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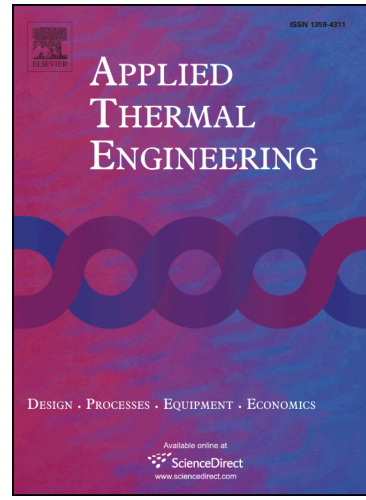

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Impact of the solution channel thickness while investigating the effect of membrane characteristics and operating conditions on the performance of water-LiBr membrane-based absorbers

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Keywords: Membrane contactor characteristics, Plate-and-frame membrane absorber, Water-LiBr, Absorption cooling systems

Highlights

1) A steady-state global heat and mass transfer model is developed for water-LiBr membrane-based absorbers.
2) Solution mass transfer resistance is dominant in thicker solution channels.
3) Membrane mass transfer resistance is considerable in thinner solution channels.
4) High absorption rate is achievable in the case of thinner solution channels.

Abstract

In this study, a numerical analysis is performed to investigate the effect of membrane contactor characteristics and operating conditions on the absorption performance in plate-and-frame membrane-based absorbers used in water-LiBr absorption cooling systems. This paper critically evaluates the impact of the solution channel thickness while investigating the effect of membrane characteristics. Results show that the effect of membrane characteristics is different in the case of different solution channel thicknesses. Increasing the membrane mean pore size from 0.25 μm to 1 μm enhances the absorption rate by 75% in the case of a 0.1 mm solution channel, whereas in a 0.5 mm solution channel the absorption rate increases by 40%. Similarly, the effect of membrane porosity and thickness on the absorption rate decreases by a factor of one third when the solution channel thickness is doubled. In addition, a parametric study is performed to study the effect of solution mass flow rate, vapour pressure, solution inlet concentration and cooling water temperature on the absorption performance, taking into consideration different solution channel thicknesses. Results show that a high absorption rate can be achieved in the case of thinner solution channels. Moreover, the percentage change in the absorption rate remains almost the same when the vapour pressure, solution inlet concentration and coolant inlet temperature are varied in the case of different solution channel thicknesses.

Nomenclature

A	Area (m^2)
C_p	Specific heat (J/kg.K)
c_B	Boltzmann constant (J/K)
D	diffusion coefficient (m^2/s)
d_p	membrane pore mean diameter (μm)
d_h	hydraulic diameter (m)
dz	discretization length (m)
H	enthalpy (J/kg)
h	convection heat transfer coefficient (W/m^2.K)
J	mass transfer flux (kg/m^2.s)
K	mass transfer coefficient (kg/m^2.s.Pa)
Kn	Knudsen number, $Kn = \lambda / d_p$
k	thermal conductivity (W/m.K)
L	channel length (m)
L^*	flow length (m)
M	molecular weight (g/mol)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, $Nu = h \cdot d_h / k$
P	pressure (Pa)
p	vapour pressure of solution (Pa)
R	universal gas constant (J/mol.K)
Sc	Schmidt number, $Sc = \mu / (\rho..D)$
Sh	Sherwood number, $Sh = K.d_h / D$
Re	Reynolds number, $\mathrm{Re} = \rho.u.d_h / \mu$
T	temperature (^{o}C, K)
t	channel thickness (m)
U	global heat transfer coefficient (W/m^2.K)
u	velocity (m/s)
w	channel width (m)
X	LiBr mass fraction

Greek letters:

α	channel aspect ratio, $\alpha = t / w$
ρ	density (kg/m^3)
ε	porosity
δ_m	membrane thickness (μm)
σ	molecular collision diameter (m)
τ	tortuosity
λ	mean free path (m)
μ	dynamic viscosity (kg/m.s)

Subscripts:

c	coolant
H_2O	water
int	solution-membrane interface
m	membrane
s	solution
v	vapour
w	wall

Abbreviations:

AMD	Advanced Micro Devices
CFD	Computational Fluid Dynamics
MATLAB	MATrix LABoratory

1. Introduction

Absorption technology, which has the ability to utilize heat directly for cooling purposes, has been one of the most widely used technologies for refrigeration and cooling applications since the early stages of refrigeration technology. Working fluid mixtures employed in absorption cooling systems are environmentally friendly and do not contribute to greenhouse gas emissions, whereas vapour compression systems, which also use costly mechanical energy input, do. The absorber is an important component of the absorption cooling system and plays a critical role in the overall performance, size, and capital cost of the system. Both heat and mass transfer take place simultaneously in the absorber. Both the design and configuration of the absorber significantly influence its performance. Many researchers have suggested continued improvements in the design and configuration of the absorber to improve its performance and thermal efficiency. In recent years, research has been carried out regarding the use in absorption cooling systems of membrane contactors in the form of plate-and-frame membrane modules and hollow fiber membrane modules. A comprehensive review on the application of membrane contactors in absorption refrigeration systems has been carried out by Asfand and Bourouis [1]. The authors reviewed in detail, the types of membrane modules used in absorption cooling systems and the effect of membrane-based components on the cycle configuration. In addition, membrane material characteristics were also discussed. They concluded, from their review, that the use of membrane contactors in the absorber and desorber of an absorption refrigeration system can not only enhance the heat and mass transfer performance of the component, but can also allow for a reduction in the size of the component. Thus, introducing polymeric hydrophobic microporous membranes into the absorber design could provide one of the alternatives for achieving highly compact absorbers, as microporous membrane contactors can provide a high specific surface area. Ali & Schwerdt [2] analytically and experimentally analysed a plate-and-frame membrane based absorber and achieved an absorption rate of 0.00125 $kg/m^2.s$ at a water vapor pressure of 2.339 kPa which is more than twice the available pressure in a typical absorber. Their experimental results show no change in absorption rate when the vapour pressure difference across the membrane was increased. Ali and Schwerdt [2] reported that their membrane mass transport resistance could have dominated the overall mass transfer process which resulted in poor absorption rates. However, the experimental studies carried out by Isfahani and Moghaddam [3] suggest that the mass transfer through the solution is the dominant resistance as compared to the membrane mass transfer resistance. Yu et al. [4] performed numerical simulations to investigate a plate-and-frame membrane absorber and observed that a 3-fold increase in the absorption rate can be achieved when the solution film thickness is reduced from 0.15 mm to 0.05 mm. Isfahani et al. [5] experimentally investigated a membrane based absorber for the absorption of water vapour in the aqueous solution of LiBr and reported that the absorption rate was 2.5 times higher than that in falling film absorbers. Isfahani and Moghaddam [3] experimentally analysed the absorption characteristics of water vapour in a thin LiBr solution constrained by superhydrophobic nanofibrous membrane structures. They studied the effect of water vapour pressure, cooling temperature, solution film thickness and solution mass flow rate on the absorption rate in a membrane based absorber. They achieved an absorption rate of 0.006 kg/m^2s with a solution film thickness of 0.1 mm and a velocity of 0.005 m/s. Bigham et al. [6] experimentally and numerically investigated the implementation of micro-scale features on the flow channel surface to induce vortices within the solution film. They reported that the mass transport mode in such a configuration could be changed from a diffusive to an advective mode. They obtained an increase in the absorption rate by a factor of 2.5 i.e. from 0.0016 kg/m^{2}s to 0.004 kg/m^{2}s for the flow channel with micro-scale features on the surface. Asfand et al. [7] performed numerical simulations to investigate heat and mass transfer behaviour in a plate-and frame absorber and observed that the absorption rate can be significantly enhanced if the solution channel thickness is reduced. However, they reported that the solution pressure drop along the channel increases exponentially with the decrease in solution channel thickness and this can significantly affect the performance of an absorber operating with water as a refrigerant under vacuum conditions. They recommended an optimal solution channel thickness of 0.5 mm and a solution velocity of about 0.005 m/s to achieve a higher absorption rate with an acceptable solution pressure drop along the channel. Venegas et al. [8] developed a numerical model to predict the performance of a membrane-based absorber. They reported that by using a plate-and-frame membrane absorber the size was reduced by 50% as opposed to using a falling film absorber for the same cooling capacity. Later, Venegas et al. [9] used this model to perform a parametric study of design and operating conditions. They evaluated the effect of these parameters on the cooling capacity and absorber size.

