

CHARACTERISTICS OF THE MEMBRANE UTILIZED IN A COMPACT ABSORBER FOR LITHIUM BROMIDE/WATER ABSORPTION CHILLERS

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Abstract. This study aims at investigating experimentally and analytically the characteristics and properties of a membrane contactor utilized to design compact absorbers for lithium bromide/water absorption chillers. The main focus of this study are the factors that influence the water vapor transfer flux into a lithium bromide/water solution in confined narrow channels under vacuum conditions, as well as the properties limits for utilization in compact absorber design. The results indicate that the desired membrane characteristics for this application are as follows: high permeability to water vapor, hydrophobic to the aqueous solution with high liquid entry pressure to avoid wettability of the membrane pores and no capillary condensation of water vapor to avoid blocking of the pores. For practical use, this membrane should have a thin hydrophobic microporous active layer with a thickness up to 60 μm , mean pore sizes around 0.45 μm and a porosity of up to 80%. The active layer should be attached to a porous support layer to meet the strength requirements needed for practical use in the absorber of lithium bromide water absorption chillers.

Key Words: *absorber, membrane, absorption chiller, lithium bromide*

1 INTRODUCTION

Among the major components of an absorption chiller the absorber has a considerable effect on the size of the whole unit. Therefore, introducing membrane technology to the absorber design could provide one of the alternatives for the conventional shell and tube absorber type in order to achieve highly compact absorbers. In the case of lithium bromide/water absorption chillers, flat hydrophobic microporous membranes can be used to form very narrow solution channels. The membrane pores are filled with vapor while the hydrophobic nature of the membrane prevents penetration of the aqueous solution into the pores. Therefore, only water vapor (refrigerant) is transported through the membrane into the solution. This technique as well as favorable mass transfer at liquid/vapor interface by forced convection in narrow channels can lead to the reduction of the absorber unit size and weight. Drost et al. 2005 cited that the development of compact absorbers enables the deployment of small heat-driven absorption heat pumps for distributed space heating and cooling applications, thermally driven automotive air conditioning and manportable cooling devices. Throughout the open literature on this field, limited investigations were carried out on the utilization of a membrane contactor for the purpose of absorption heat pump application. An osmotic-membrane absorption cycle is cited by Srihirin et al. 2001, in which rich-refrigerant solution in the absorber and weak-refrigerant solution in the generator are separated from each other by using an osmotic membrane, which allows only the refrigerant to pass. Thus, the refrigerant from the absorber can be transferred to the generator by an osmotic diffusion effect through the membrane without any mechanical pump. Yu et al. 1992 investigated experimentally this osmotic-membrane absorption cycle. Chen et al. 2006 carried out a

simulation study of a proposed hybrid absorber heat exchanger using a microporous hollow fiber membrane module for the ammonia/water absorption cycle. A large variety of research is done on utilization of membranes for vapor desorption inside the generator of absorption heat pumps, compared to only a few publications for absorber application. Drost et al. 2005 studied experimentally and simulated the ultra-thin film of lithium bromide solution in a desorption process using microporous membrane separation. Thorud et al. 2006 investigated experimentally the performance of vapor extraction from aqueous lithium bromide solution as function of thin film thickness, pressure difference across the membrane and inlet concentration to the microchannel. Riffat et al. 2004 presented and investigated experimentally a novel vapour absorption refrigeration system in which a pervaporation membrane replaces the conventional generator for the concentration of working fluids.

Despite the important need for compact and small capacity absorption chillers with the potential use of microporous membranes for solution-vapor contacting purposes in the absorber, there has been relatively little research so far concerning this topic. A membrane contactor would provide higher volumetric mass transfer rates than a conventional absorber design. Publications concerning utilization of membrane contactors for absorption chillers reveal that some membrane types with different characteristics and properties have been investigated: cellulose triacetate membranes (Yu et al. 1992), dense membranes and porous silicon membranes (Riffat et al. 2004), hydrophobic porous membranes (Thorud et al. 2006), hydrophobic porous membranes, a woven membrane and a laser-machined membrane (Drost et al. 2005). Despite the reported higher water vapor permeability of a laser-machined membrane (Drost et al. 2005), compared to commercially available hydrophobic porous membranes, its cost is very high. In addition, there is no literature available on the characteristics and properties of membrane contactors for water vapor transfer into lithium bromide solution with both sides being under equal vacuum static pressure, which is the case in the absorber of LiBr-H₂O absorption chillers. A common material for commercially available microporous hydrophobic membranes in capillary or flat sheet shape is polytetrafluoroethylene (PTFE).

This study aims at investigating experimentally and analytically the characteristics and properties of commercially available microporous hydrophobic membranes, their influence on the water vapor (refrigerant) mass transfer flux into thin films of lithium bromide solution as well as the limits for utilization in compact absorber design for absorption chillers. To achieve the objectives of this study, experimental measurements were carried out and a mathematical model was developed for heat and mass transfer of water vapor transfer into a aqueous solution through hydrophobic microporous membrane sheets. This is to clarify how the membrane properties in combination with other operating factors satisfy the required characteristics of the membrane contactor at solution/vapor interface.

