Desalination 314 (2013) 59–66

Contents lists available at SciVerse ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Numerical simulation and theoretical study on simultaneous effects of operating parameters in vacuum membrane distillation

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HIGHLIGHTS

► This research focused on Persian Gulf water desalination via VMD.
► Simulation of the effects of operating and membrane parameters on the membrane flux.
► Little impact of feed velocity on flux, but important effect on polarization reduction.
► The more the feed temperature, the more the heat transfer coefficient impacts on flux.
► Regarding the whole effects, the optimum range of membrane thickness was determined.

ARTICLE INFO

Article history:
Received 23 November 2012
Received in revised form 5 January 2013
Accepted 8 January 2013
Available online 4 February 2013

Keywords:
Vacuum membrane distillation
Mass transfer
Numerical simulation
Permeate flux
Temperature polarization

ABSTRACT

The Persian Gulf and its coastal areas are the world's largest single source of crude oil, and related industries dominate the region. Also the waste heat from refineries and petrochemical industries, which are located close to the Persian Gulf, can be used according to the simple feed inlet condition in vacuum membrane distillation (VMD). Hence, in order to enhance the performance of VMD in desalination of Persian Gulf water and to get more flux, a simultaneous heat and mass transfer model in VMD system has been developed and validated with experimental data. The model has been solved numerically using MATLAB. The influence of some operating conditions such as feed temperature, vacuum on permeate side, feed concentration, heat transfer coefficient, feed velocity and some membrane characteristics such as thickness, porosity, pore size distribution and tortuosity on permeate flux has been considered. The effects of feed temperature, feed velocity and membrane thickness on temperature polarization have also been taken into account. The results showed that the permeate flux improved with increase of feed temperature, velocity, heat transfer coefficient, porosity and pore size distribution, and decreased with enhancement of vacuum pressure, feed concentration, thickness and tortuosity of membrane.

1. Introduction

Membrane processes have become competitive with the conventional separation methods in a wide variety of applications such as distillation. As an attractive separation process, membrane distillation (MD) has been the subject of worldwide academic studies by many experimentalists and theoreticians. MD is a nonisothermal membrane technology for separation that is mainly suited for applications in which water is the major component present in the feed solution to be treated and refers to a thermally driven transport of vapor through the membranes, the driving force being the partial pressure difference between each side of the membrane pores. Its flux is not sensitive to salt concentration in the feed, since vapor pressure is not greatly affected by the salinities found in practical water treatment. Thus, it is a potential commercial desalination technique if it can be combined with solar energy, geothermal energy or waste heat available in power stations or chemical plants.

In MD, feed and permeate compartments are separated by a hydrophobic membrane. A temperature difference between two compartments leads to differing water vapor pressures, causing water vapor transport across the membrane. Vapor transport from the warm compartment produces distilled water in the cooler compartment. Since it is possible to warm the compartment well below the boiling point of feed, the use of low-grade thermal energy is possible. In many situations, this energy is available at minimal cost, so membrane distillation will not be as costly as typical desalination processes which are more energy intensive.

MD process can be applied in many areas of industrial interest, for example, the concentration of aqueous solutions such as fruit juices [1–4], removal of volatile organic compounds (VOCs) from increasingly contaminating drinking water [5–9], waste water treatment of contaminated industrial outputs as in textile and pharmaceutical industry [10,11] and ethanol recovery [12–19]. MD has also been used to treat radioactive waste, where the product could be safely discharged to the

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0011-9164/$ – see front matter
http://dx.doi.org/10.1016/j.desal.2013.01.005

environment [20]. As well, the possible application of MD for desalination has been examined by some researchers [21–31].

Depending on the process configurations, four different systems of MD have been identified: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Vacuum Membrane Distillation (VMD) and Sweep Gas Membrane Distillation (SGMD).

One possible way to increase membrane permeability in MD is removing air from its pores by deaeration or by applying a continuous vacuum in the permeate side below the equilibrium vapor pressure by means of vacuum pumps. This MD configuration of industrial interest, which proves to be very promising, is VMD.

Condensation takes place outside the module, inside a condenser or a liquid nitrogen trap [32,33]. This process allows us to reach higher partial pressure gradients and thus higher fluxes and plant productivity, in comparison with other MD configurations (Fig. 1).

Recently, VMD has become an active area of research by many. Some studies have focused on the ethanol/water separation. Other researchers studied the use of VMD in the removal of trace gases and VOCs from water. As mentioned above, also desalination from water is one of the main applications of VMD.

The Persian Gulf is certainly one of the most vital bodies of water on the planet, as gas and oil from Middle Eastern countries flow through it, supplying much of the world's energy needs. The refineries and petrochemical industries, which produce a lot of waste heat and are located close to the Persian Gulf, would be able to use the enhanced process to produce distilled water from seawater. The wider application of the desalination process could be used by companies to produce distilled water for industrial processes. This research focuses on Persian Gulf water desalination via VMD. In order to enhance the performance of VMD in desalination of Persian Gulf water and to get more flux, a simultaneous heat and mass transfer model in VMD system has been developed and validated with experimental data.