The selection of appropriate membrane contactor material with suitable characteristics, i.e. porosity, pore size, thickness, tortuosity etc. is crucial when designing a membrane-based component. In addition, the mechanical strength of the membrane contactor is dependent on the above mentioned characteristics. The objective of the present work is to analyse in detail, the effect of membrane contactor characteristics and operating conditions on the performance of a plate-and-frame membrane absorber. Although membrane material characteristics were investigated analytically in previous studies, in each case the analysis was performed for a specific solution channel thickness. As the concentration and thickness of the thermal boundary layers decrease when the solution channel thickness is decreased, the absorption potential varies for different solution channel thicknesses. Further, the resistance to the refrigerant mass transfer also differs, which means that the impact of membrane mass transfer resistance and solution mass transfer resistance varies and the relative contribution of each resistance can change. In this regard, this study critically evaluates the impact of different solution channel thicknesses while investigating the effect of membrane characteristics. A range of different membrane properties i.e. porosity, membrane thickness and mean membrane pore size is applied, so as to investigate their effect on the absorption performance. In addition, to select the most suitable operating conditions for efficient performance, a parametric study is performed to assess the effect of the operating conditions on the absorption rate in a plate-and-frame absorber. In previous studies, heat and mass transfer processes in a plate-and-frame membrane absorber were investigated by the authors at a local level using computational fluid dynamics codes [7]. However, because of the higher computational time needed for a CFD based simulation to reach converged results, it is time consuming to perform a parametric study to evaluate in detail the effect of membrane contactor characteristics and operating conditions. Therefore, the aim of this work is to develop an efficient global model using simplified one dimensional heat and mass transfer equations which can perform steady-state analysis with less computation efforts and CPU time. The numerical model can be useful to integrate into a system analysis model to evaluate the absorption cycle performance employing a membrane-based absorber and to evaluate the effect of different parameters on the size and performance of the absorber. The model can be of use to design a compact membrane-based absorber for absorption cooling systems to enhance their performance and reduce their size. This would also enable the use of absorption cooling in small scale applications.

2. Absorber Configuration

A plate-and-frame membrane absorber was selected for the analysis in this study. As in a water-LiBr based absorption cooling system, the absorber operates under vacuum conditions and therefore the plate-and-frame membrane module, which offers minimum pressure drop, could be an interesting choice. The structural unit of the absorber configuration with a membrane contactor and the sectional view of the absorber are shown in Figure 1. The configuration of the plate-and-frame absorber is set as such that the solution, coolant and vapour all flow in individual flow channels. Each coolant channel serves two solution channels and is fed in a counter flow direction. The first and last cells of the module have half the width of the coolant channels. Similarly, each vapour channel serves two solution channels and can be counter flow or co-current flow. The coolant and solution are separated using a metallic plate across which heat transfer takes place. A microporous hydrophobic membrane sheet is placed at the aqueous solution–water vapour interface in the form of a parallel sheet along the metallic plate. Both heat and mass transfer processes take place across the membrane sheet. The parallel assembly of the plates and membrane sheets minimizes the pressure drop through the absorber.

3. Methodology

Figure 2 shows the detailed modelling of the heat and mass transfer processes in a single element of the absorber cell. The vapour pressure difference across the membrane causes the refrigerant vapour to pass through the membrane pores from the refrigerant side to the solution side, where the vapour condenses and dilutes the solution at the solution-membrane interface. During the process, the heat of condensation and mixing, known as heat of absorption, releases at the solution membrane interface. As a result, the temperature of the solution increases, whereas the solution concentration decreases at the solution-membrane interface and differs from that of the bulk solution. Consequently, the water vapour partial pressure near the solution-membrane interface increases and limits further absorption of the refrigerant vapours. The formation of the concentration and thermal boundary layers represents an additional thermal and mass transfer resistance to the refrigerant mass transfer and heat transfer fluxes. Refrigerant molecules diffuse from the solution-membrane interface into the bulk solution as a result of the difference in concentration. Similarly, heat flows from the solution-membrane interface towards the coolant wall, due to the difference in temperatures of the bulk solution and the solution near the interface. This heat is dissipated by the coolant which flows in a counter current direction. The interface temperature and interface concentration are lowered, as a result of the heat dissipated by the coolant and the diffusion of the refrigerant molecules into the bulk solution, respectively. Consequently, the partial pressure of water vapour at the solution-membrane interface decreases and promotes further absorption of refrigerant vapours.

In the present simulation of heat and mass transfer, the mathematical model is based on the energy and mass balance equations in an infinitesimal area along the channel. This yields a coupled heat and mass transfer model in which both the non-linear and differential equations are solved simultaneously using a MATLAB solver to obtain the converged solution. A one dimension analysis was carried out along the channel length. Each channel was discretized into 200 cells along the length and the governing non-linear and differential equations were solved simultaneously in each cell using the Newton-Raphson and the Runge–Kutta methods, respectively. A convergence criterion of $2x10^{-07}$ was used to obtain a steady-state converged solution.

The current model is simple and can predict the absorption rate and other parameters with fine accuracy. The model is able to calculate the interface temperature and interface concentration of the solution. These values are used to calculate the partial pressure of water vapour in the solution at the solution-membrane interface. In the previous numerical models [2, 8], the bulk solution temperature and the concentration were used to calculate the partial pressure of vapour in the bulk solution from which the mass transfer flux was calculated. In a previous study [7], calculations were performed by the authors to investigate heat and mass transfer processes in a water-LiBr membrane-based absorber using CFD approach. Numerical simulations were preformed in a workstation cluster of 24 AMD Opteron 248 dual core processors (64 bits) and 7 Intel 3 Ghz processors, with 3 terabytes of disk, linked with a Giga Ethernet in a Linux environment. Simulations were performed in parallel using four processors and each case simulated took approximately 6 days to achieve a steady-state condition. The same case was simulated using the global model developed in MATLAB and a desktop computer with a 3.0 MHz processor was used to perform the simulation. In this case, steady-state results were obtained within approximately 3 minutes in the case of the coolant flowing in the counter flow direction whereas when the coolant flow was considered in the co-current direction, steady-state results were obtained in less than 20 seconds.

3.1 Model assumptions

The following assumptions are considered in the analytical model for the simulation

- Steady state conditions.
- One dimensional transfer in the flow direction along the length.
- Vapour channel pressure and temperature are assumed constant.
- Coolant thermophysical properties are assumed constant.
- No heat lost or gained from the surroundings to the absorber cells.

3.2 Governing equations

The driving force for the refrigerant vapour mass transfer across the membrane in a water-LiBr absorber is the difference in vapour pressure and partial pressure of water vapour in the aqueous solution. The mass transfer flux across the membrane is given by Martinez and Rodriguez-Maroto [10] as follows:

$$J^{i} = m^{i} / \left(w \cdot dz\right) = K_{m}^{i}\left(P_{v}^{i} - p_{\text{int}}^{i}\right) \quad (1)$$

where J is the mass transfer flux of water vapour absorbed in the solution, P_v is the water vapour pressure and p_{int} is the equilibrium water vapour partial pressure of the solution at the solution-membrane interface. It is calculated at the solution-membrane interface as a function of the solution concentration and temperature using the vapour pressure correlation given by Uemura and Hasaba [11]. m is the mass of water vapour absorbed, dz is the differential length of the segment. w is the width of the channel. K_m is the membrane equivalent mass transfer coefficient.

The bulk solution concentration is calculated from the mass balance equation given below

$$m_{s,out}^{i} = m_{s,in}^{i} + m^{i} \quad (2)$$

$$X_{s,out} = \frac{m_{s,in}}{m_{s,out}} X_{s,in} \quad (3)$$

The solution-membrane interface concentration is calculated using the equation given by Martinez and Rodriguez-Maroto [10]:

$$X_{\text{int}}^{i} = X_{s}^{i} \exp\left(-\frac{J^{i}}{K_{\text{int}}^{i} \rho_{H_2O}^{i}} \right) \tag{4}$$

where X_{int} is the interface concentration and K_{int} is the interface mass transfer coefficient. The solution-membrane interface temperature is calculated using the equation given below

$$T_{\text{int}}^{i} = T_{s}^{i} + \frac{H_{v}}{wh_{s}^{i}} \frac{m^{i}}{dz} \tag{5}$$

where T_{int} is the interface temperature, h_s is the solution heat transfer coefficient and H_v is the vapour enthalpy. The heat transfer equation in the solution channel is derived by considering a control volume and applying an energy balance. The differential equation derived to calculate the solution temperature in each segment can be written as:

$$\frac{dT_{s}^{i}}{dz} = \frac{H_{v} - Cp_{s}^{i} T_{s}^{i}}{m_{s}^{i} Cp_{s}^{i}} \frac{m^{i}}{dz} - \frac{U^{i} w (T_{s}^{i} - T_{c}^{i})}{m_{s}^{i} Cp_{s}^{i}} \tag{6}$$

where T_s is the solution temperature and T_c is the coolant temperature. U is the overall heat transfer coefficient Cp_s and Cp_c are the solution and coolant specific heat capacities, respectively. Similarly, the heat transfer equation in the coolant channel is derived by considering a control volume along the coolant channel and applying an energy balance. The differential equation derived to calculate the coolant temperature in each segment can be written as:

$$\frac{dT_{c}^{i}}{dz^{i}} = \frac{U^{i} w (T_{s}^{i} - T_{c}^{i})}{m_{c}^{i} Cp_{c}^{i}} \tag{7}$$

