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Theoretical analysis of membrane based liquid desiccant air conditioning system

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Abstract

Air conditioning systems using liquid desiccant have been gaining attention due to their great energy-saving potential, but cooling and heating load for dehumidification and regeneration process remained a vital role in energy consumption. In this research, we proposed a membrane-based liquid desiccant air conditioning system, which is a vapor transportation driven system with gas separation membrane technology, and evaluated its thermodynamic performance by equation-based simulation. The proposed system has five components: an absorber, a regenerator, a membrane for dehydration, a membrane for hydration, and a vacuum compressor. The membranes were used to control solution concentration without heating and cooling; the water vapor separated by the membrane is transported from the dehydration solution to the hydration solution. The vacuum compressor operated to separate the water vapor from the solution and then transport the separated vapor to the membranes. The results showed that the ideal COP (coefficient of performance) of the proposed system in the thermodynamic analysis is 1.55, which is 5.17 higher than that of the conventional liquid desiccant (heat driven dehumidification and regeneration system), which is 0.3 COP at the design air.

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Keywords: Separation membrane, liquid desiccant air conditioning, Dehydration, Hydration

1. Introduction

The importance of humidity control in air-conditioning systems has increased as the ratio of sensible load to total air-conditioning load of a building has decreased dramatically due to improved building envelope thermal performance [1]. Decoupling the sensible and latent cooling functions of air conditioning has been suggested as a possible alternative to the typical condensation dehumidification technique. Several unique energy-efficient systems that can individually accommodate sensible and latent loads have been disclosed in the open literature [2].

One of these systems is the liquid-desiccant-assisted air-conditioning system [3, 4], in which the process air is dehumidified by a liquid-desiccant solution and then sensible cooling to the supply air's setpoint temperature. To improve the dehumidification performance, the concentrated desiccant solution should be cooled, and the diluted desiccant solution should be regenerated in the regenerator by heating. The heating and cooling of the desiccant solution are the most energy-intensive processes [5].

Numerous research have investigated the performance of various types of liquid desiccant systems to enhance the dehumidification performance. In the previous studies, air to liquid flow direction (i.e., cross flow, counter flow), has been investigated. Recently, internally-cooling [6] and heating [7] system was introduced to increase the system performance. Nevertheless, heating and cooling of the desiccant solution, which has high regeneration temperatures between 50 and 80 °C results in considerable energy consumption if free heat sources are unavailable [8, 9].

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In previous research, heat (heating and cooling) based liquid desiccant air conditioning system have been mainly conducted for evaluating energy performance; however, it is rare to evaluate the thermodynamic and energy performance using vacuum pressure driven liquid desiccant system. In this study, we proposed a novel system that uses dehydration and hydration in the liquid desiccant with separation membrane. The sensitivity of the operating conditions to the dehumidification performance of the proposed system was analyzed by numerical simulation. The energy performance of the proposed system was also evaluated by comparing the existing liquid dehumidification system (heating and cooling-based system) with design conditions.

2. System overview

2.1. System overview

Figure 1 depicts the five components of the proposed system: an absorber, a regenerator, a membrane for dehydration, a membrane for hydration, and a vacuum compressor. The membranes were utilized to regulate solution concentration without the use of heating and cooling; the water vapor separated by the membrane is delivered from the dehydration solution to the hydration solution. The vacuum compressor was used to separate the water vapor from the solution and transfer it to the membranes.

The diluted liquid desiccant solution leaving the absorber is preheated by the sensible heat exchanger and then hydrated by the hydration membrane, which make increase of the partial vapor pressure as decreasing solution concentration. The desiccant solution is regenerated in the regenerator, and the strong solution is precooled by the heat exchanger (HX). Finally, the supply air is dehumidified by the strong solution that is made by the dehydration membrane.

