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Energy-saving in a liquid desiccant dehumidification system with a semipermeable-membrane-assisted dual sump

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HIGHLIGHTS

- The liquid desiccant dehumidification system with a membrane was proposed.
- Various types of membranes were considered to evaluate the applicability.
- Heat and mass transfer analysis was conducted to estimate the system performance.
- The proposed system can reduce the load by about 19% for solution cooling and heating.

ARTICLE INFO

Keywords:
Liquid desiccant
Membrane
Solution concentration
Dual sump

ABSTRACT

With the recent development of the independent control of temperature and humidity, the demand for dehumidification has significantly increased, and liquid desiccant dehumidification systems have attracted considerable attention because of a high dehumidification efficiency. This study presents a new design for a liquid desiccant dehumidification system that applies a membrane-assisted dual sump for maintenance the solution concentration with a low solution cooling and heating loads. A detailed heat and mass transfer analysis was conducted to evaluate the feasibility of the membrane for the maintenance the solution concentration according to the mass transfer resistance of the membranes. Moreover, the variation in the solution temperature and concentration was predicted by performing detailed simulations. The simulation results indicated that the low-mass-transfer-resistance membrane requires a large amount of solution load and the high-mass-transfer-resistance membrane cannot be used to maintain the solution concentration. Thus, the mid-mass-transfer-resistance (i.e., 15,000 s/m) membrane is suitable for the liquid desiccant dehumidification system. Compared with the conventional liquid desiccant dehumidification system based on a solution exchange, the membrane-assisted liquid desiccant dehumidification system could save about 19% load for solution cooling and heating owing to the lower heat and mass transfer rate on the absorber and regenerator sump.

Nomenclature

A	membrane area [m^2]
C_{sump}	concentration of a water in LiCl aqueous solution [kg/m^3]
C_p	specific heat [kJ/kg·K]
h	enthalpy [kJ/kg]

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h_{tot}	total heat transfer coefficient $[W/m^2 \cdot K]$
k	thermal conductivity of the membrane $[W/m \cdot K]$
h_{fg}	vaporization heat of water [= 2257 kJ/kg]
L_c	characteristic length [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number [−]
Pr	Prandtl number [−]
$\dot{Q}$	heat capacity [kW]
$\dot{Q}$	load [kW]
R_m	mass transfer resistance of the membrane [s/m]
R_{tot}	total heat transfer resistance of the membrane $[m^2 \cdot K/W]$
t	thickness of the membrane [m]
T	temperature [°C]
x	concentration [−]

Greek Symbols

Δ	difference [−]
ω	humidity ratio [kg/kg]

Subscripts

a	air
abs	absorber
conv	convection
in	inlet
out	outlet
pro	proposed
ref	reference
reg	regeneration
s	solution
tc	target cooling
th	target heating
tot	total
w	water

1. Introduction

Over the past decades, the independent control of temperature and humidity in air-conditioning systems have been studied because of the continued development of passive systems and decreased sensible loads in buildings [1–3]. The liquid-desiccant-assisted dehumidifier is considered as an effective dehumidification technology for the independent control of temperature and humidity [4]. In a conventional liquid desiccant dehumidification system, the difference in the vapor pressure between the desiccant solution and air is a driving force. The solution absorbs water vapor from the humid air in the absorber and desorbs it for solution regeneration to the scavenger air in the regenerator. The liquid desiccant dehumidification system is operated based on concurrent absorption and desorption processes [5].

The liquid desiccant dehumidification system requires specific operating conditions of a solution for system stability and effective performance. Specifically, the high concentration maintenance of the solution sprayed on the absorber is important; thus, the strong solution restored in the regenerator is transferred to the absorber. The weak solution after the dehumidification process is transferred to the regenerator to increase the solution concentration. In this process, the high-temperature solution travels from the regenerator to the absorber, whereas the low-temperature solution travels from the absorber to the regenerator. This causes the energy consumption for solution cooling and heating to meet the target temperature of each absorber and regenerator [6,7]. Thus, several studies have conducted to reduce the solution cooling and heating energy of a desiccant solution. Several configurations of a liquid-desiccant-assisted air conditioning system with various heat sources have been investigated [8–13]. Solar-assisted liquid desiccant systems have been proposed to reduce the heating energy of regenerators [8–10]. In these studies, the solar collector was considered as a renewable heat source for solution heating. A cooling tower was used to save the cooling energy for solution cooling compared with the cooling coils, chillers, and other cooling devices using electricity [11,12]. Kim et al. [12] suggested a liquid-desiccant-assisted air-conditioning system with a cooling tower and solar thermal system; this system can save about 51% of the operating energy compared with that of the conventional variable air volume system. Moreover, the heat pump was considered as an effective heat source because the heat pump could provide concurrent cooling and heating [13]. Shin et al. [13] proposed a heat-pump-driven liquid desiccant dehumidification system for primary energy conservation. This system can save about 33% of the total primary energy consumption compared with that of the conventional liquid desiccant dehumidification system. The gas consumption for solution heating was replaced by a heat pump.

Although the aforementioned approaches have significant energy-saving potential for solution cooling and heating, the load of the heat sources is similar to that of the existing liquid desiccant dehumidification system. This is because the proposed systems use free energy instead of a new design that solves the fundamental causes of cooling and heating loads owing to the transfer of a solution in each absorber and regenerator. Therefore, an innovative design is required to reduce the cooling and heating load of a solution, while maintaining the concentration through a low solution transfer between the absorber and regenerator.

