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Water desalination by pervaporation – Comparison of energy consumption

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ABSTRACT

The most common desalination technology is based on reverse osmosis, which uses semi-permeable membranes and pressures from 5.5 MPa to 6.8 MPa in order to overcome the osmotic pressure. The lowest achievable energy consumption of RO is 2 kWh/m^3. The other viable methods of desalination include membrane distillation and pervaporation. Each of these techniques has certain advantages and disadvantages but in terms of energy consumption pervaporation seems particularly promising. Over the past few years, desalination performed with the help of pervaporation has been widely investigated.

In this study, desalination experiments were carried out with a commercial membrane. The salt concentration and the feed solution temperature were varied between 0.8% and 7.0% and between 40 °C and 70 °C, respectively. The experiments helped determine the desalinated water flux and the salt rejection factor. In addition, differences in enthalpy and Gibbs free energy, representing the theoretical energy consumption, were estimated in the raw water/feed and the feed/permeate systems. For the purpose of comparing the energy consumption, three desalination techniques were considered: RO, PV and MD.

1. Introduction

Water covers about 71% of the Earth's surface. Over 96.5% of the Earth's water supply remains in seas and oceans but, because of its saltiness, is not suitable for drinking. Just 2.5% of all the water on the planet is fresh, which means it could be directly used by humans, animals and plants. In reality, however, only 0.65% of Earth's water is available for such purposes because the remaining fresh water is trapped in glaciers and snowfields [1].

According to the United Nations Millennium Development Goals Report 2015 [2]:

- 663 million people - 1 in 10 people - lack access to safe drinking water,
- 1/3 of the global population lives without access to a toilet,
- more people have a mobile phone than a toilet.

Considering the above information, it can be stated that many problems related to the availability of drinking water need to be solved, especially in developing countries.

Water, energy and food constitute three interconnected and fundamental pillars of sustainable development [3]. It should be noted that the main element of this triangle is energy. The cost of energy in water desalination amounts to about 50% of total process costs [3]. The cost of treating fresh water depends on its origin. Rich countries either exploit available fresh water supplies or use desalination techniques to treat salt water. In such a way, significant amounts of water for sanitary and domestic uses can be acquired albeit at a significant cost and energy use.

The energy consumption of desalination is of crucial importance because producing drinking water is directly related to the availability of salt water and energy. Salt water can be obtained from seas and oceans as well as mines and geothermal resources. There are certain environmental issues with the disposal of saline mine and geothermal water but obtaining drinking water is possible. The energy use of desalination is currently being studied and reported in academic papers. The authors of [4–8] investigated the energy consumption of reverse osmosis and the possibilities of energy recovery. The papers [9–13] are devoted to the desalination done through pervaporation. They focus mainly on modifying desalination membranes in order to enhance their performance. Another interesting technique of water desalination employing heat recovery is membrane distillation, which has been described in several theoretical and practical papers [14, 15].

This work examines the change in enthalpy and Gibbs free energy during the transition from cold raw (salt) water to the feed and from the feed to the final permeate. The following three membrane desalination techniques were considered: reverse osmosis (RO), pervaporation (PV) and membrane distillation (MD).

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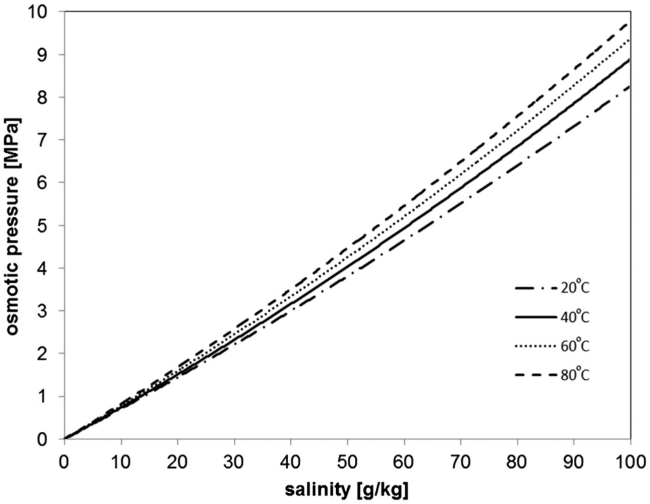

Fig. 1. Osmotic pressure vs. salinity at different temperatures.