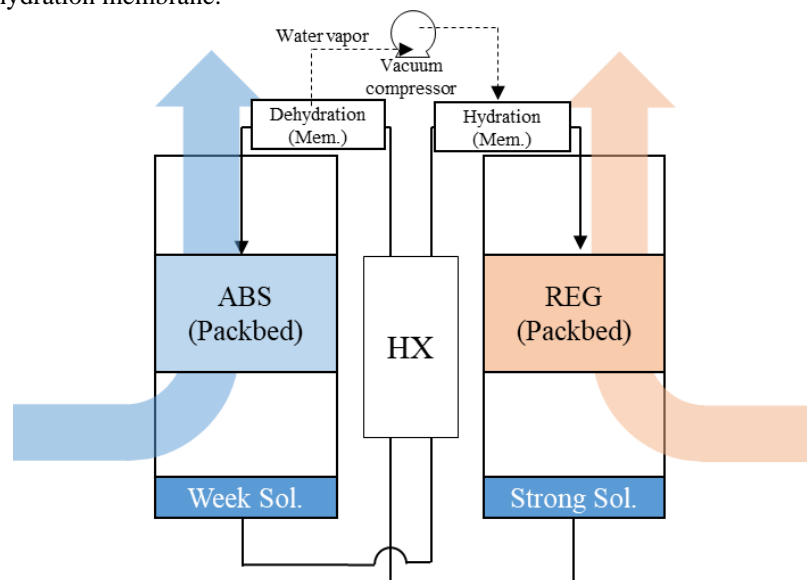


Fig. 1. Proposed system: Hydration/dehydration integrated liquid desiccant air conditioning system

Figure 2 showed the detailed configuration of the dehydration and hydration membrane (DHM) system used in the proposed system as a device for concentration control of the solution. The DHM consists of a dehydration membrane, a hydration membrane and a vacuum compressor. The dehydration and hydration membrane is separation membrane, which permeate the water vapor from solution because of the partial vapor difference between the feed-side (solution) and the permeate-side (vacuum) channels. When the week solution is introduced into the dehydration membrane, the water vapor in the dehydration membrane permeate to the vacuum compressor inlet. Then, the water vapor compressed by vacuum compressor permeate into strong solution in the hydration membrane.

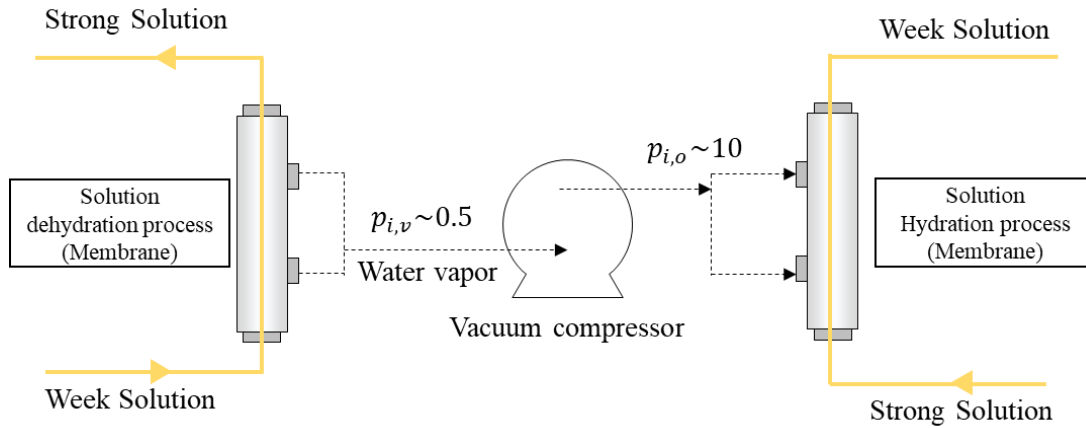


Fig. 2. Hydration and dehydration membrane

2.2. Reference system

As a reference system, a typical liquid desiccant-based air conditioning system consisting of an absorber, a regenerator, a cooling coil, a heating coil, and a liquid-to-liquid type sensible heat exchanger was chosen (Figure 3). In case of the reference system, the partial water vapor pressure of the diluted solution leaving the absorber and regenerated solution leaving the regenerator were controlled by varying the solution temperature. In an absorber, before hot, humid air and desiccant solution coincidentally cross the packing media, the desiccant solution is cooled by the cooling coil until the water vapor pressure of the desiccant solution is lower than that of the target supply air. The diluted desiccant solution leaving the absorber is then heated by the heating coil so that the water vapor pressure of desiccant solution is higher than the air introduced to the regenerator. The sensible heat exchanger pre-cools and pre-heats the regenerated and diluted solutions, which leads to reduction in solution heating and cooling loads.

