the authors knowl-

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edge, present relevant energy consumption data either in general terms, in the context of comprehensive optimization formulations [9,10,12], however lacking adequately detailed analysis of itemized contributions to SEC [13], or provide such contributions in unclear terms and with inadequate information on the computational method employed [11].

This work aims to present an analysis of contributions to SEC, through two typical case studies of RO membrane desalination of sea and brackish water. The analysis is largely made by employing an advanced comprehensive software tool, permitting performance simulation of an entire (multi SWM element) pressure vessel of RO plants, operating under steady state conditions [14,15,16]. With this software, the spatial distribution of all process parameters (throughout a vessel) is predicted [15,16] thus facilitating various types of reliable parametric studies, including those of the present paper. In the following, basic theoretical considerations are outlined first. Computational results, for the two case studies, already documented [16], are revisited and relevant data are re-cast in a form catering to the needs of the present analysis. Finally, a comparative assessment of various contributions to SEC is made, leading to useful conclusions.

2. Theoretical background

2.1. SEC in a typical membrane desalination process

Fig. 1 shows schematically a typical single stage desalination process, including concentrate-energy recovery by ERD. In addition to the variables marked in the process diagram of Fig. 1, the following parameters are defined:

By employing an energy balance over the entire process (outlined in the Supplement) one obtains a general expression for the *Specific Energy Consumption* (*SEC*), defined in Eq. (1) and expressed in terms of main process parameters in Eq. (2):

$$\mathrm{SEC} = \frac{W_{\mathrm{TOTAL}}}{Q_P} \tag{1}$$

$$\mathrm{SEC} = \frac{1}{R}\left[\frac{P_f - P_o}{\eta}\right] + (1-\beta)\left[\frac{1-R}{R}\right]\left[\frac{P_o + \eta_E \Delta P - \eta_E P_f}{\eta}\right] \tag{2}$$

where, in addition to variables depicted in Fig. 1, R is the permeate recovery fraction and η the composite efficiency of pumps, i.e. the product of hydraulic, electrical motor and variable frequency drive efficiency as subsequently discussed. For the case of "*ideal*" *operation of pumps and pressure-equipment* (i.e. $\beta = 0$, $\eta = \eta_E = 1.0$), the specific energy consumption under ideal conditions $\mathrm{SEC_i}$ is given as:

$$\mathrm{SEC_i} = \left(\frac{1-R}{R}\right)(\Delta P) + (P_f - P_o) \tag{3}$$

Therefore, energy losses due to the inefficiencies in pump and ERD operation are obtained from the difference of Eq. (2) minus Eq. (3);

$$\mathrm{SEC_{inef}} = \mathrm{SEC} - \mathrm{SEC_i} \tag{4}$$

It will be noted that SEC is readily computed in Pascal or kWh/m^3, with a conversion factor $1.0\,\mathrm{kWh/m^3} \approx 3.6 \times 10^6\,\mathrm{Pa}$. Further, it should be pointed out that in the present treatment, two simplifications will be made, with no loss of generality; i.e. that a) the feed water pressure at the pumps suction, as well as the permeate and concentrate discharge pressures are at the same reference value P_o (Fig. 1), and b) pressure drop in the interconnecting piping in the membrane trains will be ignored.

2.2. Itemized contributions to SEC

The particular contributions to SEC in the main desalination section (of an entire plant) are due to the physico-chemical and transport phenomena taking place within the several SWM modules, arranged in series in the pressure vessels, that comprise the main desalination facility. For a single stage operation considered here, suffice it to determine SEC in a single pressure vessel, schematically shown in Fig. 1.

Under steady state conditions (i.e. in the case of constant feed conditions as well as membrane properties) there is a spatial variation of all process parameters throughout the membrane sheets comprising the SWM modules. Recently, an advanced simulation tool has been developed in the authors laboratory [14,15,16] capable of predicting the spatial variation of all key parameters of interest (*including local pressures and species concentrations)*, necessary to determine the required itemized SEC contributions. The case study results reported here will be based on the stock of data obtained in parametric studies, already reported [16] for the *constant recovery* mode of operation of the desalination process. It will be added that in the analysis underpinning

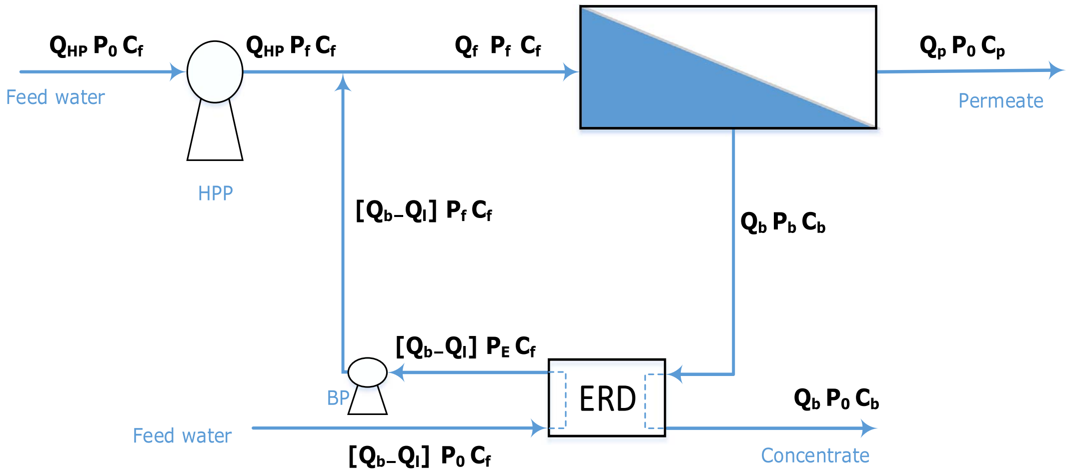

Fig. 1. Schematic of a single-stage membrane desalination unit with energy recovery device (ERD).

Pressure difference across pressure vessel	$\Delta P = P_f - P_b$
Pressure transfer efficiency of ERD	$\eta_E \approx \frac{P_E}{P_b}$
Leakage ratio of ERD	$\beta = \frac{Q_l}{Q_b}$