2. Theory

VMD process is based upon using a microporous hydrophobic membrane for the separation that the driving force is maintained by applying vacuum at the permeate side below the equilibrium vapor pressure.

This configuration has the following two advantages:

(i) A very low conductive heat loss: This is due to the insulation against conductive heat loss through the membrane provided by the applied vacuum. The boundary layer in the vacuum side is negligible, which implies a decrease in the heat conducted through the membrane and enhancement of the VMD performance.

(ii) A reduced mass transfer resistance: The diffusion inside the pores of the evaporated molecules at the liquid feed/membrane interface is favored. In other words, the resistance to heat transfer on the permeate side and the heat transfer by conduction through the membrane can generally be neglected in VMD configuration

(iii) In most VMD systems the membrane pores are extremely small compared to the mean free path of the diffusing molecules. Therefore, the number of molecule–molecule collision is negligible compared to the number of molecule–pore wall collisions, and the molecular diffusion resistance can be omitted.

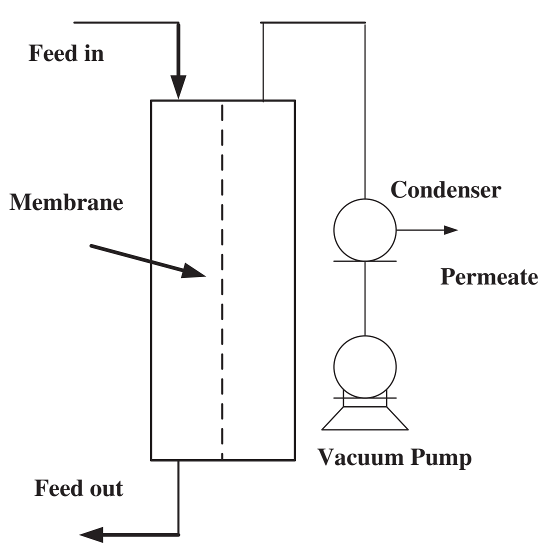

Fig. 1. Schematic drawing of vacuum membrane distillation process.

In these conditions, the Knudsen diffusion mechanism usually dominates the mass transfer through the membrane. That has been recognized by a previous thorough experimental analysis [33,34] and was also confirmed by other groups [35,36].

So, the mass flux of the water (J) is linearly related to its partial pressure gradient (ΔP) as follows:

$$J = \frac{K_m}{\sqrt{M}}(P_I - P_V) \quad (1)$$

where M is a molecular weight of water ($\text{kg} \cdot \text{mol}^{-1}$) in the permeating stream. P_V (Pa) is the downstream pressure and P_I (Pa) is the interfacial partial pressure of water.

K_m is the membrane permeability which depends on membrane characteristics and feed temperature. Making use of the gas kinetic theory applied to a fluid diffusing inside the pore of a solid medium [37], the permeability coefficient K_m ($\text{s} \cdot \text{mol}^{1/2} \cdot \text{m}^{-1} \cdot \text{kg}^{-1/2}$) can be obtained as follows:

$$K_m = \frac{4\varepsilon d_p}{3\chi\delta(2\pi RT)^{1/2}} \quad (2)$$

Apparently, the permeability coefficient K_m, depends upon temperature and on the membrane properties only, in terms of pore size distribution d_p (m), thickness δ (m), void fraction ε, and tortousity factor χ. R is the universal gas constant ($\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$).

Tortuosity factor is applied to correct for the fact that the actual distance travelled by a molecule through the membrane is larger than the membrane thickness. One of the most successfully applied empirical correlations [38] is:

$$\chi = \frac{(2-\varepsilon)}{\varepsilon} \quad (3)$$

In the frequent case of non-ideal mixtures, the vapor–liquid equilibrium is mathematically described in terms of partial pressure (P_I), vapor pressure of pure (p_i^0), activity coefficient (ξ_i) and liquid mole fraction(x_i), according to the well-known thermodynamic relationship:

$$P_I = p_i^0 x_i \xi_i \quad (4)$$

The functional dependence of the vapor pressure (measured in Pa) of pure substances (p_i^0) on temperature is generally available in the form of Antoine equation:

$$p_i^0 = \exp\left[A - \frac{B}{C+T}\right] \quad (5)$$

T is expressed in K. A, B, and C are constants deduced by regression of experimental measurements [29].

In order to consider the effect of salt concentration of Persian Gulf water on membrane performance, the required experimentally measured data, e.g. the activity coefficients of the species, has been extracted from the literature [39]. The analyses of sea water are also listed in Table 1.