2 ANALYTICAL MODEL

2.1 Heat and Mass Transfer in an Absorber Cell with Microporous Hydrophobic Membrane

In this process, a microporous hydrophobic membrane is the contactor between the lithium bromide solution and water vapor (refrigerant). The water vapor pressure and the partial pressure of water vapor in the solution induce a vapor pressure difference, which is the driving force for the vapor flux into the solution. In LiBr-H₂O absorber application, due to the hydrophobicity of the membrane, the aqueous solution cannot enter the membrane pores. At the vapor side, the vapor enters the pores and a liquid/vapour interface is formed at pore mouths on the solution side. The water vapour passes through the membrane pores and is condensed in the lithium bromide solution. Since the membrane is present as a barrier to water vapor flux, its characteristics and properties affecting the mass transfer process must be specified. Due to the water vapor concentration polarization phenomena in the solution

side, the water vapour pressure near the membrane is different from the solution bulk one. Consequently, there are two resistances to the water vapor and heat fluxes: first the membrane resistance and second the boundary layer resistances in the solution side of the membrane. Modeling of the heat and mass transfer in an absorber cell is shown in Figure (1) based on a composite membrane, in which the membrane is constituted by a thin active layer supported by a strong but also porous base material. The pore size of this support net is considerably high ($>10 \mu\text{m}$). The support layer should not interfere with the mass transport and should only serve to increase the mechanical strength of the membrane. If the support net layer is at the solution side, it is wet by the solution. Then the active layer is the only part of the membrane where water transport occurs in the gas phase. In this case, the support resistance must be taken into account. On the other hand, (Alves and Coelho 2007) show that no resistance exists if the support layer is at the water vapor side. The heat and mass transfer model is therefore based on the following assumptions: the support resistance to mass transfer is neglected; steady state conditions; one-dimensional; absorption occurs instantaneously; adiabatic process with negligible heat losses to/or gain from the surroundings. Figure (1) illustrates the water vapor pressure and temperature profiles in the case of LiBr-H₂O absorber application. The overall mass transfer resistance is expressed as a function of the individual resistances. The water vapor mass flux crossing the membrane is expressed as follows:

$$J = k_m (P_v - p_{m,s}) \quad \text{kg.m}^{-2}.\text{s}^{-1} \quad (1)$$

According to the dusty-gas model for gas transport through porous media reported in (Martínez-Díez and Rodríguez-Maroto 2006), the vapour transport through the membrane pores takes place via a combined Knudsen and molecular diffusion mechanism that will be clarified through the results, and is given by:

$$k_m = \frac{\varepsilon}{\tau \cdot \delta_m} \frac{M_{\text{H}_2\text{O}}}{RT} \left[\frac{1}{D_K} + \frac{P_{\text{air}}}{P \cdot D_{\text{H}_2\text{O}-\text{air}}} \right]^{-1} \quad \text{kg.m}^{-2}.\text{s}^{-1}.\text{Pa}^{-1} \quad (2)$$

The value of D_K is given by: $D_K = \frac{d_{pm}}{3} \left(\frac{8RT}{\pi \cdot M_{\text{H}_2\text{O}}} \right)^{1/2} \quad \text{m}^2.\text{s}^{-1} \quad (3)$

For the water–air system, $P \cdot D_{\text{H}_2\text{O}-\text{air}}$ is calculated from the equation presented in (Martínez-

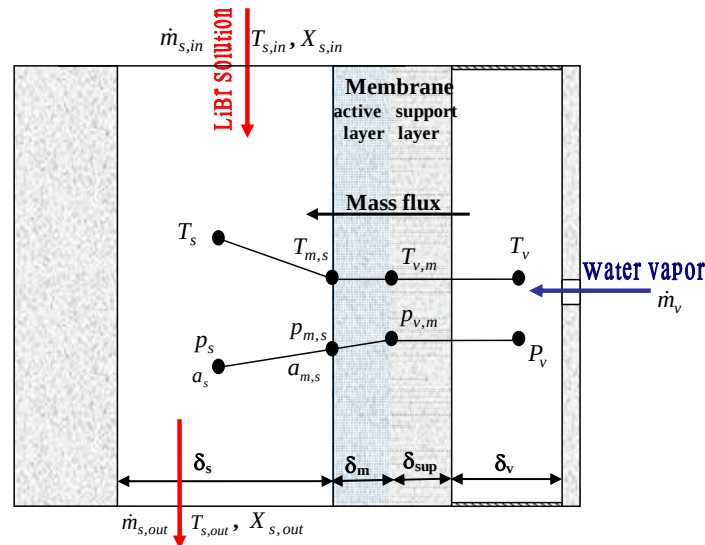


Figure 1: Modeling of the heat and mass transfer phenomena in the cell.