3.3 Heat and mass transfer coefficients

Mass transport through a microporous membrane can take place by different mechanisms depending on the flow regime. Thus, it is important to determine the flow regime in order to accurately calculate the mass flux through the membrane. Flow through a porous membrane can be classified into viscous, transitional, or free molecular flow regimes, depending on the magnitude of the Knudsen (Kn) number. The Kn number is defined as the ratio of the mean free path (λ) to the pore diameter (d_p):

$$Kn = \lambda / d_p \tag{8}$$

where λ is the mean free path and is calculated as:

$$\lambda = \frac{c_B \cdot T}{\sqrt{2} \cdot \pi \cdot \sigma^2 P} \tag{9}$$

where c_B is the Boltzmann constant (1.38 × 10^{-23} J/K), σ is the molecular collision diameter (2.7 × 10^{-10} m for water vapour), T is the absolute temperature in K and P is mean total pressure within the membrane pore in Pa.

For Kn > 10, collision between molecules and pore walls is dominant, the gas transport takes place in the free molecular regime and the flow is known as Knudesn flow, for which the membrane mass transfer coefficient can be calculated as:

$$K_m^i = \frac{M_{H_2O}}{\delta_m} \left(\frac{D_k}{RT_m^i} \right) \tag{10}$$

where M_{H2O} is the molecular weight of water, δ_m is the membrane thickness, R is the universal gas constant and T_m is the mean membrane temperature which is calculated as the average of vapour and solution interface temperatures. D_k is the Knudsen diffusion coefficient and for porous solid it can be calculated as:

$$D_k = \frac{\varepsilon d_p}{3\tau} \left(\frac{8RT_m^i}{\pi M_{H_2O}} \right)^{\frac{1}{2}} \tag{11}$$

where, ε is the membrane porosity, τ is the tortuosity of the membrane and d_p is the mean membrane pore diameter.

When Kn < 0.01, collisions between gas molecules dominate and viscous flow occurs which results in rapid convective transport. The membrane mass transfer coefficient in the viscous flow regime can be calculated as:

$$K_m^i = \frac{M_{H_2O}}{\delta_m}\left(\frac{P_m B_0}{RT_m^i \mu_v}\right) \tag{12}$$

$$B_0 = \frac{\varepsilon d_p^2}{32\tau} \tag{13}$$

where, μ is the viscosity and P is the pressure.

A transitional flow regime exists if 0.01<Kn<10 and according to the Dusty-Gas model, the mass transfer through a membrane consists of both diffusion and viscous fluxes.

$$K_m^i = \frac{M_{H_2O}}{\delta_m}\left(\frac{D_k}{RT_m^i} + \frac{P_m B_0}{RT_m^i \mu_v}\right) \tag{14}$$

In this study, the base value of the mean membrane pore size is 1 µm and at a vapour pressure of 1 kPa and a temperature of 7 ºC, the mean free path of water molecules is 13.2 µm, therefore the Knudsen number value lays in the free molecular regime for the base case and the vapour transport through the microporous membrane pores takes place via Knudsen diffusion mechanism. However, in some cases, particularly in the parametric study of membrane mean pore size and vapour pressure, the Knudsen number value lays in the transitional flow regime. In the code developed in MATLAB, the Knudsen number was calculated for each case study simulated and depending on the value of the Knudsen number an appropriate equation was used for the calculation.

The interface mass transfer coefficient K_{int} between the solution-membrane interface and the bulk solution, which is needed in Eq. (4) to calculate the interface solution concentration, is calculated using the Leveque's equation. For laminar flow in thin rectangular channels, the mass transfer coefficient is related to the Sherwood number through the following relationship:

$$K_{\text{int}} = Sh.\frac{D}{d_h} = 1.85 \cdot \left(R_e \cdot S_c \cdot \frac{d_h}{L^*}\right)^{\frac{1}{3}} \cdot \frac{D}{d_h} \tag{15}$$

where R_e is the Reynolds number, S_c is the Schmidt number and d_h is the hydraulic diameter, and L^* represents the flow length which is the distance from the mass transfer leading edge. Simplifying the above equation, we get:

$$K_{\text{int}} = 1.85 \cdot \left(u \cdot \frac{D^2}{d_h \cdot L^*} \right)^{\frac{1}{3}} \tag{16}$$

where u is the average solution velocity and D is the mass diffusivity of water molecules in the bulk LiBr solution.

The global heat transfer coefficient U , is calculated as:

$$\frac{1}{U^i} = \frac{1}{h^i{}_c} + \frac{t_w}{k^i{}_w} + \frac{1}{h^i{}_s} \tag{17}$$

where h_c and h_s are the local heat transfer coefficient of the coolant and solution and k_w is the thermal conductivity of the wall. As the ratio of the channel length to the thickness of the channel in both the coolant and solution channels is very high, the entrance region is not taken into account in the calculation and a fully developed laminar flow is considered in both the channels. The entrance region is very small in case of the flow channel with an increased length to thickness ratio and for simplification it can be neglected in the calculation as it does not significantly affect the results.

The convection heat transfer coefficient is linked to the Nusselt number through the following relationship:

$$h = Nu \cdot k / d_h \tag{18}$$

For fully developed flow in thin rectangular channels, the correlation developed by Shah and London [12] was used to calculate the Nusselt number.

$$Nu = 8.235 \cdot \left(1 - 2.0421 \cdot \alpha + 3.0853 \cdot \alpha^2 - 2.4765 \cdot \alpha^3 + 1.0578 \cdot \alpha^4 - 0.1861 \cdot \alpha^5\right) \quad (19)$$

where α is the channel aspect ratio.

3.4 Calculation sequence

Figure 3 depicts the calculation sequence used in the global model developed in the present work. After the input values have been set, the inlet conditions are calculated. At the given operating conditions and initial guess values, the thermophysical properties of the solution are calculated, followed by the calculation of the first cell in which the Newton-Raphson method is used to calculate the refrigerant mass transfer across the membrane, absorption rate, interface temperature and concentration of the solution. A loop over the flow length starts with the calculation of the second cell and is repeated until the entire flow path is covered. In this loop, the ordinary differential equations are solved by the Runge-Kutta method using the variables obtained in the previous step to calculate the solution and coolant temperatures and the concentration of the bulk solution. The non-linear equations are solved in each cell using the Newton-Raphson method to calculate the refrigerant mass transfer across the membrane, the absorption rate and interface temperature and the concentration of the solution. The Newton–Raphson iteration is repeated until the root is found and a minimal residual is left. The thermophysical properties of the working fluid mixtures are updated in each cell as a function of solution concentration and temperature. When the loop over the flow length is completed and all the variables are calculated in each cell then the output results are checked for consistency. As the coolant flows in a counter-flow direction, a guess value of coolant temperature in the first cell is taken for the calculations. If the coolant temperature predicted in the last cell is equal to the cooling water inlet temperature, then the solution terminates and results are displayed. Otherwise, the coolant initial guess value is updated and the calculations are repeated unless the exact cooling water inlet temperature is obtained in the last cell.

3.5 Thermophysical properties of the working fluid

In this study, a water-LiBr solution is used as a working fluid mixture. The thermophysical properties of the aqueous solution of lithium bromide are estimated as a function of the solution concentration in lithium bromide and temperature. The density and viscosity of the aqueous solution of lithium bromide are calculated using the correlations developed by Lee et al. [13]. The thermal conductivity of the water-LiBr mixture is calculated using the DiGuilio et al. [14] correlation. The specific heat capacity of the water-LiBr mixture is calculated using the correlation based on the Mc Neely data [15]. The diffusion coefficient of water in the aqueous lithium bromide solution is calculated from the Gierow and Jernqvist [16] experimental data which is determined at a constant temperature and different concentrations. However, at other temperatures the diffusion coefficient is estimated using the equation given below.

$$\frac{D_1 \mu_1}{T_1} = \frac{D_2 \mu_2}{T_2} \qquad (20)$$

where D is the diffusion coefficient, μ is the dynamic viscosity and T is absolute temperature in Kelvin. State 1 refers to the values calculated at 25 ^{o}C whereas state 2 refers to the values calculated at any other temperature.

