



## Membrane contactor with hydrophobic metallic membranes: 2. Study of operating parameters in membrane evaporation

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### ARTICLE INFO

#### Article history:

Received 24 September 2009

Received in revised form 2 February 2010

Accepted 8 March 2010

Available online 12 March 2010

#### Keywords:

Low temperature concentration

Membrane evaporation

Metallic membrane

Hydrophobic membrane

Thermal polarization

Electric heat system

### ABSTRACT

This paper is the second part of a work concerning a process named membrane evaporation (ME) which is approaching to a sweep gas membrane distillation and based on the concentration of an aqueous solution by its continuous evaporation through a metallic hydrophobic membrane. In the first part we described the basic principles of the process and developed a complete mass and heat transport model. In this second part we present a detailed research of the effects of operating parameters (air velocity, feed temperature, air pressure) and analyzed the interest of using metallic membranes as an electric resistance in order to bring energy directly to membrane pores by Joule effect (electric heat system, EHS). The concept of concentration by ME was validated by using pure water and the theoretical model developed in the previous work was used to understand how the temperature polarization phenomena took place in the process. The model allowed also to determine the effect of the EHS on the temperature profiles and on water evaporation flux.

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### 1. Introduction

Membrane contactors represent an emerging technology in which a macroporous membrane is used in order to create an interface for mass transfer between two phases. The membrane does not act as a selective barrier but offers a large and constant interfacial area and avoids problems encountered in classical two-phase contact processes like emulsion formation, flooding and unloading [1–5]. Among different membrane contactor processes, membrane distillation (MD) and osmotic evaporation (OE) are the most studied [4,6,7]. However these both processes present drawbacks that can be detrimental for different operations. In one hand, problems of corrosion and plant production costs due to the use of concentrated brine can reduce the interest of OE [7–9]. On the other hand, due to the relatively high operating temperatures, MD is not adapted for the concentration of thermal sensitive products and entails high energetic costs [10–13]. In addition, it is worth noting that high fluxes involved in MD induce a significant decrease of the temperature at the feed solution/membrane interface due to high evaporation rates. The resulting temperature polarization phenomena leads then to a reduction of the driving force and thus a decrease of the process efficiency.

In that view, it seems attractive to develop an alternative and complementary membrane contactor process which combines the advantages of OE (i.e. operating at low temperature) and MD but without their corresponding drawbacks.

The process described in this paper, also called membrane evaporation (ME) in a previous work [14] involves the use of a hydrophobic macroporous metallic membrane to put into contact two fluids: an aqueous feed solution (at room temperature) circulating in the feed side and dry air flowing on the downstream side. The membrane is hydrophobic and then the aqueous solution cannot penetrate inside membrane pores. Hence, the vapor/liquid interfaces are located at each pore entrance. The water evaporation flux from the liquid to be concentrated to the air is driven by the water vapor pressure difference between both phases. It is important to note that the process is carried out at very soft conditions (low trans-membrane pressure and temperature) limiting the risk of liquid transfer through the pore as well as avoiding any risk of compound degradation by thermal effect. Therefore, it is well adapted for the concentration of solutions containing thermosensitive products such as biological, pharmaceutical or food solutions.

As previously described, the vaporization of water at the liquid/membrane pore entrance creates a decrease of the temperature in the layer adjoining the membrane. Hence, boundary layers appear on both sides of the membrane according to a well-known phenomenon of temperature polarization. This decrease of temperature at the liquid/vapor interface reduces the performance in terms of water evaporation flux of the ME process. To compensate

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this problem, one solution can be to warm the whole solution. However, it is limited to non-thermal sensitive compounds and entails a high energy cost. Another alternative can be to bring thermal energy directly to the membrane and thus only heat a low quantity of liquid (the liquid which is located at the entrance or near membrane pores).

In that view, considering the metallic nature of the membrane (high thermal conductivity), the effect of the radiations of an infrared lamp placed at the top of the carter made of glass has been studied in our previous work [14]. This system was attractive due to its simplicity and to the absence of direct contact between the membrane surface and the lamp. However, a large part of energy was dissipated by conduction or convection outside of the module and the quantity of energy delivered by the lamp to the solution was not easy to control. In fact, the system was not really efficient.

Consequently, we decided to develop a more efficient process in order to bring energy only to the membrane and not to the whole solution. In that view, an electric heat system (EHS) based on Joule effect where the membrane was used as an electric resistance, was developed and described later on.

In this second part of the work we studied the influence of operating parameters (air velocity, feed temperature, air pressure) and the effect of inside heat generation by means of the EHS on the global effectiveness of the ME process carried out with three different metallic membranes. The experimental results are discussed considering the theoretical model coupling heat and mass transfer previously reported in part 1 of the work.