Díez and Rodríguez-Maroto 2006) as follows:

$$P.D_{H_2O-air} = 4.46 \times 10^{-6} T^{2.334} \quad \text{Pa.m}^2.\text{s}^{-1} \quad (4)$$

However, the value of $p_{m,s}$ as part of driving potential in the form given by Eq. (1) is representing interfacial conditions which are not always accessible. Therefore, the water vapor transport in the cell referring to the bulk conditions of the liquid and vapor streams is given by:

$$J = k_{ov}(P_v - p_s) \quad \text{kg.m}^{-2}.\text{s}^{-1} \quad (5)$$

The value of p_s is function of aqueous solution concentration and temperature. It is calculated from the correlation of (ASHRAE 2005). The overall mass transfer resistance between the bulk water vapor (refrigerant) and bulk solution, k_{ov} , is given by:

$$k_{ov} = \left[\frac{1}{k_m} + \frac{P_s^*}{\rho_{H_2O} \cdot k_{m,s}} \right]^{-1} \quad \text{kg.m}^{-2}.\text{s}^{-1}.\text{Pa}^{-1} \quad (6)$$

The value of the mass transfer coefficient between the water vapor at pore mouths of membrane and bulk of the solution, $k_{m,s}$, is calculated from the correlation of (Martínez-Díez and Rodríguez-Maroto 2006). The value of $\frac{P_s^*}{\rho_{H_2O} \cdot k_{m,s}}$ in eq. (5) is obtained as follows: the

mass transfer in the solution boundary layer can be calculated by the formula of (Alves and Coelho 2007) given by:

$$J = \rho_{H_2O} \cdot k_{m,s} (a_{m,s} - a_s) \quad \text{kg.m}^{-2}.\text{s}^{-1} \quad (7)$$

After replacing the values of the water activity, $a_{m,s}$ and a_s , by their ratios between the vapor pressure at such location to the saturated water pressure, p_s^* , corresponding to the location temperature, the equation (6) can be rewritten as follows:

$$J = \frac{\rho_{H_2O} \cdot k_{m,s}}{p_s^*} (p_{m,s} - p_s) \quad \text{kg.m}^{-2}.\text{s}^{-1} \quad (8)$$

From equation (1) the value of the water vapor mass transfer is obtained.

The energy balance equation for the cell shown in Figure (1) is obtained as follows:

$$J \cdot A_m \cdot h_{abs} = \dot{m}_s (h_{s,out} - h_{s,in}) + U \cdot A_m \cdot (T_{s,int} - T_v) \quad \text{W} \quad (9)$$

The overall heat transfer coefficient across the membrane, U , is calculated from the formula presented in (Martínez-Díez and Rodríguez-Maroto 2006). The value of h_{abs} is calculated from this equation:

$$h_{abs} = h_v - h_s(X_s, T_s) + h_{dilution} \quad \text{J kg}^{-1} \quad (10)$$

The heat of dilution of water in lithium bromide solution, $h_{dilution}$, is calculated from the data presented in (Kaita 2001).

2.2 Membrane characterization

It is clear from eq. (2) that the membrane resistance to the mass transfer depends on the size and tortuosity of the membrane pores, and on the porosity and thickness of the membrane. The membrane tortuosity (τ) reflects the length of the average pore compared to the membrane thickness. Usually pores take a more meandering path through the membrane, so typical tortuosity is in the range 1.5–2.5 as reported by (Martínez-Díez and Rodríguez-Maroto 2006). It is not normally supplied by the manufacturers but it can be evaluated from the membrane porosity formula presented in (Alves and Coelho 2007). By investigating the thermal properties of the aqueous lithium bromide solution it is found that the main desired characteristics of the membrane to be used in an absorber are: high permeability to water vapor, being hydrophobic to the solution with high liquid entry pressure to avoid wettability of membrane pores by the solution. Moreover, no capillary condensation of water vapor should occur inside the pores to avoid pore blocking. In order to verify these characteristics the membrane properties should cover these requirements. However, in evaluating the degree to which the pore capillary will affect the transport of water vapor, the Knudsen number K_n , is used (Trifunović and Trägårdh 2005). Knudsen number depends on the ratio of the distance between molecular collisions (mean free path of the water vapor, λ_v) and mean membrane pore diameter. It is given by:

$$K_n = \frac{\lambda_v}{d_{pm}} \quad (11)$$

If the Knudsen number is small ($K_n < 0.01$) the mean free path of the water vapor is much smaller than the pore diameter and viscous flow occurs, resulting in rapid convective transport. If this value is greater than the pore diameter ($K_n > 10$), molecule wall collisions occur, resulting in selective transport of the water vapor molecules to the aqueous solution, where the smallest molecules would have the highest flux (Trifunović and Trägårdh 2005). The mean free path of the water vapor, λ_v , can be estimated from the expression in (Fritzsche et al. 1990) as follows:

$$\lambda_v = \frac{3\mu_v}{2p_v} \left(\frac{\pi RT}{2M_{H_2O}} \right)^{0.5} \quad \text{m} \quad (12)$$