4 Model validation

The numerical model was validated by comparing the absorption rate predicted with the experimental data reported by Isfahani and Moghaddam [3]. In their experiment, they used a solution and cooling water channels measuring 1 mm and 4 mm in width

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respectively, and a channel length of 38 mm. They investigated two different heights for the solution channel, 0.1 mm and 0.16 mm, where the height of the cooling water channel was 0.4 mm. An important issue is that the correlations used in the present model remain valid in all the cases. A solution inlet velocity of 0.005 m/s, and an inlet solution concentration and temperature of 60 % and 25 ºC, respectively, were considered in their experiment. Further, they used a very high mass flow rate for the coolant channel and for this reason they did not observe a temperature change between the inlet and exit of the cooling channel. Therefore, in this study a constant cooling temperature is used to validate the numerical model for the given conditions. The absorption rate predicted by the model was compared to the absorption rate achieved in the experiments for both the 0.1 mm and 0.16 mm solution channels at different values of vapour pressure. Figure 4 shows the comparison of predicted and experimental results which are well in agreement with a mean absolute percentage error of about 5.35%.

5. Results and discussion

Steady-state analysis is carried out over a 200 mm long and 200 mm wide solution channel with a solution inlet concentration and temperature of 60% and 40 ^{o}C, respectively. Coolant inlet temperature is set at 30 ^{o}C. A constant vapour temperature of 7 ^{o}C is assumed and a corresponding saturation pressure of 1 kPa is considered. These input variables are typical operating conditions of an absorption cooling system working with water-LiBr mixture. In this section, a parametric study is carried out to investigate the effect of membrane characteristics and operating conditions on the absorption performance of a plate-and-frame absorber. The obtained results provide sound information on the selection of the membrane characteristics and operating conditions in the case of different solution channel thicknesses.

5.1 Effect of membrane characteristics on the absorption process

In this study, a flat sheet membrane contactor made of polypropylene material is used. The membrane material characteristics considered for the parametric study are summarized in Table 1. The effect of membrane contactor mean pore size, porosity and thickness on the absorption rate is analyzed in this section. Figure 5 shows the effect of membrane pore size on the absorption rate. Results show that the absorption rate increases logarithmically with the increase in the membrane mean pore size. The increase in the absorption rate is more significant when the membrane mean pore diameter is increased from 0.25 µm to 1 µm because the effect of membrane mass transfer resistance is more dominant in membranes with small pore size and the mass transfer resistance decreases with an increase in the membrane mean pore diameter. However, further increasing the membrane pore diameter does not substantially affect the absorption rate because in membranes with larger pore diameter the diffusion resistance into the solution is a more dominant factor instead of the membrane mass transfer resistance. It can be seen from the results that at higher values of membrane pore diameter, the change in the absorption rate is negligible. Furthermore, it is evident from Figure 5 that the increase in the absorption rate is lower in thicker solution channels when the membrane mean pore diameter is increased. An increase of about 75%, 55%, 40% and 25% in the absorption rate is achievable when the membrane pore diameter is increased from 0.25 µm to 1 µm in the case of 0.1 mm, 0.25 mm, 0.5 mm and 1 mm solution channels, respectively. Moreover, further increasing the pore diameter from 1 µm to 5 µm results in an increase of about 22%, 16%, 11% and 7% in the absorption rate in the case of 0.1 mm, 0.25 mm, 0.5 mm and 1 mm solution channels, respectively. Increasing the membrane pore diameter reduces the resistance to the vapour transport through the pore which helps in enhancing the absorption rate, however, the mechanical strength of the membrane decreases with the increase in membrane pore size. Therefore, it is crucial to select a membrane with suitable pore diameter that will not only allow a higher absorption rate but will also augment the mechanical strength of the membrane.

Figure 6 shows the effect of membrane contactor porosity on the absorption rate. Absorption rate increases almost linearly if the porosity of the membrane contactor is increased from 50% to 85%. Again, the increase in the absorption rate is lower in thicker solution channels when the membrane porosity is increased. An increase of about 68%, 49%, 35% and 23% in the absorption rate is achieved when the membrane porosity is increased from 50% to 85% µm in the case of 0.1 mm, 0.25 mm, 0.5 mm and 1 mm solution channels, respectively. Highly porous membranes exhibit less resistance to the mass transfer flux; however the mechanical strength of the membrane decreases with an increase in porosity.

Figure 7 shows the effect of the membrane contactor thickness on the absorption rate. A linear decrease in the absorption rate is observed when the membrane contactor thickness is increased from 20 µm to 100 µm. It can be seen from the results that the decrease in the absorption rate is not significant in thicker solution channels when the membrane contactor thickness is increased. A decrease of about 35%, 28%, 21% and 15% in the absorption rate is observed when the membrane contactor thickness is increased from 20 µm to 100 µm in the case of 0.1 mm, 0.25 mm, 0.5 mm and 1 mm solution channels, respectively. Mass transfer resistance increases with an increase in the thickness of the membrane contactor which reduces the mass transfer across the membrane. However, the mechanical strength of the membrane contactor increases with an increase in thickness of the membrane.

In Figure 8, the effect of the solution diffusivity on the mass transfer is evaluated by changing the diffusion coefficient. A higher value of the solution diffusion coefficient leads to a rapid transport of the refrigerant molecules within the solution. Results show that the change in the absorption rate is more significant in the case of thicker solution channels. The solution mass transfer resistance is more dominant in thicker solution channels and thus the diffusion coefficient of the working fluid significantly affects the overall absorption rate. It is observed that if the diffusion coefficient of the solution is increased from 1.5×10^{-9} m^2/s to 3×10^{-9} m^2/s the overall absorption rate increases by approximately 29%, 25%, 20% and 13% in the case of 1 mm, 0.5 mm, 0.25 mm and 0.1 mm solution channels, respectively. These results show that an absorbent solution with a high diffusion coefficient can play an important role in the enhancement of the absorption rate.

The results obtained in this study clearly show that in the case of thicker solution channels, membrane contactor characteristics have a less prominent effect on the absorption rate and the solution resistance is the dominant resistance to the mass transfer of refrigerant molecules in the solution. Moreover, it can be concluded that the membrane mass transfer resistance is dominant only when the solution channel thickness is in the range of 0.1 mm. The thickness of the concentration and thermal boundary layers in thinner solution channels is smaller and the heat is well dissipated to the coolant because of the decrease in thickness. Therefore, in this case the effect of the membrane mass transfer coefficient is more pronounced.

A membrane should have enough mechanical strength to withstand the absorption refrigeration system operating conditions. Therefore, a membrane contactor should be selected with a pore size and thickness of such that does not affect the mechanical strength of the membrane material. In this way, the use of an additional support layer of the membrane can be avoided, as it adds an additional resistance to the vapour mass transfer across the membrane contactor. The results obtained in this study urge that the selection of appropriate membrane characteristics should be made bearing in mind the solution channel thickness. It is worth noting that a solution channel thickness of the order 0.1 mm can allow a higher absorption rate. However the higher pressure drop along the channel can hinder the performance of a membrane based absorber working under vacuum conditions. In a previous study, Asfand et al. [7] observed that the pressure drop increases exponentially when the solution channel thickness is reduced. They reported that a 50% decrease in the solution film thickness causes an increase in the accumulative pressure drop by a factor of approximately 7.5. They recommended the use of a solution channel thickness of 0.5 mm to avoid a higher pressure drop in the solution channel. From the present study, it is clear that the effect of membrane characteristics is low when the solution channel thickness is in the range of 0.5 mm. Thus, it will allow us to select membrane characteristics in range that will enhance the mechanical strength of the membrane contactor without significantly affecting the absorption rate.

It is suggested that the membrane pore diameter should be in the range of 0.5 µm – 1 µm, the thickness in the range of 60 µm – 80 µm and the porosity in the range of 60% – 70% for a plate-and-frame membrane absorber with a solution channel thickness of 0.5 mm. This range achieves not only a high absorption rate, but also the mechanical strength of the membrane contactor can be enhanced. Further, it is important to select a membrane contactor with appropriate surface properties, such as the hydrophobicity of the material. This property limits the solution from passing through the pores which hinders the performance of a membrane based absorber.

5.2 Effect of operating conditions on the absorption process

A parametric study is carried out to evaluate the effect of operating conditions on the absorption performance of a plate-and-frame membrane absorber. Important parameters such as, vapour pressure, solution inlet concentration and coolant temperature are varied according to typical operating conditions of the absorber in order to study the impact on the absorption rate. Table 2 summarizes the operating conditions considered for the parametric analysis.

