REVERSE OSMOSIS BY SOLAR ENERGY

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Contents

Summary

In the first section the paper discusses the basic physical parameters for seawater desalination. The equations presented illustrate that membrane characteristics, salinity, temperature, the extraction rate, and the overall plant design influence the process. Accordingly, the set of data about the energy demand of the systems is a function of the various parameters.

Utilizing solar energy for desalination processes necessitates the conversion of the solar irradiance into electrical, mechanical, or thermal energy. The technically viable principles and the steps applied in such energy conversion systems are presented and the specific performance displayed - mainly regarding the generation of electricity as the most versatile power source for the applications in demand.

The review also presents an overview, which configurations are of technical importance for water desalination by reverse osmosis. The characteristic features of the different

concepts are outlined and additional considerations included concerning water pre-treatment practices and the performance of the other important components of a desalination plant.

1. Introduction

Membrane separation presents a favorable method for desalination of water especially that of moderate salinity. The main advantage of the method is a very low energy consumption which is closely linked with the salt content of the feed water. If salt concentrations are higher, the process of Reverse Osmosis (RO) can be performed in two stage configurations.

Commercially available RO units are usually operated by electric energy, but also direct mechanical power input to drive the pump is common. Systems sizes with drinking water capacities ranging from a few cubicmeters per day to some hundred tons per day are available from the shelf, larger plants are possible combining an adequate number of units, since most of the manufacturers apply modular design strategies, facilitating pre-assembly of the equipment in the factory. Small plants can even be installed ready for use in standard shipment containers.

For renewable energy powered desalination, preferably units of small to medium sizes are conceived. In such cases specific care should be taken to optimize the energy demand and to adapt the system to the operation conditions of solar systems. A favorable means of reducing the energy consumption of the process is energy recoupment, but also the reduction of auxiliary energy consumption is an issue of high importance.

2. Basic Parameters and Energy Demand for Osmosis

2.1. Physical Properties of Hyperfiltration

Reverse Osmosis (RO) plants utilize selective membranes capable of separating fluids of different salinity, permitting the diffusion of preferred liquid molecules, but widely barring the penetration of solute molecules and other components. The driving force to sustain the process is pressure applied to the saline water fed into the RO system or module.

Osmotic pressure and salt concentration are directly related. Data for water qualities representative for desalination applications have been compiled in Figure 1. The process is reversible, controlled by pressure and concentration differences (Δp and Δc, respectively). As long as no state of equilibrium between the two solutions is reached, mass transfer through the membrane takes place. The process temperature exerts some influence, as do the diffusion coefficients and the material characteristics of the membranes. A detailed discussion of the related effects is given in a number of publications dedicated to the issues of desalination and hyperfiltration (Perry and Chilton 1973; Spiergler and Larid 1980; Böddeker 1984; Ullmann 1984).

In fact, the semipermeability of membranes is not perfect. Different molecular species in the case of desalination water and the constituents of the salinity just penetrate at different rates. The local diffusion coefficient D_c and the concentration gradient across the membrane (x indicating the distance from the membrane surface) define the permeation rate N according to the following expression. If the diffusion coefficient is assumed to be independent of the concentration c, integration yields a linear dependency for a membrane of the thickness δ.

$$N = -D_c \cdot \frac{dc}{dx} \tag{1a}$$

$$N = \left(c_F - c_P\right) \cdot D_c \cdot \delta^{-1} \tag{1b}$$

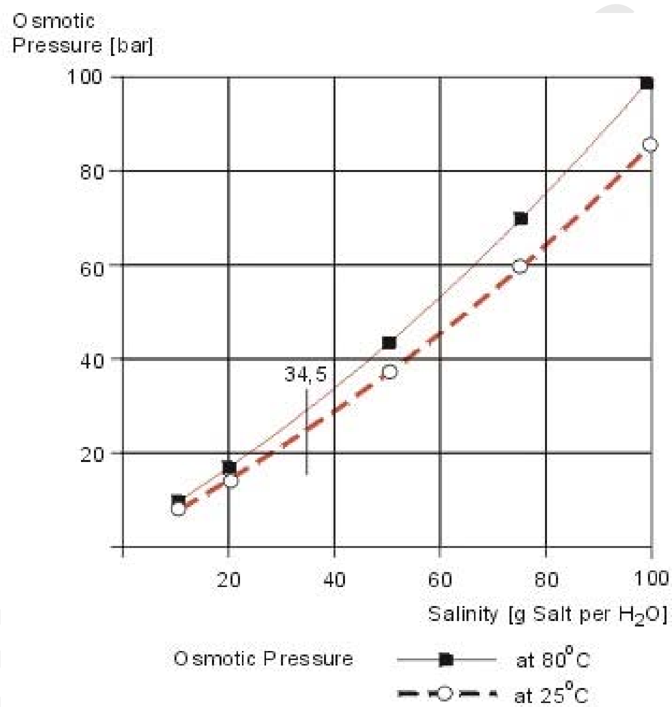

Figure 1. Osmotic pressure as a function of salinity and temperature.