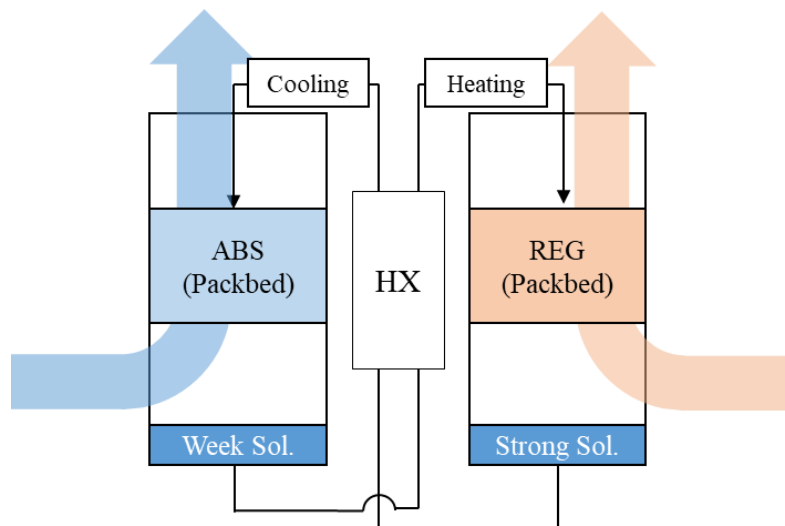


Fig. 3. Reference system: Cooling/heating coil based liquid desiccant air conditioning system

3. Simulation model

3.1. Numerical model of separation membrane: Dehydration and hydration

The process of dehydration and hydration in the membranes transfers the water vapor by the partial vapor pressure gradient between the feed and permeate sides as shown in Figure X. To estimate the mass transfer of the dehydration and hydration, the gas separation model with infinity selectivity for Water vapor was used as shown in Equation 1. The governing equation of the mass transfer driven by partial vapor gradient between membrane layers for each node. The change of the solution concentration along the membrane was estimated by mass balance equation (Equation 2), which address that the concentration change is driven by ratio of the permeated water vapor to the solution mass flow rate. As shown in Equation 3, the solution temperature change in the dehydration membrane is calculated by the evaporative cooling from desorption process of the membrane, whereas the solution temperature change in the hydration membrane is calculated by the condensation heating and air compressed heat from the vacuum compressor. To evaluate the partial vapor pressure of the solution, the desiccant solution model (Equation 4), which is driven by solution temperature and concentration was used.