Figure 9 shows the effect of the solution mass flow rate on the absorption rate for different solution channels. The absorption rate increases with an increase in the solution mass flow rate. Increasing the solution velocity brings fresh layers of solution near the membrane interface, which in turn increases the absorption capacity. Further, it can be seen from Figure 9 that the increase in absorption rate is more significant initially however, at higher solution flow rates, a further increase of the solution mass flow rate decreases the solution residence time and minimizes the diffusion of the water molecules across the solution. This causes a negative effect on the refrigerant mass transfer and therefore the increase in absorption rate is less pronounced. Increase in the absorption rate is more significant in the thinner solution channel. In the case of the 0.1 mm solution channel, increasing the solution mass flow rate from 2 kg/hr to 10 kg/hr causes an increase of about 65% in the absorption rate whereas as in the case of the 0.5 mm solution channel a 48% increase in the absorption rate is observed. It is also observed that about 50% increase in the absorption rate is achievable at the same operating conditions when the solution channel thickness is reduced by half from 1 mm to 0.5 mm. The thickness of the concentration and thermal boundary layers are reduced in the case of thinner solution channels and the heat of absorption at the interface is well dissipated by the coolant which lowers the partial pressure of water vapour in the solution and consequently increases the absorption capability of the solution.

Figure 10 shows the effect of vapour pressure on the absorption performance. It can be seen that the absorption rate increases linearly with an increase in the vapour pressure. The absorption rate increases by approximately 10% when the vapour pressure is increased by 7% and the same mass flow rate is kept in each solution channel. However, at higher vapour pressure values, the increase in the absorption rate reduces gradually to about 7% when the vapour pressure is increased by 7%. Increasing the vapour pressure from 0.873 kPa to 1.498 kPa increases the absorption rate by 87% from 1.06 kg/m^2s to 1.98 kg/m^2s in the case of the 0.5 mm solution channel, whereas in the 0.1 mm solution channel, the absorption rate increases by 89% from 1.97 kg/m^2s to 3.72 kg/m^2s. The higher absorption rate achieved in the case of the 0.1 mm solution channel is because of the thinner concentration and thermal boundary layers which lessens the solution mass transfer resistance at the interface. Figure 11 shows the effect of the solution inlet concentration on the absorption rate. It can be seen that the absorption rate increases with an increase in the inlet concentration of the solution. The partial pressure of water vapour in the solution decreases at a higher solution concentration which in turn increases the absorption capacity. However, the increase in the absorption rate is less prominent at higher concentrations because at higher solution concentrations the mass diffusivity of water in the LiBr solution decreases and the solution mass transfer resistance increases and limits the absorption rate. In addition, the increase in the absorption rate is lower in case of the thicker solution channels because the solution mass transfer resistance is more dominant in thicker solution channels. Increasing the inlet concentration from 55% to 63% mass fraction of LiBr increases the overall absorption rate from 0.66 kg/m^2s to 1.43 kg/m^2s in the case of the 0.5 mm solution channel whereas in the 0.1 mm solution channel the absorption rate increases from 1.19 kg/m^{2}s to 2.98 kg/m^{2}s. These results show that a higher absorption rate can be achieved if the solution inlet concentration is around 60%. In addition, at the given solution temperature and concentration, the aqueous solution of LiBr is not prone to crystallization according to the solubility chart of water/LiBr. Figure 12 shows the effect of the cooling water temperature on the absorption performance of a plate-and-frame membrane based absorber. Increasing the cooling water temperature has a negative effect on the absorption performance as at higher cooling water temperatures the coolant is not well able to dissipate the heat of absorption and as a consequence the solution temperature increases. At higher solution temperatures, the partial pressure of water vapour in the solution increases and lessens the absorption capacity of the solution. Increasing the coolant water inlet temperature from 25 ^{o}C to 35 ^{o}C results in about a 35% decrease in the absorption rate. For instance, increasing the cooling water inlet temperature from 25 ^{o}C to 35 ^{o}C decreases the absorption rate from 1.61 kg/m^{2}s to 1.07 kg/m^{2}s in the case the of the 0.5 mm solution channel, whereas the absorption rate decreases from 3.02 kg/m^{2}s to 1.98 kg/m^{2}s when the solution channel thickness is 0.1 mm.

The operating conditions of an absorption cooling system are critically important for the efficient performance of the system. Therefore, the selection of appropriate operating conditions is essential when designing a membrane based absorber. It is concluded that for a water-LiBr absorption air-conditioning system utilizing membrane-based absorbers, a vapour pressure of about 1.3 kPa, a solution inlet concentration of 60% and a cooling water inlet temperature of 30 ^{o}C are recommended to achieve a higher efficiency. Although, the cooling water inlet temperature should be low for efficient performance, to eliminate the need of a cooling tower, a temperature in the range of 30 ºC is selected. This will reduce both the size and cost of the system.

5. Conclusions

This study is focused on the impact of the solution channel thickness while investigating the effect of membrane contactor characteristics and operating conditions on the absorption process in water-LiBr membrane based absorbers. The effect of the membrane mass transfer resistance is critically evaluated in the case of different solution channels with thickness in the range of 0.1–1.0 mm. It is observed from the results that the membrane characteristics have a less prominent effect on the absorption rate and the solution resistance is the dominant resistance in refrigerant mass transfer in the case of thicker solution channels. Furthermore, the membrane mass transfer resistance is considerable in the case of thinner solution channels. The membrane mass transfer resistance is more dominant in membranes with small pore size whereas the diffusion resistance into the solution is a more dominant factor in the case of membranes with larger pore diameter. The selection of appropriate membrane characteristics should be made keeping in mind the solution channel thickness. Although solution channel thickness of the order 0.1 mm can allow for a higher absorption rate, the higher pressure drop along the channel can hinder the performance of a membrane based absorber working under vacuum conditions. The pressure drop along the channel length increases exponentially when the solution channel thickness is reduced, therefore a solution channel thickness of about 0.5 mm is considered appropriate to avoid a higher pressure drop in the solution channel. Moreover, the analysis performed in this study shows that the effect of membrane characteristics is low when the solution channel thickness is in the range of 0.5 mm. Therefore, a membrane contactor with a pore size and a thickness that do not affect the mechanical strength of the membrane material is recommended. In this way, the additional support layer of the membrane can be avoided as it adds a resistance to the membrane mass transfer resistance. Further, emphasis should be placed on the selection of a membrane contactor with appropriate surface properties such as the hydrophobicity of the material as it is important to prevent the solution from passing through the pores which hinders the performance of a membrane based absorber. The selection of suitable operating conditions is important to achieve high absorption rates. The parametric study carried out to evaluate the effect of operating conditions shows that a high absorption rate is achievable in the case of thinner solution channels. Moreover, it is observed that the percentage change in the absorption rate remains almost the same when the vapour pressure, solution inlet concentration and coolant inlet temperature are varied in the case of different solution channel thicknesses.

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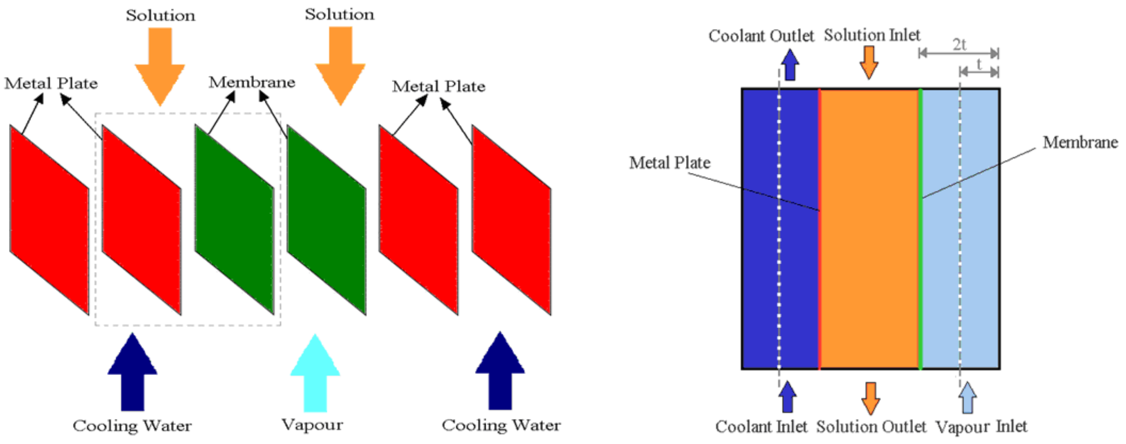