Membranes have been investigated in several fields owing to their selectivity and permeability to specific materials [14–16]. In particular, reverse osmosis (RO) and forward osmosis (FO) membranes have been studied for seawater desalination and wastewater reuse [15,16]. Ren and McCutcheon [15] analyzed and compared the salt rejection and coefficients of the water permeance of a thin-film composite membrane with that of a cellulose acetate membrane. Emadzadeh et al. [16] fabricated a thin-film nanocomposite (TFN) membrane to develop water permeability. The effects of TiO_2 nanoparticles were investigated, and a PSf-TiO_2 nanocomposite substrate-based TFN membrane was proposed for various FO applications. Farrell and Babb [14] established a significant correlation between the membrane resistance and molecular radius based on experimental data. Moreover, several membrane-related applications have been investigated for liquid desiccant regeneration and desalination technologies [17]. Guo et al. [17] evaluated the feasibility of electrodialysis and ion-exchange membranes for aqueous solution regeneration. The lithium chloride solution was regenerated by the transfer of ions via the membrane.

Although there are several membrane types and applications that use different membranes with various features, solution regeneration or concentration maintenance applications with a membrane for liquid desiccant dehumidification systems have not been investigated. As the membrane enables the transfer of only water vapor without ions of the desiccant solution, the low mass flow rate transfers for maintenance of the solution concentration. The low mass flow rate can help to save energy for solution cooling and heating through low heat and mass transfer. However, detailed solution regeneration or concentration maintenance methods for liquid desiccant dehumidification systems using the membrane and their energy benefits have not been extensively studied.

Thus, a new design of the liquid desiccant dehumidification system with a membrane to maintain the solution concentration is suggested in this study. To evaluate the feasibility of a membrane, the dehumidification performance of the proposed liquid desiccant dehumidification system and variations of the solution concentration were analyzed by conducting detailed heat and mass transfer simulations under the various types of a membrane. The solution temperature and system load were compared with those of the conventional liquid desiccant system to reveal the energy-saving potential of the proposed liquid desiccant dehumidification system with a membrane. Consequently, the applicability of the membrane applied to the liquid desiccant system was comprehensively evaluated by performing detailed simulations using MATLAB 2021a and engineering equation solver programs.

2. System overview

2.1. Semipermeable membrane

There are various types of membranes based on the separation principle: semipermeable and selectively permeable membranes. The semipermeable membrane allows some particles to pass through the pore and particle size, whereas the selected particles can pass through the selectively permeable membrane [15,18]. Semi-permeable membranes can be classified into RO, nanofiltration, ultra-filtration, microfiltration, and particle filtration membranes based on the pore size in liquid-to-liquid separation [14,19,20]. In previous studies, the RO membrane had pores whose size ranged from 0.0001 to 0.001 μm, which is similar to that of the aqueous salt, and it can reject ions [21,22].

Fig. 1 shows the transfer mechanism of the water molecule through the RO membrane. LiCl exists in a state of ions in the forms of Li^+ and Cl^- in an aqueous solution because it is an ionic bond. The water molecules surround the LiCl ions and are larger than the pore size of the membrane. Thus, the ions cannot pass through the RO membrane, whereas the water molecules pass through the membrane. The water molecule automatically diffuses from the high concentration to low concentration of the water molecules owing to the difference in the water molecule concentration.

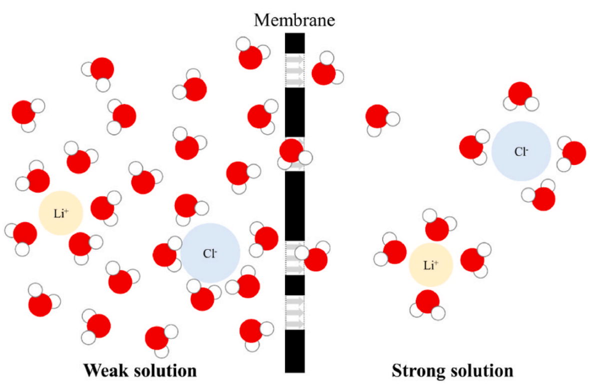


Fig. 1. Transfer mechanism of the water molecules through the membrane.

2.2. Liquid desiccant dehumidification system with membrane-based dual sump

Fig. 2 depicts a liquid desiccant dehumidification system with a membrane-based dual sump. The dehumidification of the intake outdoor air occurs in the absorber owing to the difference in the vapor pressure between the air and solution. The sprayed solution into the absorber is weakened by the dehumidification process and it is collected in the absorber sump. Similarly, the heated solution for the regenerator is sprayed, and the water vapor is desorbed to the scavenger air. In addition, the strong solution after the regeneration process is gathered in the regenerator sump. The solution concentration in the absorber sump has decreased with the intake of the diluted solution, and the concentration of the solution in the regenerator sump has increased with the intake of the strong solution. Thus, the concentration gap of the solution between the absorber and regenerator sump is bigger.

With increasing the concentration difference in each sump, the water vapor in the solution diffuses from the absorber sump to regenerator sump through the membrane. Owing to the membrane pore size, the water vapor is transferred without other materials, e.g., ions of an aqueous solution, until the concentration of the solution in each sump is the same. The water transfer rate increases as the difference in the concentration increases, whereas the water transfer rate decreases as the difference in the concentration decreases. The dehumidification, regeneration, and water-vapor transfer processes occur simultaneously.

The solution is cooled and heated before entering the absorber and regenerator to maintain the dehumidification and regeneration performance. Thus, the solution temperature in each sump nearly converges at the target cooling and heating temperatures. As the solution in each sump exchanges to maintain the concentration or the solution circulates between the absorber and regenerator, a large amount of heat is transferred in conventional liquid desiccant dehumidification systems. However, the temperature variation in each sump in the proposed system is less than that in the conventional system because the membrane is activated as a thermal barrier between the absorber and regenerator sump.