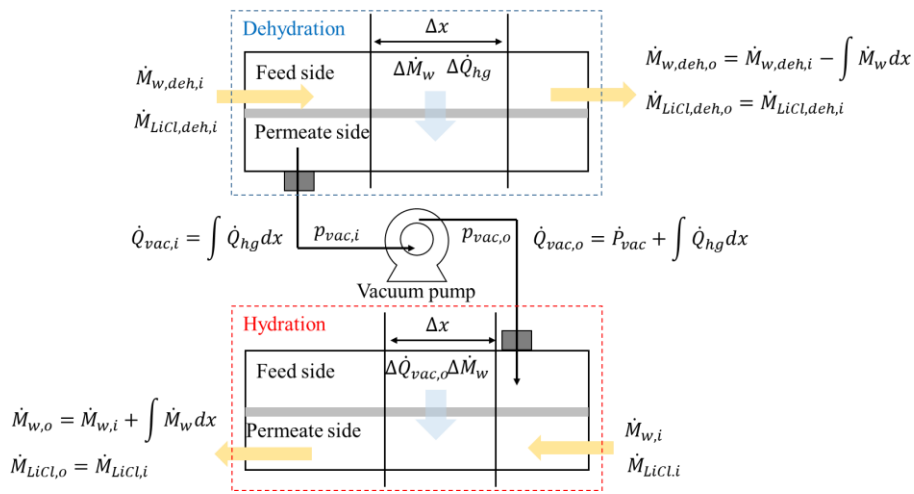


Fig. 4. Heat and mass balance of the dehydration and the hydration membrane

$$\Delta \dot{M}_{deh} = Permeance(p_{v,sol}^i - p_{vac})M_{mass}\Delta A \quad (1)$$

$$p_{v,sol}^i = f(T_{s,i}^i, X_{s,i}^i) \quad (2)$$

$$X_{s,i}^{i+1} = X_{s,i}^i / (1 - (1 + X_{s,i}^i)) \times (\Delta \dot{M}_{deh} / \dot{m}_{sol}) \quad (3)$$

$$T_{s,i}^{i+1} = T_{s,i}^i - (h_{fg}\Delta \dot{M}_{deh}) / (c_{p,sol}\dot{m}_{sol}) \quad (4)$$

3.2. Liquid desiccant

The temperature and concentration of the liquid desiccant at each point (i.e., inlet and outlet conditions at the absorber and regenerator) were calculated by using the empirical models predicting the dehumidification/regeneration effectiveness the absorber and regenerator.

The first model for the dehumidification effectiveness of the absorber ($\varepsilon_{abs,m}$) was derived by Chung and Luo [10]. As shown in Equation 5, this model was derived for the packed-bed type liquid desiccant dehumidifier using the seven variables – the inlet temperature of air ($T_{abs,i,a}$), inlet partial water vapor pressure of air ($p_{v,abs,i,a}$), inlet temperature of desiccant solution ($T_{abs,i,s}$), inlet partial water vapor pressure of solution

($p_{v,abs,i,s}$), mass flow rate of air ($\dot{m}_{abs,a}$), and mass flow rate of solution ($\dot{m}_{abs,s}$), and packing specific surface area (aZ). Based on the existing literature, it was assumed that the heat exchange effectiveness of the absorber ($\epsilon_{abs,T}$) between the air and solution was similar to the dehumidification effectiveness [11].

$$\epsilon_{abs,m} = \left(1 - \frac{0.024 \left(\frac{\dot{m}_{sa}}{\dot{m}_{abs,i,s}} \right)^{0.6} \cdot \exp\left(1.057 \frac{T_{abs,i,a}}{T_{abs,i,s}}\right)}{(aZ)^{-0.185} \left(\frac{p_{v,abs,i,a} - p_{v,abs,i,s}}{p_{v,abs,i,a}} \right)^{0.638}} \right) \left/ \left(1 - \frac{0.192 \cdot \exp\left(0.615 \frac{T_{abs,i,a}}{T_{abs,i,s}}\right)}{\left(\frac{p_{v,abs,i,a} - p_{v,abs,i,s}}{p_{v,abs,i,a}} \right)^{-21.498}} \right) \right. = \frac{\omega_{abs,i,a} - \omega_{abs,o,a}}{\omega_{abs,i,a} - \omega_{abs,eq,s}} \quad (5)$$

$$\epsilon_{abs,T} = \frac{T_{abs,i,a} - T_{abs,o,a}}{T_{abs,i,a} - T_{abs,i,s}} \quad (6)$$

As for the empirical model of the regenerator, the model established by the Martin and Goswami [12] was used in this study (Equation 7). As shown in Equation 8, the regeneration effectiveness ($\epsilon_{reg,m}$) is predicted by using five parameters – enthalpy of inlet air ($h_{reg,i,a}$), enthalpy of inlet desiccant solution, mass flow rate of air ($\dot{m}_{reg,a}$), and mass flow rate of solution ($\dot{m}_{reg,s}$), and packing specific surface area (aZ). Identical to the absorber, the thermal effectiveness of regenerator was assumed to be similar to the regeneration effectiveness.