(a) Flow channel configuration (b) 2D sectional view of a single unit

Figuer 1: Plate-and-frame absorber configuration with membrane contactor

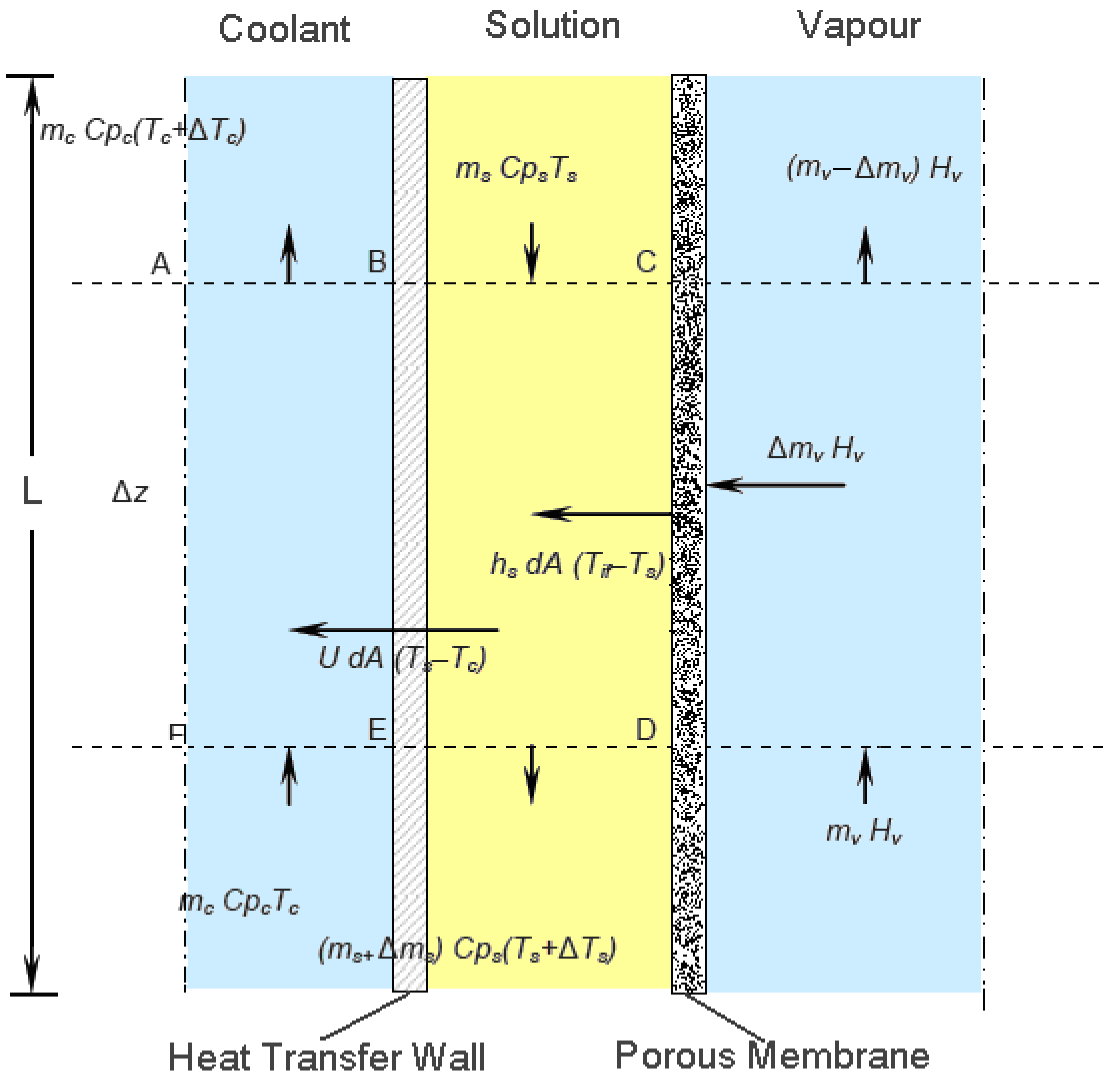

Figure 2: Schematic of heat and mass transfer processes in an absorber cell segment

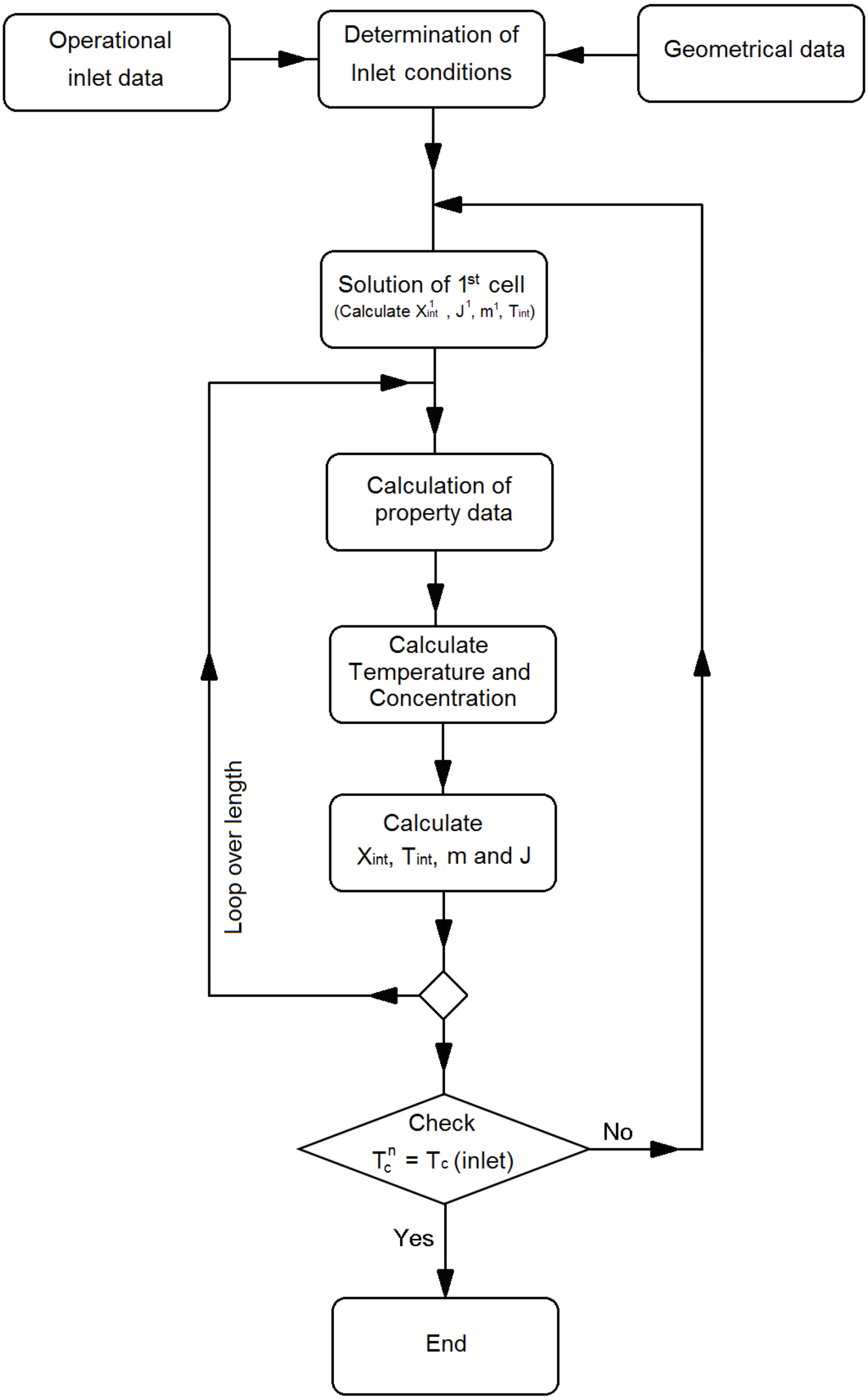

Figure 3: Schematic of the programme to perform simulations of the heat and mass transfer processes along the absorber length

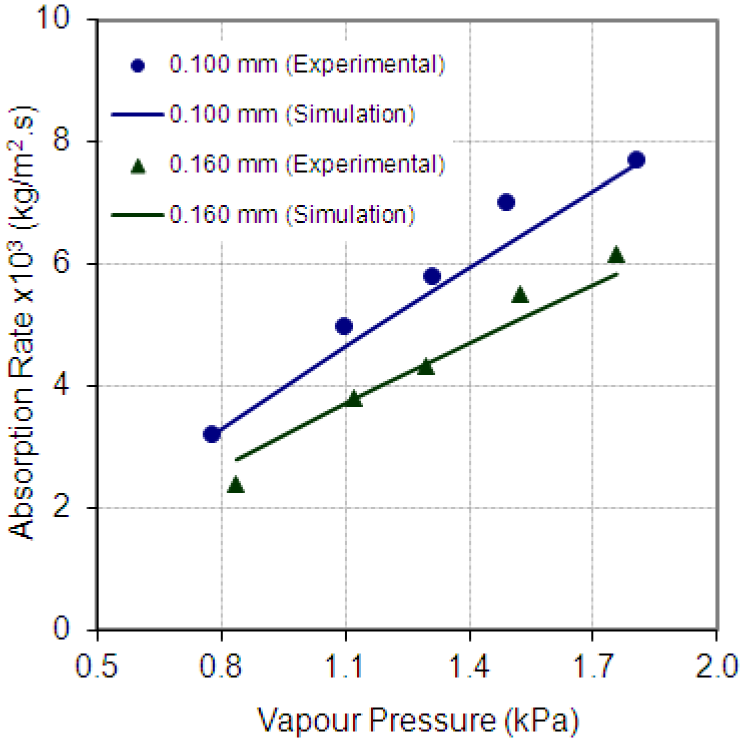

Figure 4: Model validation with data from the literature [3]