## 2. Model formulation

The resistances-in-series model developed and validated in part 1 of this work, considers the coupling of heat and mass transfer for ME process for pure water as model solution without any energy supply. Indeed, when the evaporation flux becomes important, we can have a polarization temperature effect [15,16], where the temperature at the gas in pores/water interface decreases and consequently reduce the global performance of the process. To avoid this problem, we can heat the membrane by Joule effect in order to compensate only the evaporation heat loss at the interface concerned. Then, a low voltage generator was connected to the metallic membrane which was considered uniformly heated. This applied energy is transmitted from the membrane to gas and liquid phases. This effect has now to be included in the model developed in part 1 of this work with the following equations:

The heat balance at the membrane-gas interface can be written as:

$$Q_m^{\text{cond}} + Q_{\text{ext}} = Q_a^{\text{conv}} \quad (1)$$

where  $Q_{\text{ext}}$  is the heat flow rate generated by Joule effect to compensate the heat loss by evaporation,  $Q_m^{\text{cond}}$  the heat flow rate transported by conduction through the membrane pores and  $Q_a^{\text{conv}}$  is the heat flow rate taken off by the gas phase at the boundary layer level. We have to be aware that this equation is valid only if we consider a very thin metallic membrane (very good thermal conductivity), then the temperature profile across the membrane thickness is not important compared to the temperature profile of gas and liquid boundary layers.

If we consider the temperature differences at interfaces we can now write this equation as follows:

$$\frac{\lambda_m}{\delta} (T_{w,m} - T_{a,m}) + Q_{\text{ext}} = h_a (T_{a,m} - T_a) \quad (2)$$

where  $T_{w,m}$  and  $T_{a,m}$  are respectively the membrane temperatures at feed side and at the permeate side,  $\lambda_m/\delta$  represents the ratio between the membrane thermal conductivity and its thickness, and  $h_a$  is the heat transfer coefficient in the gas boundary layer.

**Table 1**  
Membrane properties after the hydrophobic surface treatment.

	Membrane A	Membrane B	Membrane C
Structure	Granular	Fibrous	Granular
Separation layer thickness <sup>a</sup> (μm)	120	450	75
Porosity <sup>b</sup> , $\alpha$ (%)	29	71	28
Mean pore diameter <sup>b</sup> (μm) of the separation layer	2.4	6.4	2.0
Contact angle (°)	120	135	120
Liquid entry pressure ( $\times 10^5$ Pa)	0.31 ± 0.02	0.06 ± 0.02	0.40 ± 0.02

<sup>a</sup> From SEM analysis.

<sup>b</sup> Measured by mercury porosimetry.

For the heating by Joule effect we took the assumption that the energy is homogeneously produced in all of the thickness and surface of the metallic membrane.

For simulation purposes, we combined these equations to those presented in part 1 of this work coupling mass and heat transfer and solved them using Matlab<sup>TM</sup> software.

## 3. Materials and methods

### 3.1. Membranes

Three flat macroporous metallic membranes made from stainless steel ASI 316L were used after being modified by impregnation and cross-linking with a polydimethylsiloxane (PDMS) solution. Their main characteristics determined in part 1 of this work and after PDMS treatment are resumed in Table 1. All membranes have an effective geometric area equal to 0.0209 m<sup>2</sup> and presented a hydrophobic behavior with a contact angle up to 120°.

### 3.2. Experimental procedure and pilot unit

The schematic diagram of the experimental setup is presented in part 1 of this work. As explained above, in order to compensate the temperature decreases, we developed an electric heat system (EHS) coupling a low voltage generator and the metallic membrane as shown in Fig. 1.

A voltage generator (PWS-1500-10, Nemic-Lambda) was connected between two electrodes fixed on both edges of the membrane (see Fig. 1); it delivers low voltage (0–10 V and 0–150 A). The electric power was controlled by regulating the applied voltage. The energy  $P_{\text{elect}}$  (W) delivered to the membrane depends on the current  $I$  (A) and the voltage  $U$  (V) imposed between both electrodes by the relation  $P_{\text{elect}} = U \times I$ . Experiments were carried out at low voltage in order to limit electrocution risks, avoid the degradation of the membrane and to limit the heat furnished.

Experiments were carried out with pure water (model solution) and the feed flow was varied from  $5.6 \times 10^{-3} \text{ m s}^{-1}$  ( $Re_{\text{water}} = 55$ ,  $Q_{\text{water}} = 13.2 \text{ l h}^{-1}$ ) to  $1.47 \times 10^{-2} \text{ m s}^{-1}$  ( $Re_{\text{water}} = 142$ ,  $Q_{\text{water}} = 34.5 \text{ l h}^{-1}$ ) whereas the air velocity varied from  $6.4 \times 10^{-3}$  to  $9.3 \times 10^{-2} \text{ m s}^{-1}$  ( $Re_{\text{air}}$  from 10 to 149 and  $Q_{\text{air}}$  from 40 to  $592 \text{ l h}^{-1}$  respectively). The calculations of Reynolds number were carried out taking into account the hydraulic diameter of each compartment. For water compartment which has a simple geometry (rectangular: dimensions 0.175 m  $\times$  0.127 m  $\times$  0.005 m) the  $d_h$  was  $9.63 \times 10^{-3} \text{ m}$  whereas for the gas compartment which presents a more complicated geometry a  $d_h$  of  $2.4 \times 10^{-3} \text{ m}$  was calculated. The temperature of the feed solution ranged from 15 to 45 °C with an accuracy of 0.2 °C.

Relative humidity probes were used to determine the water evaporation flux in the system. It is important to notice that the use of humidity probes allowed a very precise evaluation of the water

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