1.1. Reverse osmosis

Reverse osmosis, performed with semi-permeable membranes, is the most common method of desalinating seawater [7]. The difference in pressure between the high pressure side of the membrane and the osmotic pressure is the driving force of the process. The permeation flux J_P, given by Eq. (1), depends on the pressure difference between both sides of the membrane but also on the difference in osmotic pressure:

$$J_P = \rho L_{RO}(\Delta P - \sigma\Delta\pi) \quad (1)$$

where

J_P - permeation flux, [kg/(h m^2)]
ρ - density of the permeate, [kg/m^3]
ΔP - pressure difference, [Pa]
Δπ - osmotic pressure difference, [Pa]
L_{RO} - RO permeability coefficient, [m^3/(m^2 Pa h)]
σ - reflection coefficient, [−]

Fig. 1 shows the changes in osmotic pressure with the salt concentration and temperature. The osmotic pressure increases with increasing temperature, which causes the driving force to decrease. On the other hand, an increase in temperature enhances the mass transfer from the feed into the membrane, which consequently lowers the mass transfer resistance and can have a positive impact on the permeation flux in the RO process [16].

1.2. Pervaporation

Pervaporation is a complex process involving several sub-processes. The feed flow along the membrane causes a polarization layer to form at the membrane surface. Its thickness depends on the Reynolds number related to the boundary layer. Diffusion of the components through the layer causes additional resistance to mass transfer. On the membrane surface adsorption takes place, at the same time penetration of the solvent into the active layer causes the membrane to swell. Then, water and salt diffuse through the active layer as a result of the chemical potential difference. Water changes its phase but it is still unknown whether this phenomenon takes place inside or on the low pressure side of the active layer [17]. Afterwards, the permeate desorbs from the opposite side of the active layer and flows through the porous layer, the support layer and condenses in a cold trap. No single equation allows calculating the permeation flux. When the solution-diffusion mechanism is assumed, mass transfer through the membrane can be expressed by Eq. (2) [18]:

$$J_P = \rho\ L_P(a_P - a_F) \quad (2)$$

where

J_P – permeation flux, [kg/(h m^2)]
a – activity of the component, [−]
x – distance/membrane thickness, [m]
L_{PV} – PV permeability coefficient, [m^3/(m^2 h)]

According to several studies, the permeation flux increases with increasing temperature [19–22].

1.3. Membrane distillation

In membrane distillation, a hydrophobic and porous membrane (e.g. made of polytetrafluoroethylene, polyvinylidene fluoride or polypropylene) separates an aqueous salt solution at elevated temperature. Water, kept cooler than the feed, flows along the other side of the membrane. Water from the salt solution having a higher temperature evaporates and diffuses through the pores of a non-wettable membrane and condenses on the cooler side (distillate side). The mechanism enables desalination of the feed solution. Other variations of the MD process are also possible such as air gap MD, direct contact MD, sweeping gas MD and vacuum MD.

The temperature dependent difference in vapor pressure on both sides of the membrane influences the permeation flux. The higher the temperature difference, the higher the flux, which can be estimated with the following equation:

$$J_P = \rho L_{MD}(P_F^{sat}(T_F) - P_P^{sat}(T_P)) \quad (3)$$

J_P – permeation flux, [kg/(h m^2)]
ρ – density of the permeate, [kg/m^3]
$P_F{}^{sat}$ – saturated vapor pressure of water on the feed side, [Pa]
$P_P{}^{sat}$ – saturated vapor pressure of water on the permeate side, [Pa]
L_{MD} – MD permeability coefficient, [m^3/(m^2 Pa h)]

Theoretically, the permeability coefficient L_{MD} should be temperature independent. However, when the temperature difference between the feed and the permeate is remarkable, assuming temperature independence of L_{MD} may be questionable.

2. Theoretical aspects of energy consumption in RO, PV and MD

Comparison of RO, PV and MD can be made from the perspective of energy consumption. The mass balance concept is illustrated in Fig. 2.

For the purpose of calculations the following assumptions were made:

1. Concentration of NaCl in the feed (cold raw water) was equal to 3.5%.
2. Concentration of NaCl in the permeate was equal to 0.025%.
3. Desalination by reverse osmosis was performed at 60 °C, feed pressure of 7 MPa and permeate pressure of 0.1 MPa.
4. Desalination by pervaporation was performed at a feed temperature of 60 °C, permeate temperature of 20 °C, feed pressure of 0.1 MPa

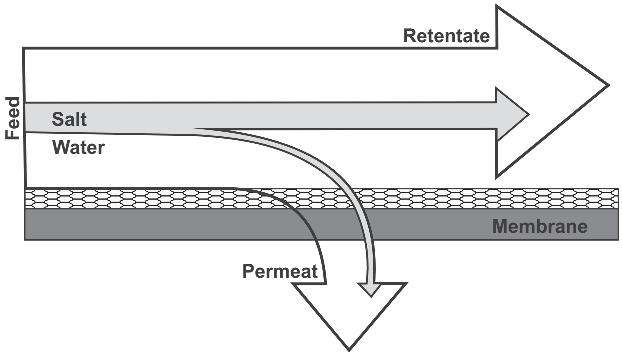

Fig. 2. Sankey diagram of membrane desalination.