$$\epsilon_{reg,m} = 1 - 48.3 \left(\frac{\dot{m}_{reg,a}}{\dot{m}_{reg,s}} \right)^{(0.396(\gamma_L/\gamma_c) - 1.57)} \left(\frac{h_{reg,i,a}}{h_{reg,i,s}} \right)^{-0.751} (aZ)^{(0.0331(\gamma_L/\gamma_c) - 0.906)} = \frac{\omega_{reg,o,a} - \omega_{reg,i,a}}{\omega_{reg,i,s} - \omega_{reg,i,a}} \quad (7)$$

$$\epsilon_{reg,T} = \frac{T_{reg,o,a} - T_{reg,i,a}}{T_{reg,eq,a} - T_{reg,i,a}} \quad (8)$$

The equilibrium humidity ratio of desiccant solution, which determines the ideal maximum humidity ratio variance between the process air and the desiccant solution, was obtained by Equation (9).

$$\omega_{eq,s} = 0.622 \cdot \frac{p_{v,s}}{101.325 - p_{v,s}} \quad (9)$$

4. Results

4.1. Parametric analysis of the separation membrane: mass transfer of the water vapor

In order to estimate the dehumidification performance of dehydration and hydration of the membrane, the effect of mass transfer was evaluated by varying the desiccant solution conditions. Parametric analysis was performed by solution temperature, solution concentration, and liquid to gas ratio in the dehydration and the hydration side. The base case of the solution in the dehydration and the hydration side set to 20 °C, 20%, and 0.01 of liquid to gas ratio. The compression ratio of the vacuum compressor was set to 10. Range of each parameter was set 10 °C to 40 °C (temperature), 10% to 40% (concentration), and 0.0025 to 0.16 (liquid to gas ratio).

In the Figure 5 (a) to (c), as the dehydration solution changes, the solution temperature and concentration have the greatest effect. As the temperature of the solution increases and the concentration of the solution decreases, the partial pressure of water vapor in the solution increases. As the temperature changes, the partial pressure of water vapor in the steam solution rises from 0.84 kPa to 5.12 kPa, and as the concentration changes, the partial pressure of water vapor decreases from 2.08 kPa to 0.41 kPa. Therefore, it can be confirmed that the mass transfer increases as the driving force between the membranes increases.

In the Figure 5 (d) to (f), the solution temperature and concentration have the greatest effect as solution changes in the hydration membrane. When the water vapor partial pressure of the solution increases, the water vapor partial pressure difference (driving force) between the membranes decreases, and thus the overall mass transfer of the proposed system decreases. As the temperature changes, the partial pressure of water vapor in the steam solution rises from 0.84 kPa to 3.89 kPa, and as the concentration changes, the partial pressure of water vapor decreases from 5.12 kPa to 0.41 kPa. The effect of solution of hydration was lower than that of

solution of dehydration, which shows that the effect of water permeation in hydration is greater than the effect of water permeation of dehydration.