3. Simulation overview

3.1. Transient analysis of the absorber and regenerator sump

The temperature and concentration of the solution in the sump affect the performance of the system, such as the effectiveness of dehumidification, regeneration rate, and solution cooling and heating load; thus, an analysis of the transient sump is required. The temperature and concentration of the solution in the sump can be predicted by the heat and mass transfer into the sump. The components of the heat and mass transfer occurring in the sump are shown in Fig. 3.

Fig. 3 (a) shows the mass transfer. In the absorber sump, the solution leaving the absorber after the dehumidification process ($\dot{m}_{abs,\ out}$) is the mass gain, whereas the solution sprayed into the absorber ($\dot{m}_{abs,\ in}$) and the water transferred using osmosis through a membrane ($\dot{m}_{w,membrane}$) represent the mass loss. However, the water transferred through osmosis indicates the mass gain in the regenerator sump. The solution sprayed into the regenerator ($\dot{m}_{reg,\ in}$) and the solution leaving the regenerator after the regeneration process ($\dot{m}_{reg,\ out}$) are the mass loss and gain, respectively.

Fig. 3 (b) depicts the heat transfer. The heat capacities of the solution entering the absorber ($\dot{Q}_{abs,\ in}$) and regenerator ($\dot{Q}_{reg,\ in}$) are the heat loss in the absorber and regenerator sump, respectively, whereas the heat capacities of the solution leaving the absorber ($\dot{Q}_{abs,\ out}$) and regenerator ($\dot{Q}_{reg,\ out}$) denote the heat gain in the absorber and regenerator sump. Heat transfer through a membrane occurs in two ways: from the absorber to regenerator sump and from the regenerator to absorber sump. The heat transfer from the absorber to the regenerator sump ($\dot{Q}_{w,\ membrane}$) occurs via water through the membrane. It demonstrates the loss for the absorber sump and gain for the regenerator sump. The heat transfer from the regenerator to absorber sump ($\dot{Q}_{membrane}$) occurs owing to the

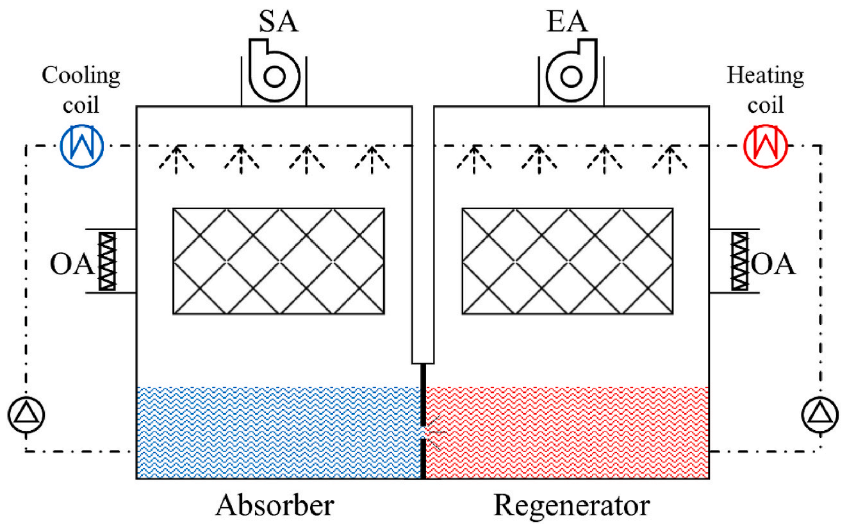
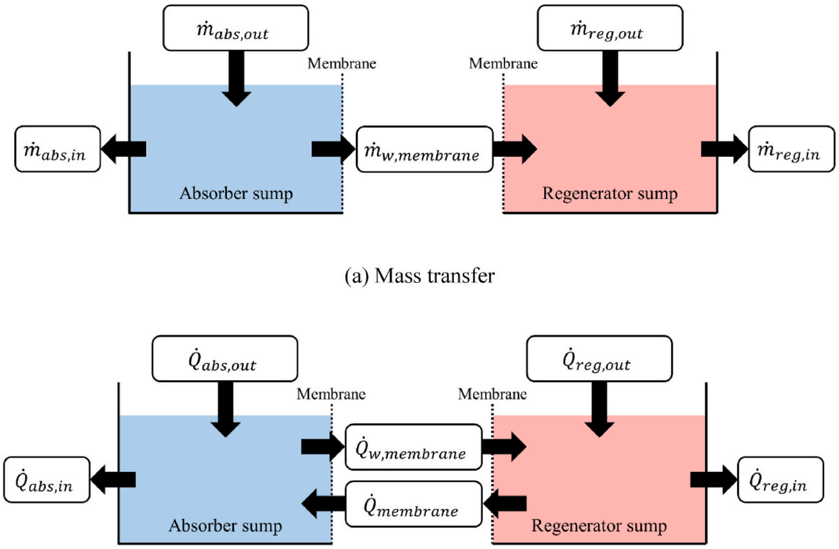


Fig. 2. Liquid desiccant dehumidification system with the membrane-based dual sump.



(a) Mass transfer

(b) Heat transfer

Fig. 3. Heat and mass transfer direction and components.

temperature difference of the solution in each sump.

Consequently, the concentration of the solution in the absorber and regenerator sump can be estimated by using Eq. (1) based on the mass balance equation and mass fraction of the solution [7]. The concentration of the solution was changed by varying the mass of the water and solution and LiCl. The mass variation is expressed by the mass gain and loss; the mass gain and loss in each sump are listed in Table 1. The initial values of the solution concentration and mass are estimated to be 30% and 25 kg, respectively [23].