The second main desired characteristic of the membrane is to be hydrophobic to the aqueous solution and to have a high liquid entry pressure (LEP). LEP is known as the minimum hydrostatic pressure that must be applied around the membrane before the aqueous solution overcomes the hydrophobic forces of the membrane and penetrates into the membrane pores. The mechanism for membrane wetting is that aqueous solution enters the larger pores of the membrane by breaking the surface tension at the interface between solution and vapor at the membrane pore mouth. The relationship between the maximum pore size and liquid entry pressure is given in (Gabino et al. 2007) as follows:

$$\Delta P = \frac{4B\sigma \cos \theta}{d_{p,max}} \quad \text{Pa} \quad (13)$$

The pore geometry coefficient, B , is equal one for cylindrical pores.

The third main desired characteristic of the membrane is to prevent capillary condensation of water vapor (refrigerant) inside the membrane pores. The following equation for calculating the critical water vapor pressure at which condensation can occur in the large pore, known as Kelvin equation, is presented in (Trifunović and Trägårdh 2005) and given by:

$$\frac{p_v^c}{p_v} = \exp\left(\frac{4\sigma_{H_2O}}{d_p M_{H_2O} RT}\right) \quad (14)$$

3 EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental set up shown schematically in Figure (2) is used to carry out measurements on absorption of water vapor into a lithium bromide solution through different hydrophobic microporous membranes under vacuum static pressure conditions in a narrow flow channel. The apparatus consists mainly of an absorber membrane cell that is included in the lithium bromide solution flow loop, an evaporator, a vacuum pump and the appropriate measuring instrumentations. The test cell was designed to create a thin film of the solution between the membrane and the back, made of acrylic glass, in which a gasket ring is used to control channel depth. The test cell has a net contact membrane area of 46.6 cm² and, in this study, 4 mm in depth. Different hydrophobic PTFE membranes with various average pore diameters and thicknesses were tested in the cell. The membrane is in direct contact with both the solution and the water vapor from the other side. The vapor chamber has the same membrane area but with a depth of 5 mm. A gear pump is used to circulate the solution from a reservoir through the test cell. Flow-controlling valves were used to adjust the solution flow rate, which is measured by a turbine meter. The solution flow loop and the test cell were designed to operate over a wide range of operating conditions. The evaporator was kept in a temperature controlled water bath in order to keep the evaporation condition constant. The water vapor flux is estimated by the time required for the absorption of a vaporized amount of water filled in the evaporator at the beginning of each experiment. An additional heat exchanger was used to control the solution temperature. All temperatures were measured at the locations as shown in Figure (2), by using type K thermocouples with a diameter of 1.5 mm. Pressure transducers with a measuring range from 0.0 to 0.4 bar absolute were used for pressure measurements. The electrical conductivity of the aqueous lithium bromide solution, which is converted into weight ratio of the LiBr to the aqueous solution, was measured by type "Tetracon 325" sensor with a measuring range from (0-500) × 10⁻³ Siemens/cm. A data acquisition system type "Top Message" manufactured by "Delphin Technology AG" was used for recording all measured signals. Additionally contact angle measurements were performed with a Dataphysics DCTA21 (Data Physics Instruments GmbH) in a three-phase system consisting of the membrane surface and aqueous lithium bromide solution at atmospheric pressure. The dynamic contact angle was measured using the Wilhelmy method. The contact angle was determined for clean dry and wet PTFE membranes. The test cell was used to determine the permeability of water vapor transfer into the solution at various flow rates for different membranes. The uncertainties were calculated through the data reduction of the experimental measurements based on the formula for computing overall errors of (Doebelin 1990). The maximum uncertainties are estimated in measured water vapor mass flux ranging from 5.3% to 11.2%, respectively.

4 RESULTS AND DISCUSSIONS

4.1 Experimental Results

The time average of the measured values of the permeability of water vapor into the LiBr solution at various solution flow rates for different membranes is shown in Figure (3). Throughout all presented experimental results the concentration of the solution varied within 50.8 to 54.0 wt% LiBr, its temperature was varied between 24 and 29 °C, and the evaporator temperature was varied between 16 and 25 °C. As seen from the figure, the water vapor flux increases with an increase of the mean membrane pore diameter and with a decrease of the active membrane layer thickness for the same mean pore diameters. It can be seen from

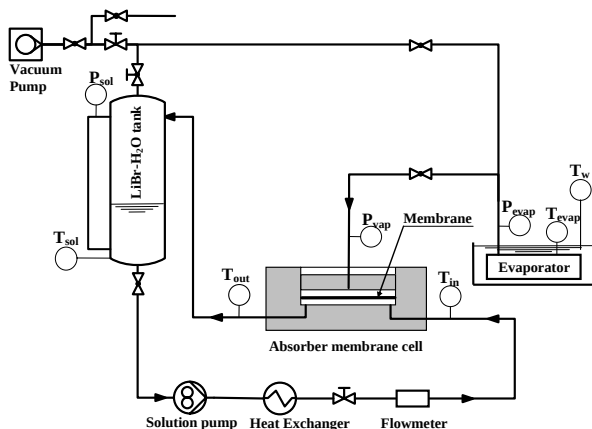


Figure 2: Schematic diagram of the experimental apparatus.