Indices F and P refer to the "feed" and "product" side of the membrane, respectively (Figure 2).

Salt concentration on the high pressure side of the membrane increases due to extraction of permeate. Thus, also the equilibrium conditions between the solutions change with the coordinate λ. At a surface element ΔA the amount of water ΔM transgressing the membrane in a time interval Δt is given by the condition:

$$\Delta M_{(\lambda)} = K_w \cdot \Delta p \cdot \Delta A \cdot \delta^{-1} \cdot \Delta t \tag{2}$$

K_w can be assumed as a constant, summarizing the diffusion characteristics of water across the membrane, which includes the influences of the physical coefficients within the membrane (diffusion) and the related effects at the membrane surfaces (adsorption; desorption). The dominant pressure difference Δp is characterized by the external pressure applied by the high pressure pump minus the osmotic pressure difference for the two solutions (π_F - π_P). With changing salinity the local osmotic pressure difference increases as compared to the initial process conditions. Accordingly, the specific quantity of water passing per surface element of the membrane is variable.

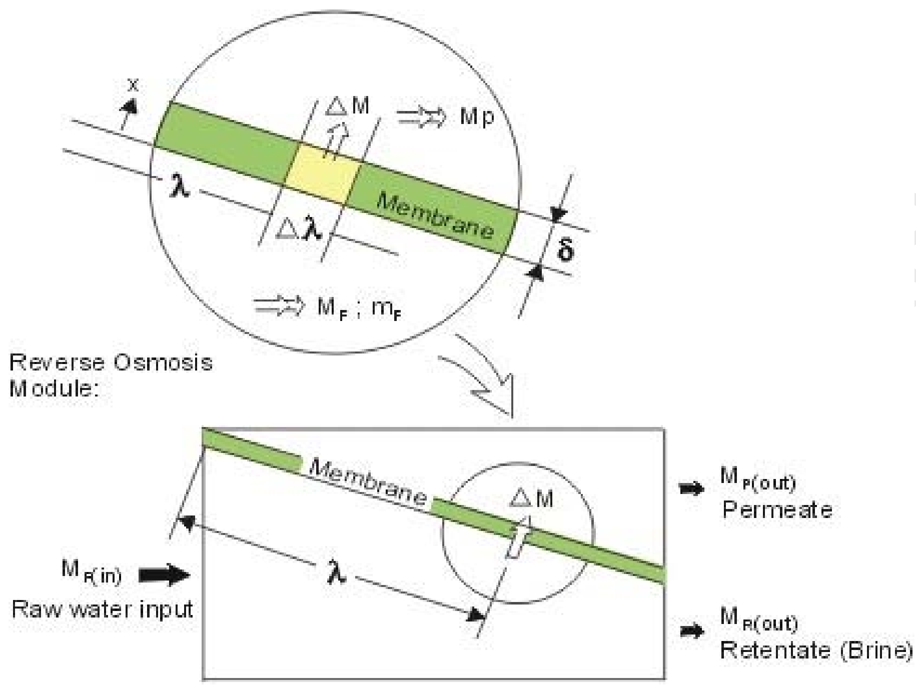

Figure 2. RO functional schematic.

The amount of salt Δm penetrating the membrane can be derived by a very similar expression as presented above. Here the dominant role is exerted by the concentration gradient (with K_s denominating the diffusion parameters of salt).

$$\Delta m_{(\lambda)} = K_s \cdot \Delta c \cdot \Delta A \cdot \delta^{-1} \cdot \Delta t \quad (3)$$

For technical application and assuming steady-state conditions the definition of a retention factor R is common to characterize the quality of the process in separating solutions of different salt concentration.

$$R = (1 - c_F / c_p) \cdot 100\% \quad (4)$$

With common salinity levels of the raw water ranging from <10 000 to >35 000 ppm, values of R between 98 and 99.5 per cent are necessary for seawater desalination plants, lower values may be admitted for brackish water treatment.