The temperature of the solution in the absorber and regenerator sump can be predicted by using Eq. (2) based on the energy conservation equation [24]. The temperature is affected by the heat capacity of the solution, the heat capacity of the water vapor through the membrane, and the heat transfer rate through the membrane. The heat gain and loss in each sump according to the heat capacities and heat transfer rates are listed in Table 2. The solution in the absorber and regenerator sump is initially estimated to be at room temperature (i.e., 26 °C). The detailed simulation methods and equations are described in the following section:

$$x_{s,\ sump}^{(i+1)} = \frac{m_{s,\ sump}^{(i)} \cdot x_{s,\ sump}^{(i)} + \sum_{Gain} m_s^{(i)} \cdot x_s^{(i)} - \sum_{Loss} m_s^{(i)} \cdot x_s^{(i)}}{m_{s,\ sump}^{(i)} + \sum_{Gain}\left(m_s^{(i)} + m_w^{(i)}\right) - \sum_{Loss}\left(m_s^{(i)} + m_w^{(i)}\right)} \tag{1}$$

$$T_{s,\ sump}^{(i+1)} = T_{s,sump}^{(i)} + \frac{\sum_{Gain}\left(Q_s^{(i)} + Q_{w,membrane}^{(i)} + Q_{membrane}^{(i)}\right) - \sum_{Loss}\left(Q_s^{(i)} + Q_{w,membrane}^{(i)} + Q_{membrane}^{(i)}\right)}{m_{s,\ sump}^{(i)} \times C_{p,\ s}} \tag{2}$$

3.2. Heat and mass transfer in the membrane

Mass transfer in a membrane occurs owing to the diffusion of water vapor across the semi-permeable membrane. The mass flux of water ($\dot{m}_{w,membrane}$) through the membrane can be calculated by using Eq. (3) [25]. The difference in the water concentration in desiccant solutions in the absorber and regenerator sump is the driving force of the mass transfer process. The mass transfer area (A) is 0.06 m^2; the width and height of the membrane are 0.38 and 0.16 m, respectively, because the membrane is affected by the size of the sump and system [23]. The mass flux of water passing through the membrane is inversely proportional to the mass transfer resistance. The mass transfer resistance (R_m) varies according to its characteristics, such as material, thickness, and pore size [26]. To evaluate the applicability of the membrane for the maintenance of a solution concentration, various mass transfer resistances ranging from 350 to

Table 1
Mass gain and loss components of each sump.

		Components	Equation
Absorber sump	Gain	$\dot{m}_{abs,\ out}$	Eq. (12)
	Loss	$\dot{m}_{abs,in}$	Assumption
		$\dot{m}_{w,\ membrane}$	Eq. (3)
Regenerator sump	Gain	$\dot{m}_{reg,\ out}$	Eq. (13)
		$\dot{m}_{w,\ membrane}$	Eq. (3)
	Loss	$\dot{m}_{reg,\ in}$	Assumption

Table 2
Heat gain and loss components of each sump.

		Components	Equation
Absorber sump	Gain	$\dot{Q}_{abs,\ out}$	Eq. (15)
		$\dot{Q}_{membrane}$	Eq. (5)
	Loss	$\dot{Q}_{abs,in}$	Eq. (14)
		$\dot{Q}_{w,\ membrane}$	Eq. (4)
Regenerator sump	Gain	$\dot{Q}_{reg,\ out}$	Eq. (16)
		$Q_{w,\ membrane}$	Eq. (4)
	Loss	$\dot{Q}_{reg,\ in}$	Eq. (14)
		$\dot{Q}_{membrane}$	Eq. (5)

100,000 s/m have been considered [27–31].

$$\dot{m}_{w,membrane} = \frac{A \times (C_{sump,abs} - C_{sump,reg})}{R_m} \tag{3}$$

Heat transfer through a membrane occurs in two ways: from the absorber to regenerator sump based on the mass transfer of the water vapor ($\dot{Q}_{w,\ membrane}$) and from the regenerator to absorber sump based on the heat transfer through the difference in the temperature ($\dot{Q}_{membrane}$). The heat transfer from the absorber to regenerator sump ($\dot{Q}_{w,\ membrane}$) is expressed as the heat capacity of the water vapor transferred through the membrane (Eq. (4)).

$$\dot{Q}_{w,membrane} = \dot{m}_{w,\ membrane} \times C_{p,s} \times T_{s,abs,\ sump} \tag{4}$$

The heat transfer from the regenerator to absorber sump occurs because of the difference in the solution temperature of each sump. The heat transfer rates based on convection and conduction ($\dot{Q}_{membrane}$) can be estimated from the total heat transfer coefficient, area, and temperature variation using Eq. (5).

$$\dot{Q}_{membrane} = h_{tot} \times A \times (T_{s,\ reg,\ sump} - T_{s,\ abs,\ sump}) \tag{5}$$

The total heat transfer coefficient is related to the thermal resistance, and the thermal resistance is estimated by using Eq. (6) [29,32]. The heat transfer coefficients ($h_{abs,\ sump}$ and $h_{reg,\ sump}$) indicate the convection heat transfer rate between the solution in the absorber and regenerator sumps and the membrane surfaces. The convection heat transfer coefficients can be calculated using the Nusselt number and thermal conductivity of the LiCl aqueous solution (Eq. (7)) [33]. The Nusselt number is derived using Eq. (8), and the thermal conductivity of the LiCl solution is estimated to be 0.6 W/m · K [33]. The thermal conductivity ($k_{membrane}$) and thickness ($t_{membrane}$) of the membrane are estimated to be 0.334 W/m · K and 0.5 mm, respectively [25]. Although the thermal conductivity and thickness of the membrane vary according to the material and other properties, the total heat transfer coefficient is assumed to be a constant value because the impact of the convection heat transfer is greater than that of the conduction heat transfer [29]. Finally, the total heat transfer coefficient is estimated to be 602.2 $W/m^2 \cdot K$.