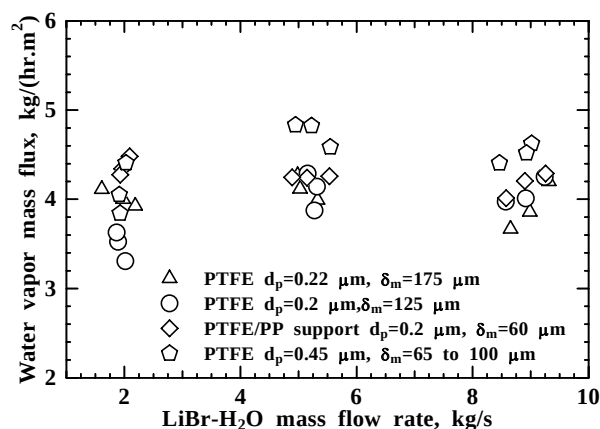


Figure 3: Measured values of water vapor flux for different membranes.

Figure (3) that the mass flow rate of the solution did not significantly affect the water vapor flux. This is due to the nature of the driving potential of the water vapor flux, which is primarily a function of the partial vapor pressure difference across the membrane. Nevertheless, the membrane mass transfer resistance dominates the overall mass transfer resistance, which is much higher and rather constant. Thus, any increase in solution flow rate would have an insignificant effect on the increase of the water vapor flux. Indeed the results indicate that for comparable mean pore diameters the thin membranes with support show a larger water vapor flux than those having a thick active layer without support. Additionally, improvement in the water vapor flux is evident for larger mean pore diameters at similar active membrane layer thickness.

4.2 Analytical Results

4.2.1 Validity of the model results

A comparison between the experimentally measured values of water vapor flux and the solution temperatures (at cell outlet) with their corresponding values obtained from the analytical model as a function of the driving potential (vapor pressure difference) is shown in Figure (4). The given process parameters of the experiments shown in the figure were also taken as input to the model. It is clear from the figure that the predicted outlet temperature of the solution was close to the measured values thus giving a good congruence. The measured water vapor flux is based on the time average of absorbing 20g of water vapor into the aqueous solution. In contrast, the flux obtained from the model is a function of the driving potential, which varies with time as the solution concentration, temperature and evaporator pressure are slightly varying with time. However, the average value of the calculated vapor flux is close to the average results of the measurements. In addition, the model results are comparable to experimental data of (Albrecht 2005) for absorption of water vapor into aqueous Lithium Chloride solution. The properties of the lithium chloride solution presented in (Conde 2004) and the unit parameters of (Albrecht et al. 2005) are input to the model. The obtained results are shown in Figure (5). It is clear from the figure that, both the predicted and the measured water vapor mass flux values are quite congruent. Therefore, it can be clearly stated that the analytical model is capable of describing the heat and mass transfer of the membrane absorber cell within the measurements accuracy. Thus, the model can be used for investigating the effect of membrane properties on its desired characteristics for utilization as a contactor at solution/vapor interface in the absorber of absorption chillers.

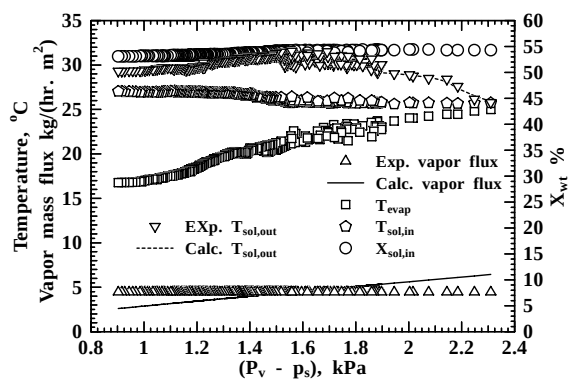


Figure 4: Comparison of calculated values with corresponding measured data.

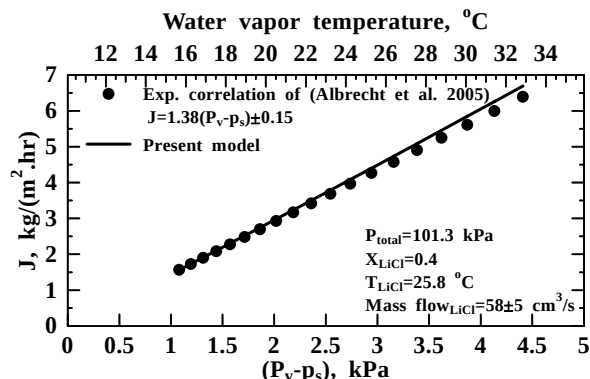


Figure 5: Verification of the calculated water vapor flux and corresponding measured data.