Under steady-state conditions and if the difference is sufficiently high the amount of raw water fed to the reactor separates into permeate (product) and retentate (brine), where $M_{P(out)}$ refers to the product water output; $M_{F(in)}$ to feed water input, and $M_{R(out)}$ to the brine rejected (retentate):

$$M_{F(in)} = M_{R(out)} + M_{P(out)} \tag{5}$$

With the assumption mentioned that nearly no (or at least only a minor amount of) salt molecules will pass the membranes, and supposing that only few salt deposits are formed at the membrane surface, a compilation of the salinity increase yields for the status S_{out} at the brine exit:

$$S_{out} \cong S_{in} \times (1 - e_R)^{-1} \tag{6}$$

The term e_R represents the extraction rate as defined by:

$$e_R = M_{P(out)}/M_{F(in)} \tag{7}$$

It is obvious that in cases of high extraction rates specific care has to be applied to cope with the salinity increase.

Still more effort may be necessary, if chemical elements are dissolved in the raw water, which are not present in common water sources. For instance, brackish water may contain elements not prevalent in standard seawater. When such molecules exist, the characteristics of the membranes need to be checked for suitability.

2.2. Energy required for the RO Process

The dominant energy demand of reverse osmosis is required to power the high pressure feed pump. Hydraulic laws correlate the mechanical energy W_{PUMP} for to the product of mass flow M_F and the overall pressure difference Δp:

$$W_{PUMP} = K_{PU} \times \Delta p \times M_{F(in)} \times \eta_{PU}^{-1} \tag{8}$$

In this equation the parameters K_{PU} and η_{PU} represent the factors accounting for the influences of water density, scale parameters (accounting to the dimensions of the input values), and the pumping efficiency.

According to the physical principle of osmosis the product (permeate) leaves the osmosis module at ambient pressure. Only minimal pressure losses occur on the feed water/retentate side. By modifying the internal pressure the desired product quality and the function of the semipermeable membrane can be influenced. Thus, a device for pressure adjustment is needed at the brine exit port. In simple systems the expansion is controlled by means of a reduction valve.

Depending on the extraction rate the energy needed to pressurize the "brine" represents a significant part of the overall pumping effort. Thus, energy recovery by expansion turbines is state-of-the-art in plants of larger capacity. The advantage can be assessed by a similar expression as valid for pumping, the recuperated energy W_{REG} and the constant k_{RE} and η_{RE} being defined accordingly:

$$W_{REG} = k_{RE} \times \Delta p \times M_{R(out)} \times \eta_{RE}^{+1} \qquad (9)$$

Combining the equations for pumping energy and recovered amount of energy the resulting net energy demand for the osmotic process W_{RO} can be estimated. The total consumption can be derived by allowing for an additional amount of energy counting for the auxiliary energy demand W_{aux}. Raw water pumps (mainly to convey the raw water to the plant overcome the pressure drop in the filters), process control, and water treatment procedures add to the overall amount of energy. For small systems in particular auxiliary energy can play a considerable role.

$$W_{RO} = (W_{PUMP} - W_{REG}) + W_{AUX} \qquad (10)$$

It is usual to define the specific energy demand W_{RO} with reference to the product output (i.e. per m^3 of permeate):

$$W_{RO} = W_{RO}/M_{P(out)} = (W_{(PUMP)} - W_{REG} + W_{AUX})/M_{P(out)} \qquad (11)$$

Usually, reverse osmosis desalination requires between 6.5 and 24 kWh per m^3 of product water, lower figures for plants with energy recuperation, higher values for plants with a simple throttling device at the brine rejection port. The formula mentioned above can be rearranged, using the extraction rate to link the product output with the flow figures for water input and rejected amount of brine, which are bound to the pumping and recuperative energy. The resulting expression describes the influence of single parameters (some deduction steps omitted):

$$W_{RO} = (\Delta p \times e_R^{-1}) \times [k_{PU} \times \eta_{PU}^{-1} - k_{RE} \times \eta_{RE} \times (1 - e_R)] + w_{AUX} \qquad (12)$$

The first term in this equation illustrates the influences of the pressure difference and of the extraction rate. Also the effect of the pumping efficiency is obvious. The subtracted terms in brackets stands for the energy recovery (and will become zero for $\eta_{RE} = 0$, i.e. if there is no expansion turbine). The last term w_{AUX} describes the specific energy demand for the auxiliary components.

Figure 3 presents a schematic energy flow diagram in two versions: For a "direct" process without, and for a RO system with energy recuperation.