$$R_{tot} = \frac{1}{h_{tot}} = \frac{1}{h_{abs,\ sump}} + \frac{t_{membrane}}{k_{membrane}} + \frac{1}{h_{reg,\ sump}} \tag{6}$$

$$Nu = \frac{h_{conv} \times L_c}{k} \tag{7}$$

$$Nu = 0.664 \times Re^{0.5} \times Pr^{\frac{1}{3}} \tag{8}$$

3.3. Dehumidification and regeneration process

The concentration and temperature of the solution in each sump are affected by the variance of the solution condition after the completion of the dehumidification and regeneration processes. The solution leaving each sump, i.e., the solution entering the absorber and regenerator, has a constant flow rate of 13 L/min. Thus, the mass flow rate of LiCl and the water in the solution are calculated using Eqs. (9) and (10), respectively.

$$\dot{m}_{licl,\ abs,in\ or\ licl,\ reg,\ in} = \dot{m}_{abs,\ in\ or\ reg,\ in} \times x_{s,sump} \tag{9}$$

$$\dot{m}_{w,\ abs,in\ or\ w,\ reg,\ in} = \dot{m}_{abs,\ in\ or\ reg,\ in} - \dot{m}_{licl,\ abs,\ in\ or\ licl,\ reg,\ in} \tag{10}$$

The mass flow rate of the solution changes owing to the consideration of the dehumidification and regeneration rates. The dehumidification and regeneration rates ($\dot{m}_{deh}$ and $\dot{m}_{reg}$) are predicted by the variance of the air humidity ratio using a dehumidification and regeneration process (Eq. (11)). The air humidity ratio leaving the absorber and regenerator can be estimated by the dehumidification and regeneration effectiveness models of previous studies [7,34].

$$\dot{m}_{abs\ or\ reg} = \dot{m}_a \times \Delta\omega_a \tag{11}$$

As the water vapor is only transferred between the air and solution, the mass flow rate of LiCl in the solution did not change during the dehumidification and regeneration processes. Thus, the mass flow rate of the water in the solution can be obtained using Eqs. (12) and (13), respectively.

$$\dot{m}_{w,abs,out} = \dot{m}_{w,\ abs,in} + \dot{m}_{deh} \tag{12}$$

$$\dot{m}_{w,reg,out} = \dot{m}_{w,\ reg,in} - \dot{m}_{reg} \tag{13}$$

The heat transfer rate based on the solution flow ($\dot{Q}_{abs,\ in}$, $\dot{Q}_{abs,\ out}$, $\dot{Q}_{reg,\ in}$, and $\dot{Q}_{reg,\ out}$) is estimated as the heat capacity (Eq. (14)). The enthalpy of the solution entering the absorber or regenerator is predicted based on the temperature and concentration of the solution in each sump [24,35].

$$\dot{Q}_s = \dot{m}_s \times h_s \tag{14}$$

The dehumidification process is exothermic, and the humidification process is endothermic [36]. Thus, the enthalpy of the solution increases during the dehumidification process and decreases during the regeneration process. The enthalpy of the solution leaving the absorber is calculated using Eq. (15) based on the heat balance equation between the process air and solution. Similarly, the enthalpy of the solution leaving the regenerator is estimated using Eq. (16) [12].

$$h_{s,\ abs,\ out} = \frac{\dot{m}_{s,\ abs,\ in} \times h_{s,\ abs,\ in} + \dot{m}_{abs} \times h_{fg}}{\dot{m}_{s,abs,out}} \tag{15}$$

$$h_{s,\ reg,\ out} = \frac{\dot{m}_{s,\ reg,\ in} \times h_{s,\ reg,\ in} - \dot{m}_{reg} \times h_{fg}}{\dot{m}_{s,reg,out}} \tag{16}$$

3.4. *Cooling and heating load of the desiccant solution*

The desiccant solution should be cooled and heated using the cooling and heating coils, respectively, to maintain the dehumidification and regeneration performance before it enters the absorber and regenerator. The load of the cooling and heating coils can be obtained from the inlet temperature, target temperature, and mass flow rate (Eq. (17) and (18)). The target temperatures of the absorber and regenerator are estimated to be 20 and 50 °C, respectively.

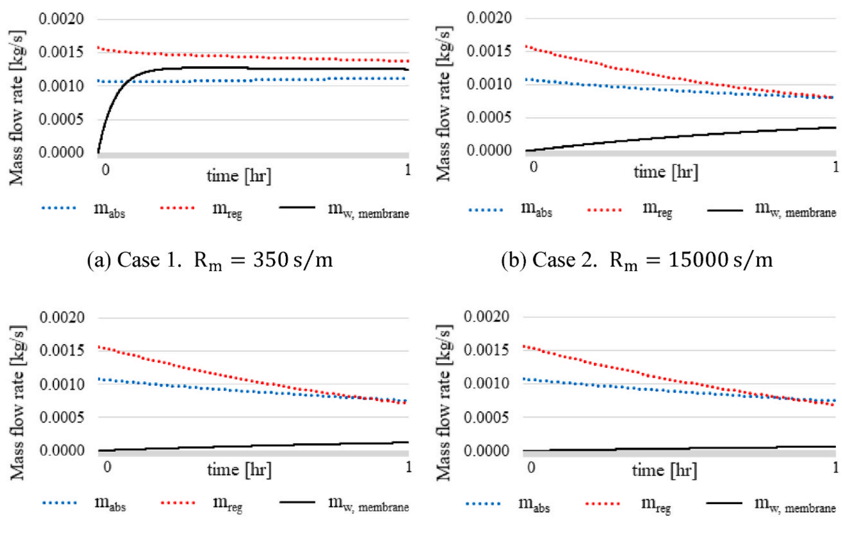
$$\dot{Q}_{cooling} = \dot{m}_s \times C_{p,s} \times (T_{s,in} - T_{s,tc}) \tag{17}$$

$$\dot{Q}_{heating} = \dot{m}_s \times C_{p,s} \times (T_{s,th} - T_{s,in}) \tag{18}$$