4.2.2 Influence of the mean membrane pore diameter on the transport mechanism of the water vapor flux

The effect of the mean membrane pore diameter on the mechanism of water vapor transfer through the membrane, represented by Knudsen number, as function of the evaporator temperature (corresponding to water saturation pressure) is shown in Figure (6). The values of the evaporator temperature are chosen corresponding to the usual chilled water temperatures in air conditioning applications. As seen from the figure for all possible evaporator working temperatures, the mean free path of the water vapor is higher than the presented mean membrane pore diameter. For the membranes with mean pore diameters of 0.22 and 0.45 μm the value of Knudsen number (K_n) for most of the evaporator operating conditions is between 0.01 and 10. This is the transition zone, where both Knudsen and viscous flow mechanisms contribute to the mass transfer, resulting in selective and convective transport of the water vapor molecules to the aqueous solution. Therefore, the smallest molecules would have the highest flux. In contrast to the membranes with mean pore diameters of 0.8 and 1.0 μm the value K_n is larger than 10 for all evaporator temperatures. Thus molecule wall collisions occur, resulting in the selective transport of the water vapor molecules to the solution where the smallest water vapor molecules would have the highest flux. The results indicate that for the evaporator temperatures in the range of 2 to 12 $^{\circ}\text{C}$ membranes with larger pore diameters would have the best vapor flux.

4.2.3 Influence of the membrane pore diameter on the liquid entry pressure

For use in the suggested membrane absorbers application, hydrophobic membranes are required. The membrane hydrophobicity is based on the polymer the membrane is made from, as well as the liquid entry pressure (LEP). Nevertheless, the maximum LEP also depends on the operating conditions of the membrane. During startup or shutdown of the absorption chiller, exceptional conditions with high static pressure difference across the membrane can occur, would this force the solution to penetrate the membrane pores, serious problems would arise. However, for a given pore size there is a critical penetration pressure above which the solution will penetrate the membrane. Based on measurements of (Martínez-Díez and Vásquez-González 1996) for pore sizes distribution for some commercially available membranes, the maximum pore diameter is found to be about twice the mean pore diameter. In this study the hydrophobicity (i.e. aqueous solution contact angle with the membrane in dry and full wet condition) of some commercial PTFE membranes were investigated. For dry conditions the measured contact angles were $95.5^{\circ} \pm 5.1$ and under wet conditions $90.6^{\circ} \pm 4.4$. These values are input into eq. (13). The LEP

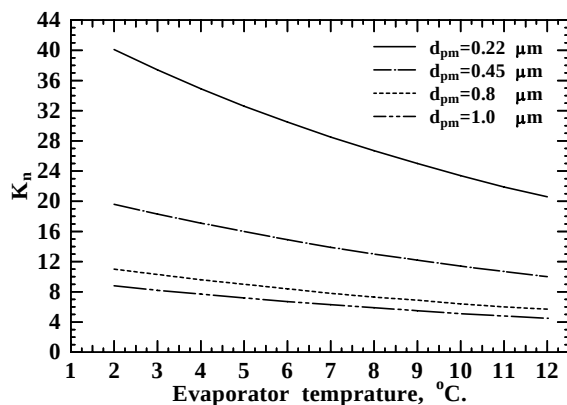


Figure 6: Effect of d_{pm} on K_n as function of the evaporator temperature.

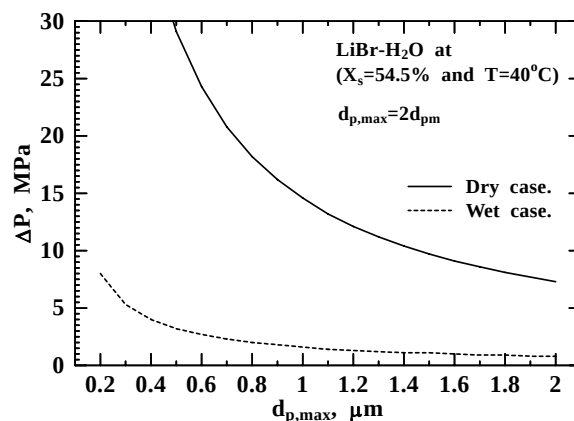


Figure 7: Effect of d_{pm} on the liquid entry pressure.

value was calculated for the case of LiBr solution at $X_s=54.5\%$ and $T_s=40^\circ\text{C}$. This condition is close to the absorber operating condition at an evaporator temperature of 4°C , a condenser temperature of 35°C and a generator temperature of 85°C . The LEP as a function of mean membrane pore diameter is shown in Figure (7). As can be seen from the figure the results indicate that the membrane with mean pore diameter up to $1.0\ \mu\text{m}$ (with max. pore being about $2.0\ \mu\text{m}$) has an LEP of more than $797\ \text{kPa}$. In contrast, for the above absorber chiller conditions, the maximum possible pressure difference that can occur around the membrane is about $5.0\ \text{kPa}$. Therefore, concerning the LEP, any hydrophobic membrane with mean pore diameter up to $1.0\ \mu\text{m}$ can be safely used as a contactor in the absorber of LiBr absorption chillers.

