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COP Evaluation for a Membrane Liquid Desiccant Air Conditioning System Using Four Different Heating Equipment

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***Abstract* – Liquid desiccant air conditioning (LDAC) is a promising technology in terms of energy efficiency, comfort and indoor air quality. The major components of a LDAC system are the dehumidifier and regenerator. The most commonly used design of dehumidifiers/regenerators is the packed-bed, which might result in the entrainment of desiccant droplets in air streams. A promising solution for the entrainment of desiccant droplets in air streams is to use a liquid-to-air membrane energy exchanger (LAMEE) as the dehumidifier/regenerator. A membrane LDAC system, which uses two LAMEEs as the dehumidifier and regenerator, is investigated in this paper.**

The operation of a LDAC system requires the continuous supply of heating and cooling energy to the desiccant solution. In this study, the COPs of four membrane LDAC systems are evaluated when four different heating equipment are used to provide the solution heating loads as follows: a gas boiler, a solar thermal system, a heating heat pump, and the condenser of a solution cooling heat pump. The COPs of the four systems studied are evaluated under wide ranges of six design/operating parameters as follows: ambient air temperature (T_{amb}) and humidity ratio (W_{amb}), number of heat transfer units (NTU), solution-to-air heat capacity ratio (Cr^*), and solution inlet temperatures to dehumidifier ($T_{sol,deh,in}$) and regenerator ($T_{sol,reg,in}$).

TRNSYS and CYCLE_D programs are used in this paper to simulate the performances of different systems studied. Results show that the membrane LDAC system which uses a single heat pump to provide the solution heating and cooling loads is the most promising among the systems studied.

***Keywords* – Desiccant cooling, humidity control, heat pump, membrane energy exchanger.**

I. INTRODUCTION

Liquid desiccant air conditioning (LDAC) is a promising air conditioning technology. Compared to conventional air conditioning systems, LDAC systems can be more energy efficient due to their ability to dehumidify humid air without overcooling the air below its dew point temperature.

As shown in Fig. 1, the core components of a liquid desiccant cycle are: a dehumidifier, a regenerator, cooling equipment, and heating equipment. The processes take place in a given LDAC system are as follows. Hot-humid air enters the dehumidifier, where moisture transfers from the air stream to a cold-concentrated desiccant solution stream. The desiccant solution leaves the dehumidifier at a higher concentration than its inlet condition, and thus it should be regenerated prior being reused in the dehumidifier. The regeneration of the diluted desiccant solution takes place in a regenerator, where water vapor transfers from the diluted desiccant solution stream to a regeneration air stream. In order to ensure that water vapor transfers from the diluted solution stream to the regeneration air stream and not vice versa, the surface vapor pressure of the diluted solution should be higher than the vapor pressure of the regeneration air. Thus, the diluted solution is heated prior entering the regenerator to a specific set point temperature, which ensures that the aforementioned condition is met. The concentrated desiccant solution leaving the regenerator is warm and has high surface vapor, and it has to be cooled to a specific set point temperature in order to reduce its surface vapor pressure below the vapor pressure of the hot-humid air required to be dehumidified. Thus, the warm-concentrated solution leaving the regenerator is cooled to a specific temperature, which ensures that the aforementioned condition is met.

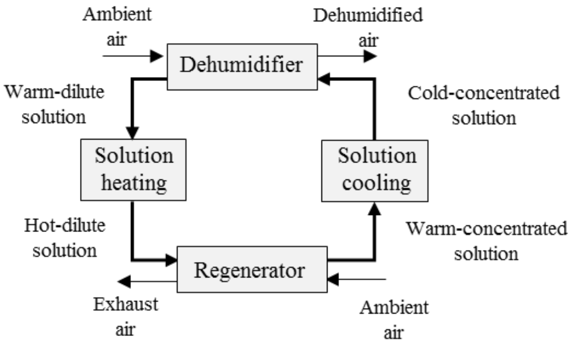

Fig. 1. Basic components of a LDAC system [1].