4. Simulation results

4.1. *Mass transfer rate of each sump per hour*

The mass flow rates were estimated to compare the concentrations of the solution under various mass transfer resistances of the membrane. Fig. 4 shows the dehumidification, regeneration, and mass transfer rates of the absorber, regenerator, and membrane for



(a) Case 1. $R_m = 350$ s/m (b) Case 2. $R_m = 15000$ s/m

(c) Case 3. $R_m = 50000$ s/m (d) Case 4. $R_m = 100000$ s/m

Fig. 4. Dehumidification, regeneration, and mass transfer rate of each case.

each case for 1 h. The dehumidification and regenerator rates are estimated based on the effectiveness of each component. As dehumidification and regeneration occurred when the system operated, the difference in the solution concentration in each sump was high. Thus, the mass transfer rate gradually increased, as shown in Fig. 4. The water molecules can be transferred easily in case 1, which has a membrane with a low-mass-transfer resistance, compared with those with a high mass transfer resistance membrane.

The water transfer rate was related to the solution concentration in each sump, and the concentration of the solution was the main component to maintain the dehumidification and regeneration performance of the liquid desiccant system. In case 1, the mass transfer rate was sufficient to maintain the solution concentration in each sump of the proposed system. Thus, the dehumidification and regeneration rates were constant, as shown in Fig. 4 (a). The dehumidification and regeneration rates rapidly decreased in cases 3 and 4, as shown in Fig. 4 (c) and (d). This is because the concentration of the solution in each sump was not sufficient to satisfy the dehumidification and regeneration performance because the water molecules hardly transported. Fig. 4 (b) shows the middle resistance of the mass transfer, and the results showed a declining tendency with regard to the dehumidification and regeneration performance. Nevertheless, it can be used as a liquid desiccant system because the gradient of the decreasing dehumidification and regeneration rates is smoother than those in cases 3 and 4.

4.2. Heat transfer rate of each sump per hour

The heat transfer rates were predicted to compare the temperature of the solution in each sump under various mass transfer resistances of the membrane. Figs. 5 and 6 show the heat transfer rate based on the mass flow rate through the absorber, regenerator, and membrane in the absorber and regenerator sumps. Moreover, the heat transfer rate through the membrane for 1 h based on convection and conduction is shown in Figs. 5 and 6. The heat transfer rates are estimated based on the mass flow rate and temperature of the fluid. As the system operates, the variation in the solution temperature in each sump increases. Thus, the proportions of the heat transfer rate through the membrane ($\dot{Q}_{membrane}$) based on convection and conduction gradually increased, as indicated by the orange lines in Figs. 5 and 6. Moreover, the heat transfer rate based on the transfer of water molecules through the membrane increased with an increase in the number of water molecules transferred, as indicated by the light blue lines in Figs. 5 and 6.

Fig. 5 shows the heat transfer rate in the absorber sump under various mass transfer resistances of the membrane. The heat transfer rate based on the absorber inlet and outlet solutions is higher than the transfer rate based on the membrane, and it demonstrates similar values in cases 1, 2, 3, and 4. The heat transfer rate based on the transfer of the water molecules ($\dot{Q}_{w,\ membrane}$) increased as the mass transfer resistance decreased, which is caused by the increase in the number of water molecules transferred. Thus, the amount of heat transfer is maximum in case 1. Finally, the total variation in the heat in the absorber sump is maximum in case 1, and the change in the heat is minimum in case 4.

Fig. 6 shows the heat transfer rate in the regenerator sump under various mass transfer resistances of the membrane. The heat transfer rate in the regenerator sump is similar to that in the absorber sump, whereas the sign of the heat transfer with regard to the membrane is opposite. As the water molecules move from the absorber to the regenerator sump, the sign of heat transfer with regard to the water molecules is positive for the regenerator sump and negative for the absorber sump. The heat transfer through the membrane based on convection and conduction is a gain and loss for the absorber and regenerator sumps, respectively, because the temperature of

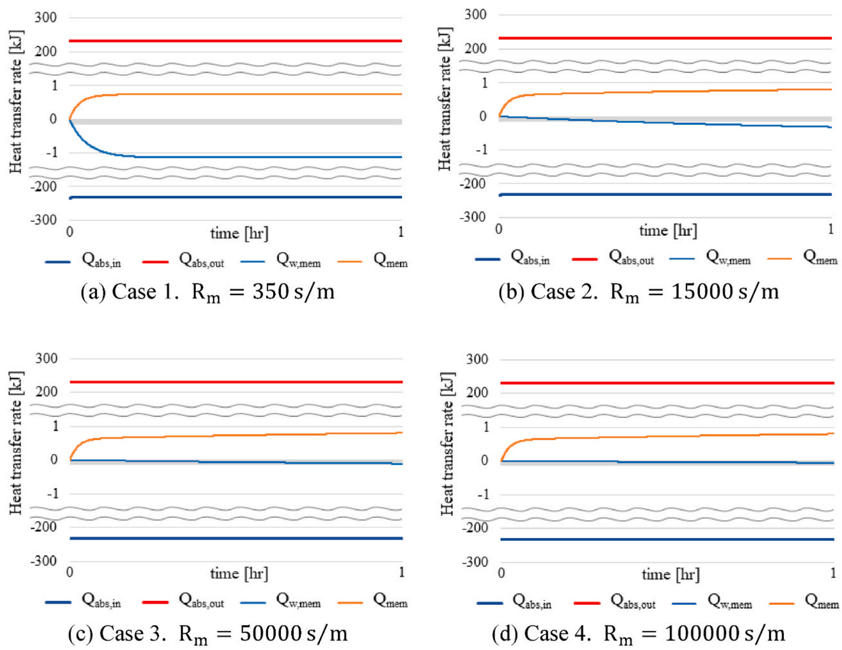


Fig. 5. Heat transfer rate of each case in the absorber sump.