4.2.4 Influence of the membrane pore diameter on the critical water vapor condensation pressure

The calculated ratio of the critical condensation pressure to the actual water vapor pressure (evaporator pressure) p_v^c/p_v for different mean membrane pore diameters as function of the evaporator temperature (corresponding to water saturation pressure) is shown in Figure (8). It can be seen from the figure that for the all presented mean membrane pore diameters, the value of p_v^c/p_v is larger than one. Its value slightly decreases with an increase of the evaporator temperature. In addition, it is clear from the figure that for membranes with mean pore diameters of 0.8 and $1.0\ \mu\text{m}$ the ratios of p_v^c/p_v are 1.009 and 1.007 respectively. In contrast for membranes with mean pore diameters of 0.22 and $0.45\ \mu\text{m}$ the values of p_v^c/p_v are 1.034 and 1.016 respectively. However, under real absorption conditions the membrane temperature is expected to be somewhat higher than the evaporator temperature due to the released portion from the heat of the water vapor absorption in the solution adjacent to the membrane transferred into the water vapor. Based on the results quoted, it can be concluded that membranes with mean pore diameters of 0.22 and $0.45\ \mu\text{m}$ (considering that $d_{p,max}=2d_{pm}$) are safer from the perspective of avoiding capillary condensation of water vapor inside the membrane pores.

4.2.5 Influence of the membrane porosity on the water vapor flux

The calculated water vapor flux passing the membrane into LiBr solution ($X_s=57.7\%$, $T_s=36.6$, evaporator temperature 4°C) as a function of membrane porosity is shown in Figure (9) for different mean membrane pore diameters. As generally agreed, the figure shows that

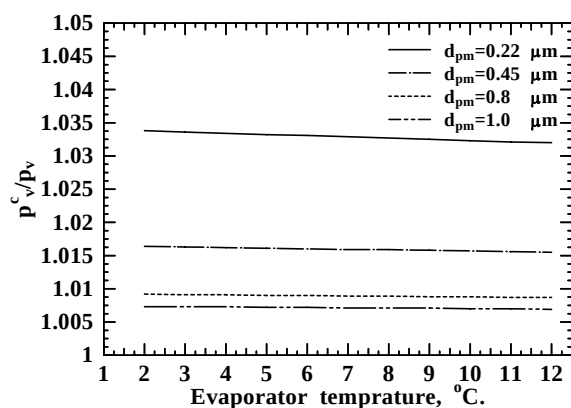


Figure 8: Effect of d_{pm} on the ratio p_v^c/p_v .

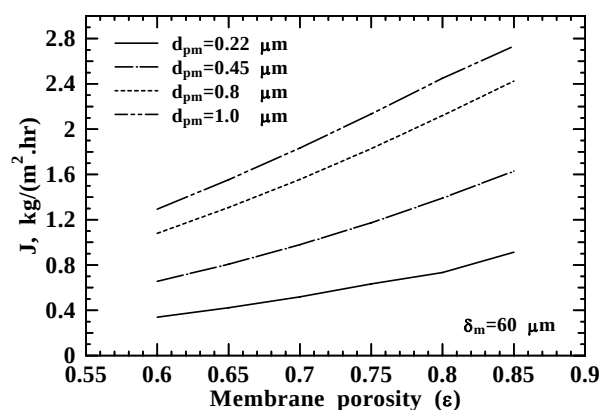


Figure 9: Effect of membrane porosity on the water vapor flux for different d_{pm} .

higher membrane porosity results in higher water fluxes regardless of the membrane pore diameters. It must be pointed out that in practice, the membrane must be able to withstand all the operating conditions such as mechanical stress, pressure, temperature and a highly aggressive working fluid. However, the desired membrane to be used in the absorber of an absorption chiller should have porosity ranged 0.7 to 0.8, in order to have the sufficient strength needed by a secure fixation inside the absorber. In the case of higher porosity than 0.8, it is expected that the membrane strength would be decreased significantly.