In a real RO process the energy demand will be definitely higher than predicted theoretically. Provisions for this can be made either by correcting the efficiency data or by choosing a higher feed pressure. The overall pressure difference Δp controlling the energetic behavior is composed of the following factors:

$$\Delta p = p_{F(in)} - p_{P(out)} \geq (\pi_F - \pi_P) + \Delta p' + \Delta p'' + \Delta p^* + \Delta p^+ \qquad (13)$$

$p_{F(in)}$ = nominal pressure of the feed (high pressure pump output)
$p_{P(out)}$ = pressure at the product port (i.e. ambient pressure, if no further treatment or storage is provided. Otherwise the pressure required to perform such processes has to be accounted for).
$(\pi_F - \pi_P)$ = the difference between the osmotic pressures in the feed and the output. The value should be calculated for the maximum salinity levels conceived.
$\Delta p'$ = hydraulic pressure losses in the membrane stack and in ducts and fittings.
$\Delta p''$ = pressure losses across the membrane.
Δp^* = additional pressure demand due to salinity polarisation at the membrane.
Δp^+ = excess hydraulic pressure to support a minimal speed in the membrane stack (e.g. to avoid stratification of brine at the membrane) and to compensate for any losses.

Especially for the different loss components appointed to the semipermeable effect the build-up of inhibiting layer (fouling and scaling) and the material parameters of the membrane are essential. Also aging of components and unwanted deposits may affect the performance. Careful filtering of raw water may prohibit or reduce such effects.

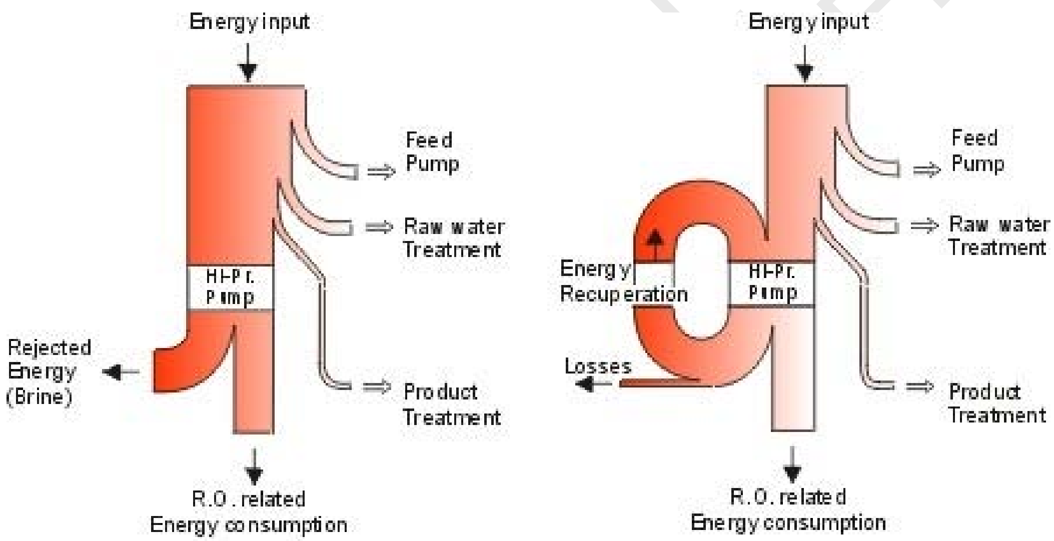

Figure 3. Energy flow diagrams: Effects of internal energy recuperation.

In practical applications the pressure $p_{F(in)}$ applied is set between twice to three times the "net" osmotic pressure difference. Factors demanding such high safety margins in the design values refer to possible influences of process temperatures, changes in the raw water salinity (e.g. seasonal variation), and deterioration of the membrane functions with time. Agglomeration of salt on the membrane surface (polarization) and changes in its porosity as a consequence of the high mechanical stresses act in the same way.

Auxiliary demand figures for the overall energy requirements have to be determined in each specific case and added to the directly process-related energy consumption to get the total amount of energy, which has to be covered by solar power conversion.

Auxiliary energy demand is in part correlated to the total mass flow. For a detailed deduction it is advisable to look for those constituents, and to correlate them to the extraction rate to get the specific figures related to the plant output. Examples for such demand are the energy to drive the raw water pump(s); energy to power the components for raw water treatment, and the energy consumption of the control system. For the raw water pump similar equations apply as for the high pressure pump. So, the energy demand can be calculated, if the pressure head according to the geodetic difference between raw water source and the desalination plant and pressure losses in the filtering devices, raw water treatment plant, and in pipes and ducts, are defined.

Any clean water treatment, if performed, will also influence the energy demand. Moreover, basic consumption independent of the operational regime (e.g. continuous load monitoring) also needs to be accounted for. The relative importance of these factors depends largely on the plant size. The parasitic energy demand affects small systems to a much higher degree than large ones.

Operation strategies also play a role. This is a factor to be dealt with especially in solar powered systems, since even plant stand-still periods usually do not attenuate the energy consumption to zero. Accordingly, at plants with permanent production the parasitics are of less importance.

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