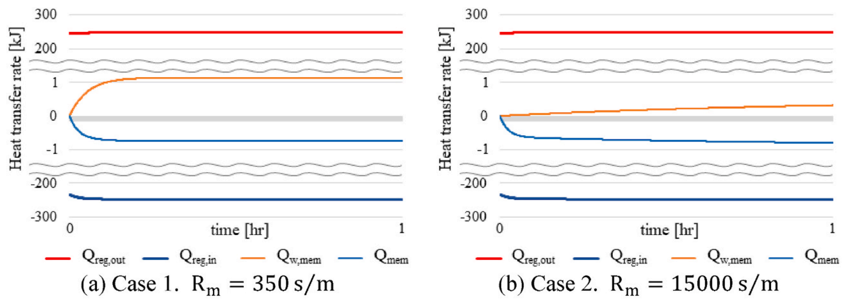


Fig. 6. Heat transfer rate of each case in the regenerator sump.

the solution in the regenerator sump is higher than that in the absorber sump. Consequently, the total variation in the heat in the regenerator sump is maximum in case 1, and the change in the heat is minimum in case 4.

4.3. Variation of the solution temperature and concentration in each sump

Fig. 7 illustrates the temperature and concentration of the solution in the sump according to the membrane resistance during the summer season. According to Fig. 7 (a), the solution temperature converges close to the set temperatures of the absorber and regenerator inlet solution (i.e., 20 °C for the absorber and 50 °C for the regenerator). As the mass transfer rate increases, the change in the total heat capacity of the absorber or regenerator sump increases, as described in Sections 4.1. and 4.2. Moreover, the temperature of the solution in the absorber and regenerator is related to the change in the total heat capacity of the absorber or regenerator sump. The temperature converges closer to the setting temperature because the impact on heat changes caused by the mass transfer rate is reduced. Thus, case 1 demonstrates a lower temperature in the regenerator sump and higher temperature in the absorber sump than the other cases (cases 2, 3, and 4) (Fig. 7 (a)).

The concentration of the solution in the sump according to the membrane resistance during the summer season is shown in Fig. 7 (b). The solution concentration is changed by the system operating under summer outdoor air conditions. As shown in Fig. 7 (b), the concentration of the solution in each sump is almost the same in case 1, whereas the difference in the concentration in each sump is significant in other cases. This is because the water molecule transfer rate converges on a balance point between the dehumidification and regeneration rates in case 1; however, in other cases, the water molecule transfer rate does not reach the balance point. Moreover, the difference in the solution concentration in each sump increases as the resistance of the membrane increases.

In the previous study [6,33], the liquid desiccant system operated in the range of 20%–40% concentration of the solution to

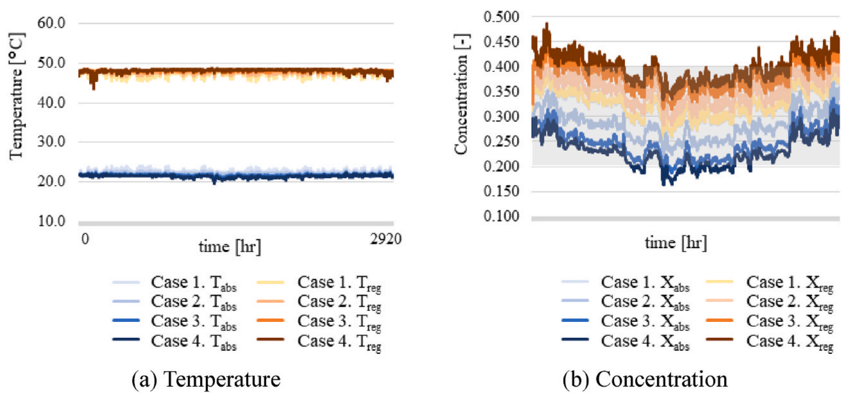


Fig. 7. Conditions of the solution in the sump of each case.

maintain the dehumidification and regeneration performance. The solution concentration of each sump is within the limit defined for the system operation in cases 1 and 2; however, it becomes difficult to maintain the concentration in cases 3 and 4. Thus, the high-resistance membrane disrupts the maintenance of the solution concentration, and a membrane with a mass transfer resistance of <15,000 s/m should be used in a liquid desiccant system.

5. Discussion

In this section, the energy-saving potential of the proposed system is discussed and compared with that of the conventional liquid desiccant dehumidification system during the summer season. A simulation was conducted based on the heat and mass transfer, sump analysis, and loads of the solution cooling and heating of the liquid desiccant dehumidification system.

5.1. Reference sys\tem

Fig. 8 shows a conventional liquid desiccant dehumidification system with solution exchange. The air and solution are dehumidified and regenerated in the absorber and regenerator, similar to the proposed liquid desiccant dehumidification system. The concentration of the solution in the absorber sump is diluted, and that in the regenerator sump becomes strong as the dehumidification and regeneration processes continue to be implemented.

To reduce the difference in the solution concentration in the two sumps, the solution exchange method is applied in the conventional liquid desiccant dehumidification system. The strong solution transfers from the regenerator sump to absorber sump at 1.5 L/min, and the weak solution transfers from the absorber sump to regenerator sump. The transfer rate of the strong solution is lower than that of the weak solution to maintain the solution level in each sump. Thus, the strong solution moves at a constant flow rate, and the weak solution transfers at a variable flow rate. Other operating conditions, such as the inlet solution temperature of the absorber and regenerator, initial solution concentration, and airflow rate, were the same as those of the proposed system.