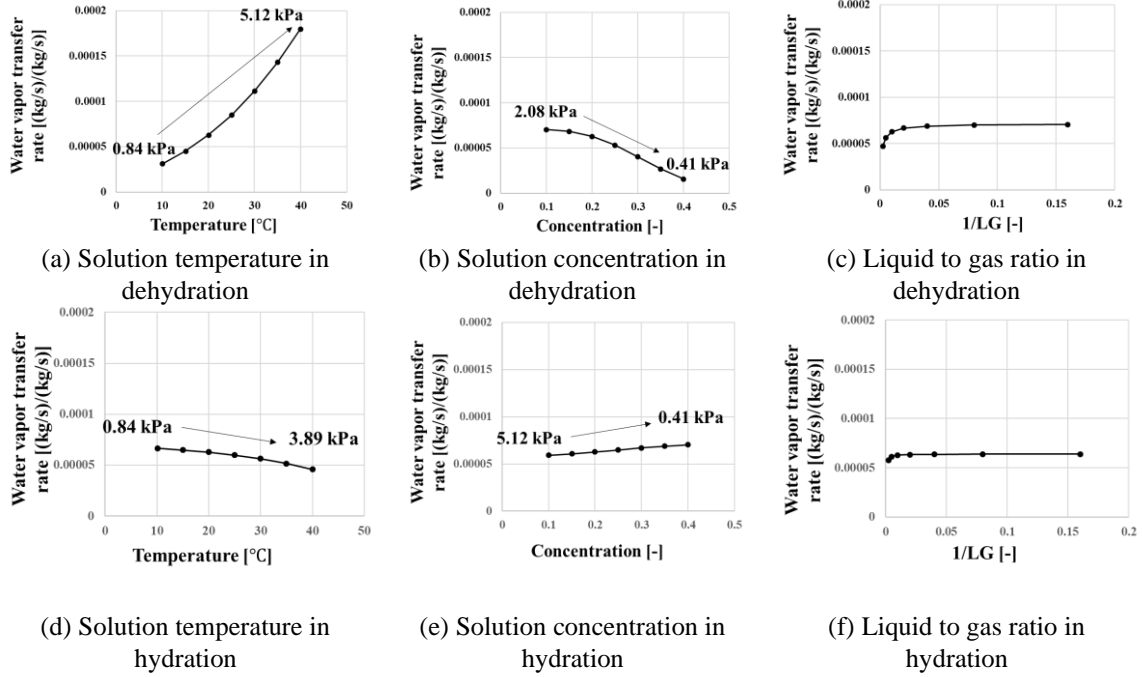


Fig. 5. Effect of water vapor transfer rate

4.2. Performance evaluation: COP

For the performance evaluation of the proposed system, the thermodynamic changes of the existing system, heat demand and solution were confirmed. (Figure 6) The design air condition of the absorber and regeneration was set to 32 °C and 60%, and LG was assumed to be 1. The solutions of the reference system were 25 °C and 35% (Absorber) and 58 °C and 34.5% (Regeneration) respectively, and the proposed system reference system solutions were 25 °C and 35% (Absorber) and 63 °C and 33.5% (Regeneration) respectively.

As shown in Equation 10, in the reference system, the enthalpy change of the absorber was 27.96 kJ/kg (120.2 kJ/kg to 92.24 kJ/kg), and the enthalpy change of heating and cooling was 54.7 kJ/kg and 36.66 kJ/kg, respectively. The COP of the reference system is 0.3.

On the other hand, in the proposed system, the absorber's enthalpy change was 27.96 kJ/kg (120.2 kJ/kg to 92.24 kJ/kg) as in the reference system. As shown in Equation 11, The power of the vacuum pump can be expressed as the enthalpy change of hydration and the enthalpy change of dehydration, and was 54.7 kJ/kg (hydration) and 36.66 kJ/kg, respectively. Therefore, the power of the vacuum pump at unit mass flow rate (1 kg/s) is 18.04 kW/(kg/s). The COP of the proposed system is 1.55. The results showed that the ideal COP (coefficient of performance) of the proposed system in the thermodynamic analysis is 5.17 higher than that of the conventional system.

$$COP_{Ref} = \frac{Q_{a,c}}{Q_{h,s} + Q_{c,s}} \quad (10)$$

$$COP_{Ref} = \frac{Q_{a,c}}{P_{vac}} = \frac{Q_{a,c}}{Q_{Hyd} - Q_{dehyd}} \quad (11)$$