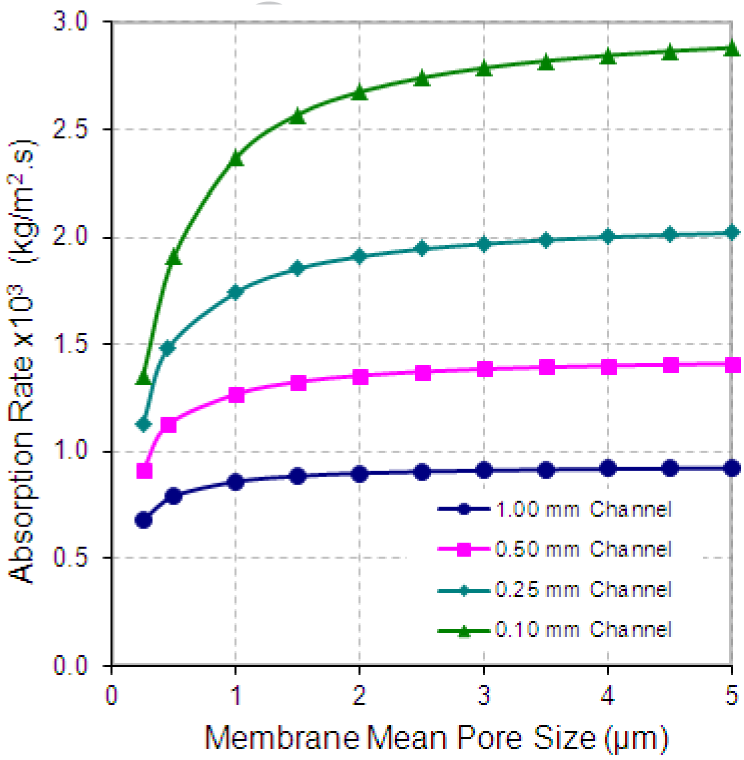

Figure 5: Effect of mean membrane pore size on the absorption process

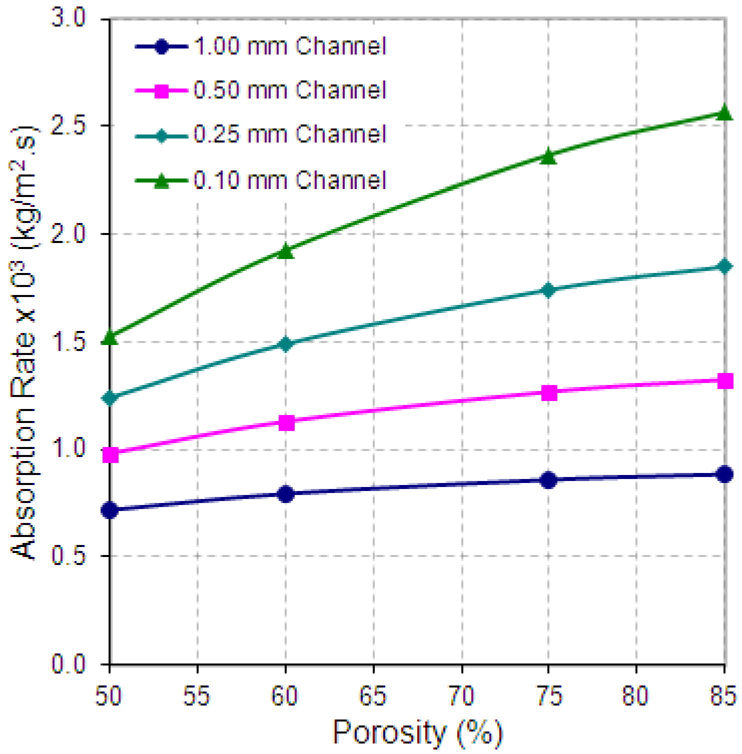

Figure 6: Effect of membrane porosity on the absorption process

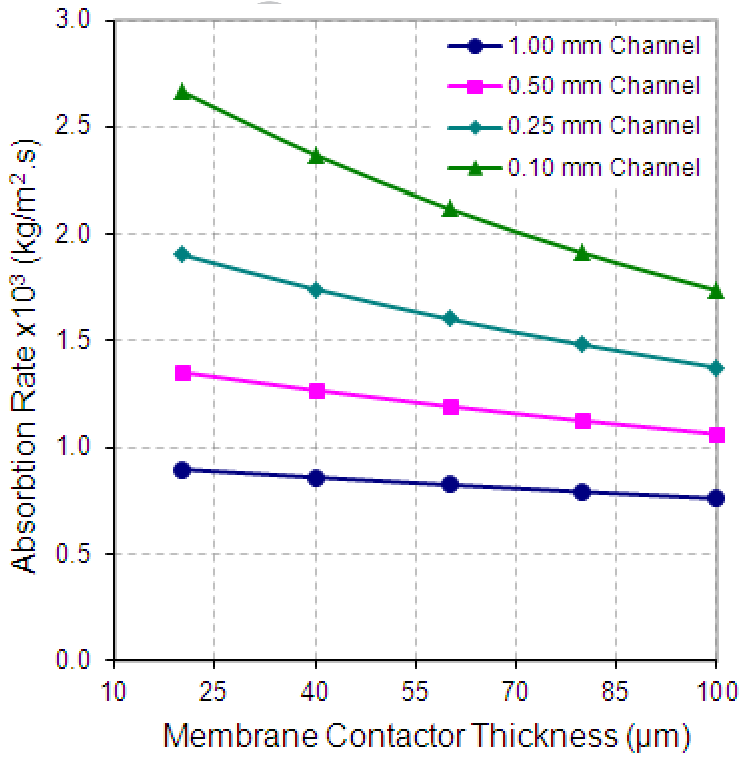

Figure 7: Effect of membrane contactor thickness on the absorption process

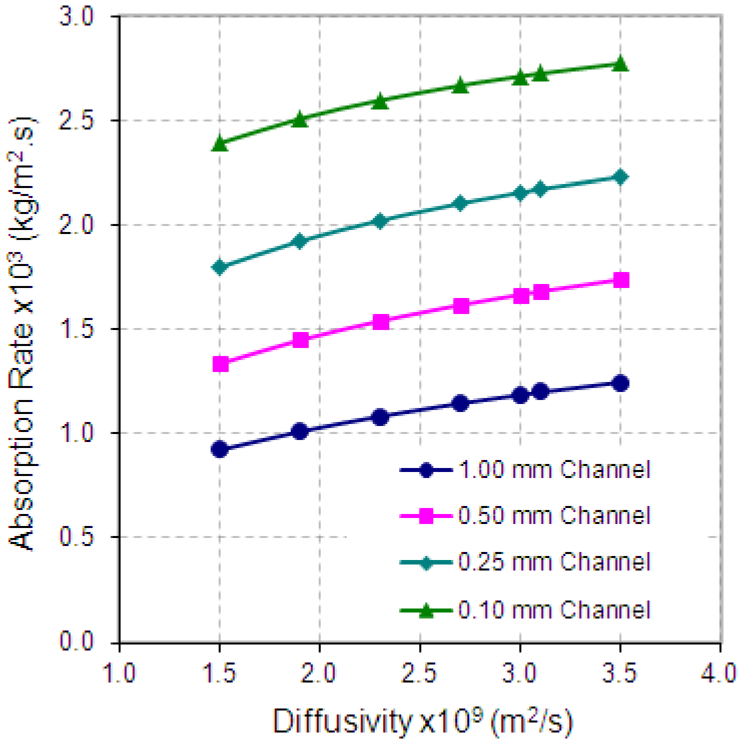

Figure 8: Effect of solution mass diffusivity on the absorption process

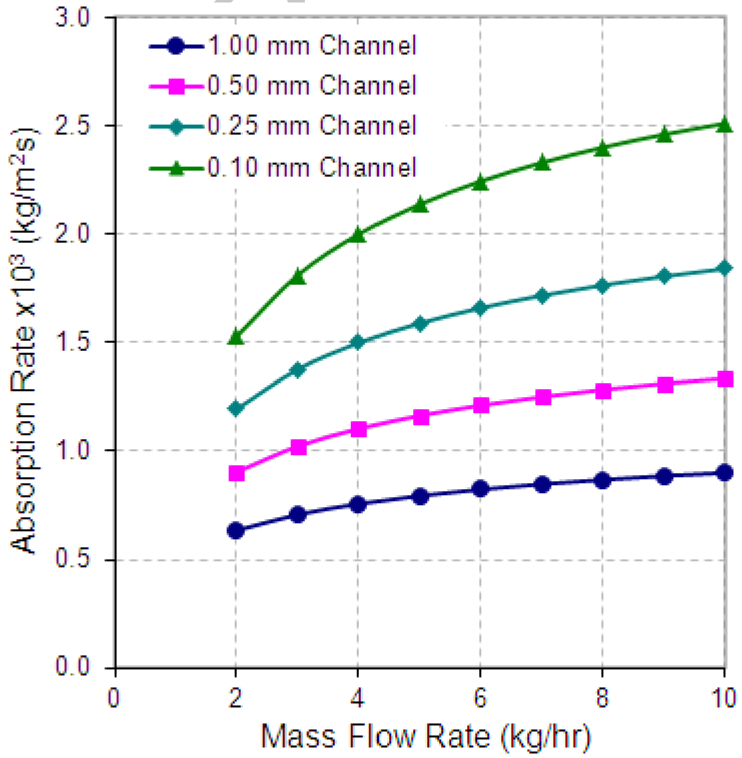

Figure 9: Effect of solution mass flow rate on the absorption performance

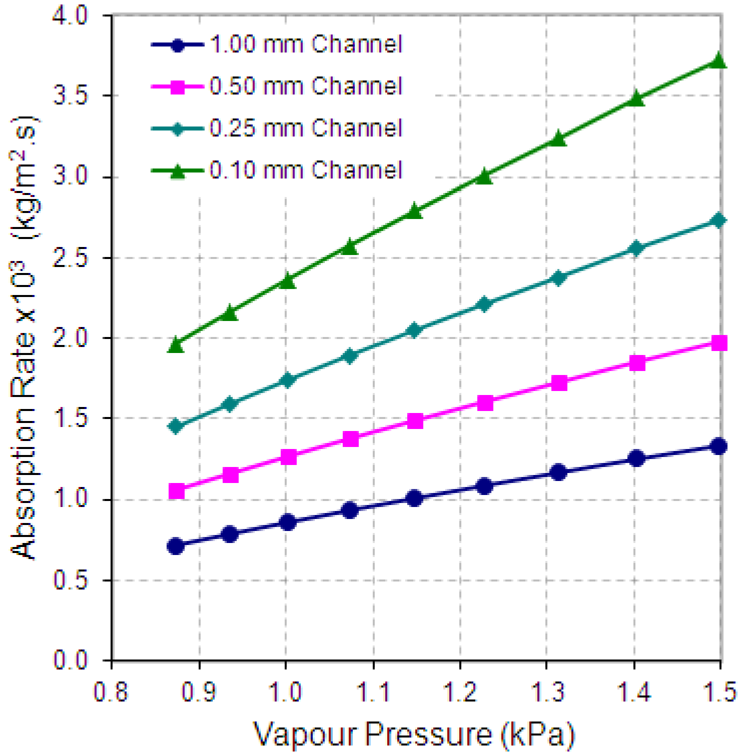

Figure 10: Effect of vapour pressure on the absorption process

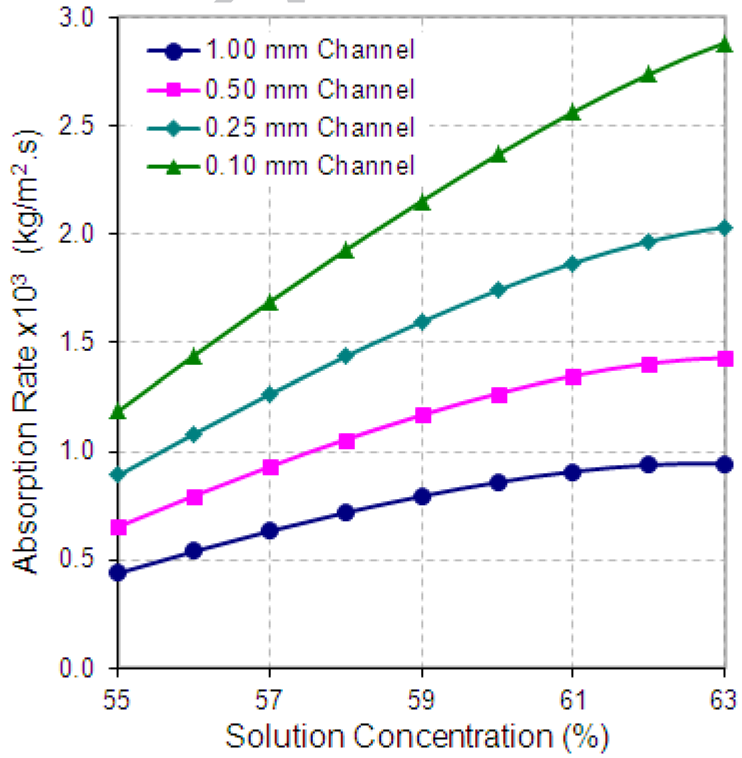

Figure 11: Effect of solution inlet concentration on the absorption process

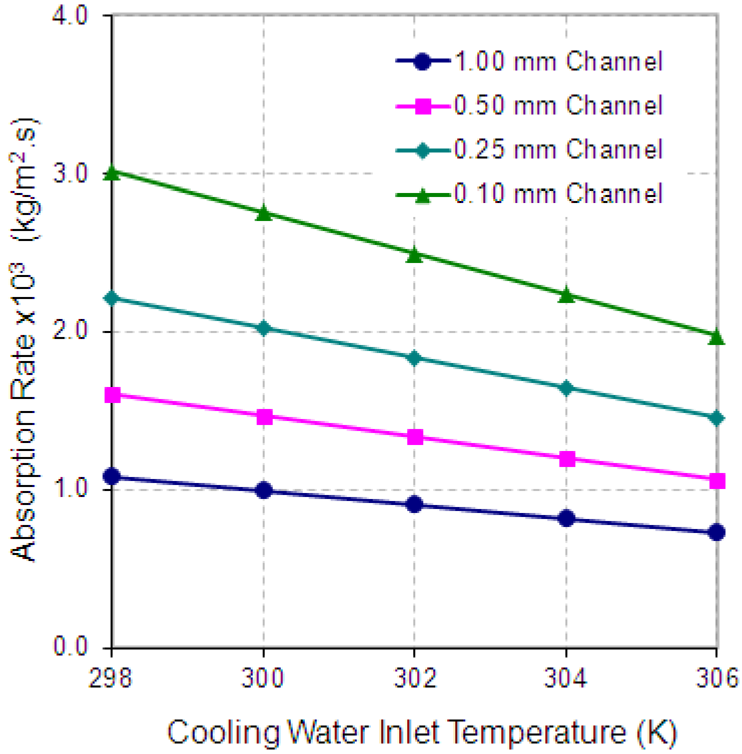

Figure 12: Effect of cooling water temperature on the absorption process

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Table 1. Membrane material characteristics

Parameter	Base value	Range
Porosity, ε (%)	75	50 – 85
Tortuosity, τ $(2-\varepsilon)^2/\varepsilon$	$(2-\varepsilon)^2/\varepsilon$	NA
Thickness, δm (μm)	40	20 – 100
Mean pore diameter, dp (μm)	1.0	0.25 – 3.00

Table 2: Operating conditions for the parametric study

Parameter	Base value	Range
Absorber pressure (Pa)	1000	872.5 – 1500
Inlet solution concentration (% LiBr)	60	55 – 63
Solution mass flow rate (kg/h)	7.5	2 – 10
Solution inlet temperature (ºC)	40	NA
Solution channel thickness (mm)	0.1	0.1 – 1.0
Channel length (mm)	200	NA
Channel width (mm)	200	NA
Coolant inlet temperature (ºC)	30	25 – 35
Coolant mass flow rate (kg/h)	36	NA
Coolant channel thickness, t (mm)	1	NA
Heat transfer wall thickness (mm)	0.5	NA

Impact of the solution channel thickness while investigating the effect of membrane characteristics and operating conditions on the performance of water-LiBr membrane-based absorbers

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Highlights

1) A steady-state global heat and mass transfer model is developed for water-LiBr membrane-based absorbers.
2) Solution mass transfer resistance is dominant in thicker solution channels.
3) Membrane mass transfer resistance is considerable in thinner solution channels.
4) High absorption rate is achievable in the case of thinner solution channels.