5.2. Comparison of the load for each system

Fig. 9 (a) shows the mass flow rates of the proposed and reference systems. In the proposed system, the dehumidification, regeneration, and mass transfer rates through the membrane were similar. The mass transfer rate of each sump is higher than the dehumidification and regeneration rates of the reference system. This is because the water vapor is only transferred through the membrane in the proposed system, whereas the LiCl aqueous solution exchanges in the reference system.

As the mass transfer rate through the membrane is smaller than the solution exchange rate in the conventional system, the heat transfer rate of the proposed system is less than that of the conventional system. Thus, the solution temperature of the proposed system in the absorber sump is lower than that of the conventional system (Fig. 9 (b)). Moreover, the temperature of the solution in the regenerator in the proposed system is higher compared to the conventional system.

Owing to the difference in the flow rate in each system, the cooling and heating loads of the solution can be reduced in the proposed system compared with the reference system. Fig. 10 shows the detailed results of the load consumption during summer. The reference and proposed systems required 7.23 and 7.33 MWh and 5.84 and 5.92 MWh for the cooling and heating coils, respectively. Consequently, the proposed system with the membrane to maintain the solution concentration can save ~19% of the load over the reference system based on the solution exchange.

6. Conclusions

This study proposed a liquid desiccant dehumidification system with a membrane. The detailed heat and mass transfer analysis was conducted for various types of membranes to evaluate the applicability of a liquid desiccant dehumidification system while maintaining the solution concentration. The variation in the concentration of a solution and its temperature in the absorber and regenerator sumps were predicted during system operation.

The results show that the high-mass-transfer-resistance membrane (i.e., 100,000 s/m) cannot be used to maintain the solution concentration in each sump to meet the desired dehumidification and regeneration performance because the water vapor transfer rate is insufficient. Moreover, a membrane with a low-mass-transfer-resistance (i.e., 350 s/m) requires a large amount of heating and cooling load because the water transfer rate is considerably high. Therefore, the membrane with a mass transfer resistance of 15,000 s/m is suitable for the liquid desiccant dehumidification system. Moreover, the load of the cooling and heating coils with regard to the solution was compared to the conventional system. The proposed system can reduce the load by about 19% compared with the conventional system because the solution temperature in the proposed system reaches closer to target cooling and heating temperatures during the summer season.

There are several membranes of various thicknesses, heat transfer coefficients, and mass transfer resistances. This study evaluated the feasibility of the membrane and its energy benefits; however, it is necessary to demonstrate the performance of the proposed system through an experiment.

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Contribution statement

Soo-Jin Lee: Conceptualization, Methodology, Data curation, Writing – original draft. **Jae-Weon Jeong:** Supervision, Validation,

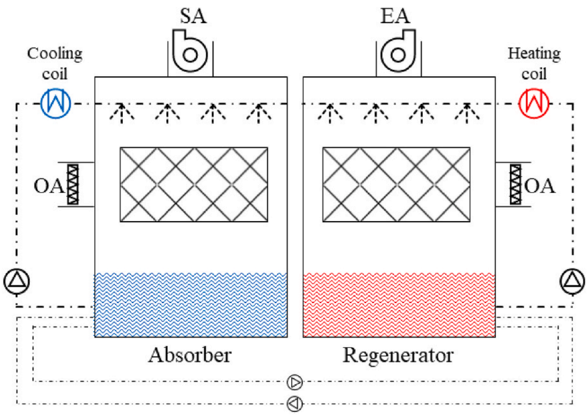

Fig. 8. Conventional liquid desiccant dehumidification system with solution exchange.

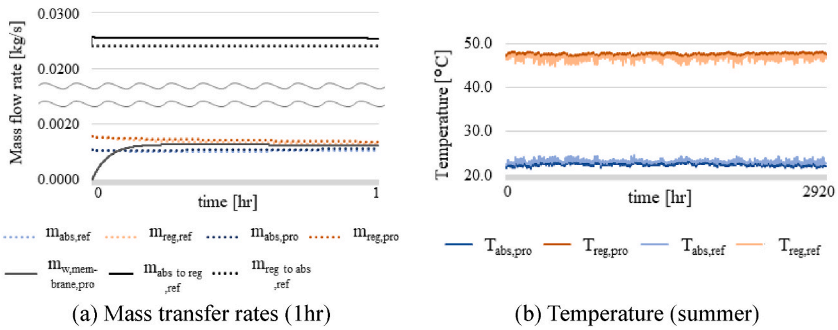

Fig. 9. Comparison of the performance of each system.

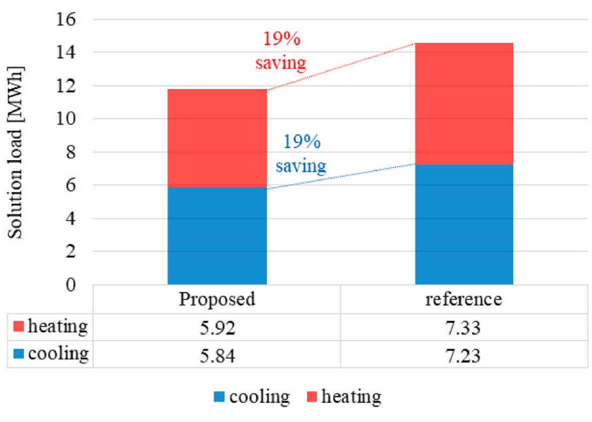

Fig. 10. Cooling and heating load of the solution of each system.

Writing – review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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