Packed-bed dehumidifiers/regenerators have been used in several previous studies about LDAC systems, which is mainly attributed to the simple design of a packed-bed. Although the packed-bed design has a promising performance in terms of heat and mass transfer [2], it might result in the entrainment of desiccant droplets in air streams. The carryover of desiccant droplets in air streams might lead to indoor chemical pollution and has limited the wide spread of LDAC technology in residential/commercial applications. A promising solution for the entrainment of desiccant droplets in air streams is to use a liquid-to-air membrane energy exchanger (LAMEE) as the dehumidifier/regenerator. In a LAMEE, air and solution streams are separated using semi-permeable membranes as shown in Fig. 2. These membranes allow the transfer of moisture but do not allow the transfer of any liquid droplets. Previous studies have showed that membrane LDAC systems, which use LAMEEs as the dehumidifier and regenerator, have

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promising performances [1-8]. Thus, a membrane LDAC system is studied in this paper.

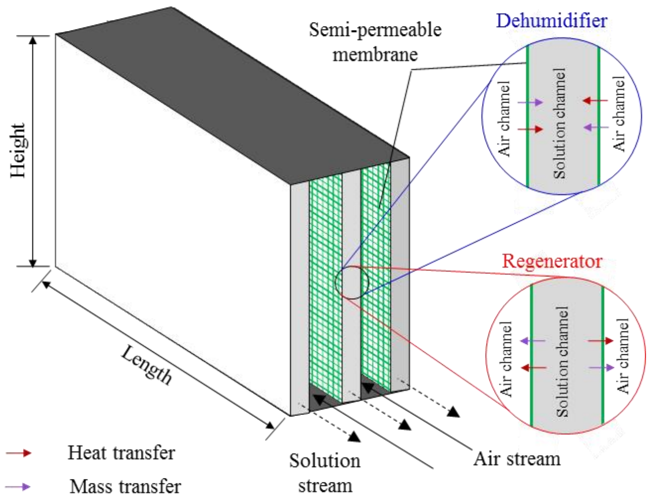

Fig. 2. A schematic for a liquid-to-air membrane energy exchanger (LAMEE) [1].

A variety of heating and cooling equipment can be used in a given LDAC system to cover solution heating and cooling loads, respectively. In this study, four membrane LDAC systems are investigated, where solution cooling loads are covered in all the systems studied using cooling heat pumps, while solution heating loads are covered using different heating equipment as follows: a gas boiler, a heating heat pump, a solar thermal system with a gas boiler back up, and the condenser of the solution cooling heat pump (i.e. hybrid heat pump). Parametric studies are conducted to evaluate the influences of six key design/operating parameters on the performances of the systems. The performances of the four membrane LDAC systems studied are simulated using TRNSYS and CYCLE_D programs.

II. SYSTEMS DESCRIPTION AND MODELLING

Fig. 3 shows schematic diagrams for the four membrane LDAC systems investigated in this study. The specifications of the LAMEEs and heat pumps are given in [1]. The performances of the membrane LDAC systems are evaluated in this study using TRNSYS and CYCLE_D models developed in [1; 3-5]. The four membrane LDAC systems studied have the same design and the solution cooling loads are covered in all of them using a cooling heat pump. Four heating equipment are used to cover the solution heating loads as follows:

- A gas boiler (see Figure 3(a));
- A solar thermal system with a gas boiler backup (see Figure 3(b));
- A heating heat pump (see Figure 3(c)), and
- The condenser of the solution cooling heat pump (see Figure 3(d)).

A constant boiler efficiency of 95% was assumed because the solution inlet temperature to the boiler lies between 34ºC and 45ºC under all the conditions investigated in this study. According to the 1996 ASHRAE Handbook: *HVAC Systems and Equipment* [9], the boiler efficiency remains nearly equal to 95% for this temperature range. The solar thermal system is assumed to only cover 76% of solution heating energy. This assumption is based on a study by Abdel-Salam et al. [4], which shows that the optimum life cycle cost for a solar membrane LDAC system with a gas boiler backup was achieved when the solar thermal system was sized to cover 76% of the solution heating energy.

The hybrid heat pump, which simultaneously covers the solution heating and cooling loads, includes an auxiliary evaporator and auxiliary condenser in order to match the capacities of the evaporator and condenser with the solution heating and cooling loads, respectively. The air flow rates through the auxiliary evaporator and auxiliary condenser are adjusted to reject any extra condensing or evaporating heat not needed by the solution. This results in the operation of the hybrid heat pump under one of three operating conditions as follows:

- Auxiliary evaporator mode: the capacity of condenser matches the solution heating load, while the capacity of evaporator is greater than the solution cooling load.
- Auxiliary condenser mode: the capacity of evaporator matches the solution cooling load, while the capacity of condenser exceeds the solution heating load.
- Matched capacity mode: the capacities of condenser and evaporator match the solution heating and cooling loads.