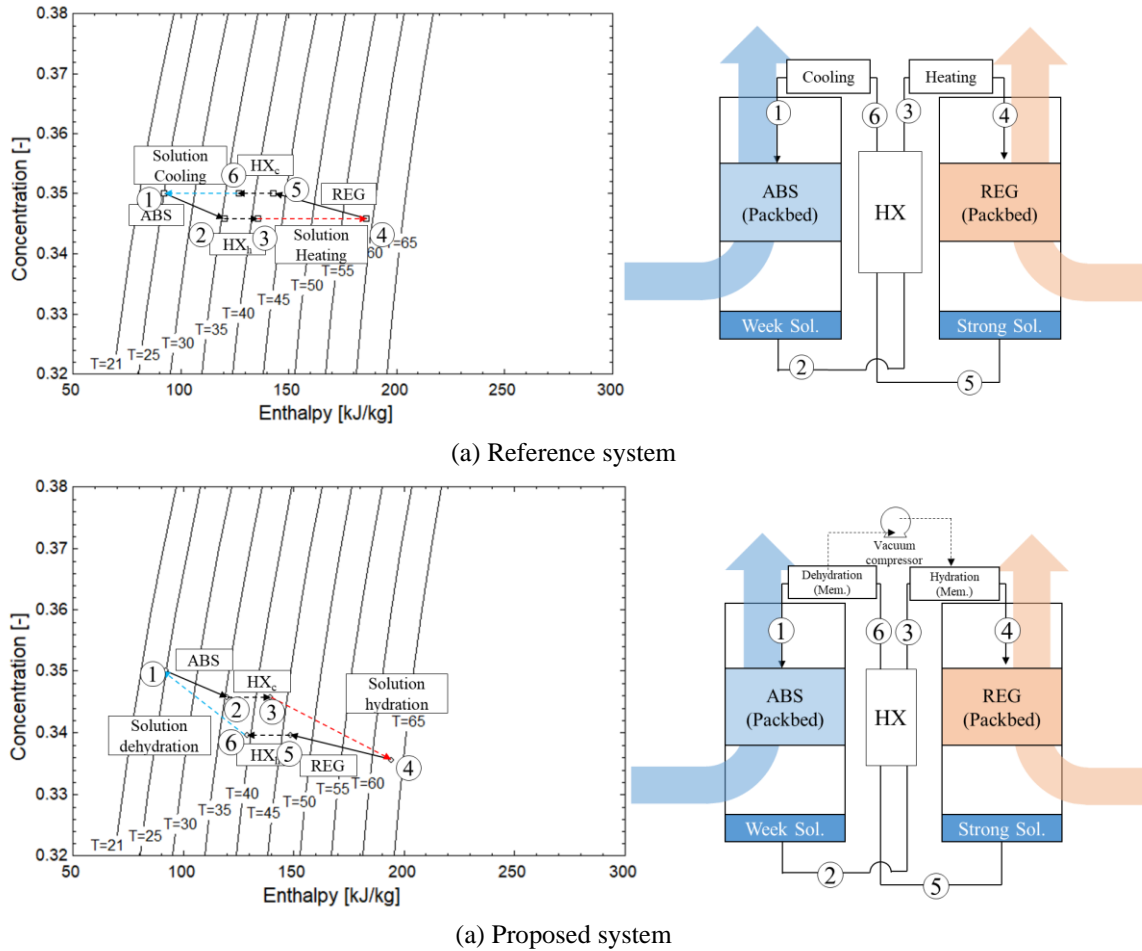


Fig. 6. Thermodynamic characteristic of desiccant solution in the systems

5. Conclusion

In this research, a membrane-based liquid desiccant air conditioning system, which is a vapor transportation driven system with gas separation membrane technology, was proposed and its thermodynamic performance (dehumidification and energy performance) evaluated by equation-based simulation.

The parametric study of the proposed system for dehumidification performance (mass transfer) showed that the solution temperature and concentration is mainly affected as driving force. Especially, the mass transfer of the dehydration membrane side is more affected than that of the hydration membrane side on dehumidification performance. The vacuum compressor operated to separate the water vapor from the solution and then transport the separated vapor to the membranes. The results showed that the ideal COP (coefficient of performance) of the proposed system in the thermodynamic analysis is 1.55, which is 5.17 higher than that of the conventional liquid desiccant (heat driven dehumidification and regeneration system), which is 0.3 COP at the design air condition. This study demonstrates the thermodynamic analysis of the proposed system in simple principles. In further studies, we will construct a prototype unit of proposed system, and experimentally analyze the effect of thermodynamic and energy performance of the proposed system.

Acknowledgements

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