4.2.6 Influence of the membrane active layer thickness on the water vapor flux

Membrane thickness plays a significant role in dictating the resistance to the membrane mass transfer as shown in Figure (10). However, if membrane absorbers are to take advantage of a high specific area per unit volume although the membrane creates an additional obstruction to mass transfer, the active layer should be as thin as possible. Additionally, in order to meet the mechanical strength requirements, the membrane should have the active layer laminated on a support structure. (Khayet et al. 2006) reported that for PTFE membranes the measured thickness of the active layers responsible for vapor transport was found to have similar sizes ($54.8 \pm 6.2 \mu\text{m}$ for $d_{pm}=0.2 \mu\text{m}$ and $60.0 \pm 6.7 \mu\text{m}$ for $d_{pm}=0.54 \mu\text{m}$). However, for the operating conditions mentioned for the chiller, the most suitable of four membranes has a mean pore size of $0.45 \mu\text{m}$, an active layer thickness of $60 \mu\text{m}$ and a porosity of 80%. From the experiments, it has a calculated water vapor flux of $1.4 \text{ kg m}^{-2} \text{ hr}^{-1}$. However, it can be concluded that the membrane should have a thin active layer with thickness of order $60 \mu\text{m}$, attached to a porous support layer to meet the strength requirements.

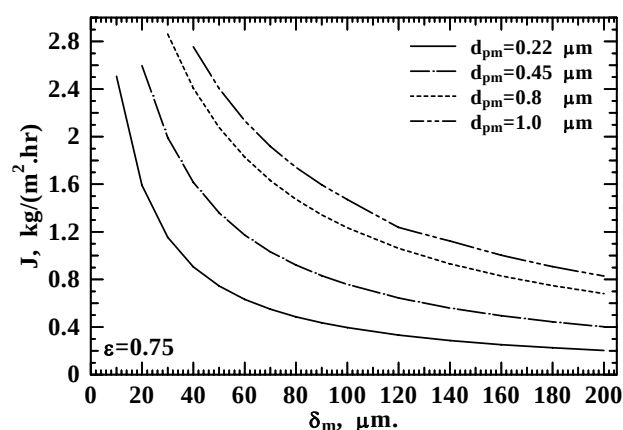


Figure 10: Effect of membrane thickness on the water vapor flux at different d_{pm} .

5 CONCLUSIONS

This study aims at investigating experimentally and analytically the characteristics and properties of commercially available microporous hydrophobic membranes, which influence the water vapor (refrigerant) mass transfer flux into a thin film of lithium bromide/water solution, as well as the limits for utilization in the design of a compact absorber for absorption chillers. It can be concluded that the desired characteristics of membranes needed for this application are as follows:

- Having high permeability for water vapor and being hydrophobic to the aqueous solution. For a high vapor flux, the membrane pore sizes should range from 0.45 to 1.0 μm , while having a porosity of up to 80%
- No capillary condensation of water vapor should occur inside the membrane pores to avoid pore blocking. Therefore the pore size should be as small as possible; around 0.45 μm is recommended
- Having a high liquid entry pressure to avoid wettability of membrane pores by the solution. To avoid penetration of membrane pores by the solution, the pore size must be as small as possible; a range from 0.45 to 1.0 μm is recommended.
- The active membrane layer thickness should be in a range up to 60 μm as a compromise between required mechanical stability and low resistance to water vapor transfer. An additional highly porous support layer on the vapor side of the membrane would significantly increase mechanical stability without degrading the vapor flux.

NOMENCLATURE

$\dot{m}$: mass flow rate (kg s^{-1})
A: surface area (m^2)
a: water activity -
B: pore geometry coefficient -
d: diameter (m)
D: mass diffusivity ($\text{m}^2 \text{s}^{-1}$)
 D_k : Knudsen mass diffusivity ($\text{m}^2 \text{s}^{-1}$)
h: enthalpy (J kg^{-1})
J: water vapor mass flux ($\text{kg m}^{-2} \text{s}^{-1}$)
k: mass transfer coefficient (m s^{-1})
 K_n : Knudsen number -
LEP or ΔP : liquid entry pressure (Pa)
M: molecular weight of water ($\text{kg kg}^{-1} \text{mol}^{-1}$)
P: total pressure (Pa)
 P^* : saturated water pressure (Pa)
 P_c : critical condensation pressure (Pa)
p: partial or vapor pressure (Pa)
PTFE: polytetrafluoroethylene -
R: the universal gas constant
(8314 $\text{J kg}^{-1} \text{mol}^{-1} \text{K}^{-1}$)
T: temperature ($^{\circ}\text{C}$ or K)
U: overall heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
X: LiBr mass fraction (%)

Greek letters

δ : thickness (m)
 ε : membrane porosity -
 λ : molecule mean free path (m)
 μ : dynamic viscosity (Pa s)
 θ : contact angle (degree)
 ρ : liquid water density (kg m^{-3})
 σ : liquid surface tension (N m^{-1})
 τ : membrane pore tortuosity

Subscripts

abs: heat of absorption
air: air
H₂O: water
in: inlet
int: aqueous solution-vapor interface
m: membrane
max: maximum
out: outlet
ov: overall
p: pore
pm: pore mean value
s: aqueous lithium bromide solution
sup: support layer
v: water vapor

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