A recent study by Abdel-Salam and Simonson [1] presents more details about the performance and operating modes of a hybrid heat pump in a membrane LDAC system.

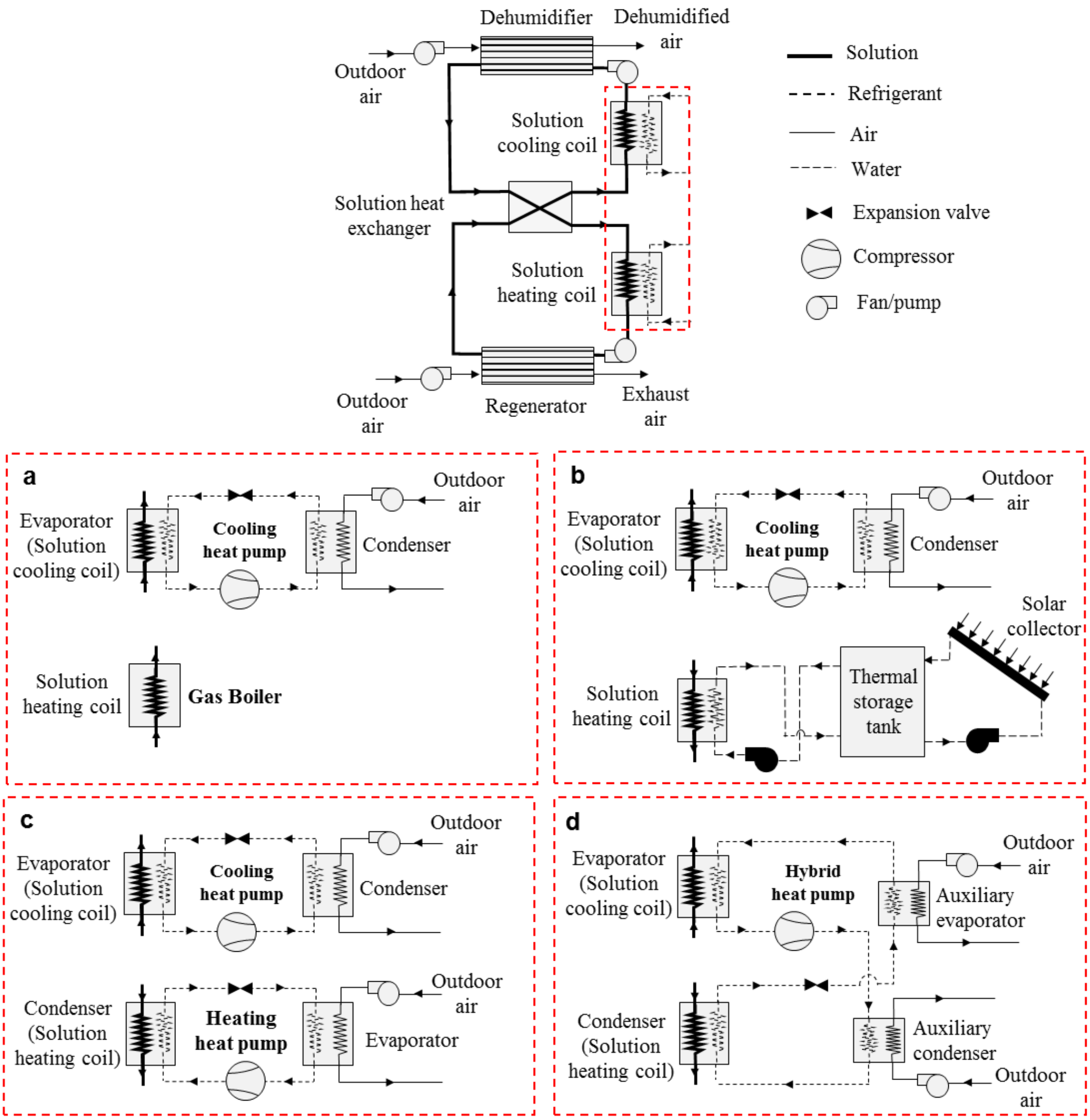

Fig. 3. Schematic diagrams for the four membrane LDAC systems studied with different solution heating equipment: (a) a gas boiler, (b) a solar thermal system with gas boiler backup, (c) a heating heat pump, and (d) the condenser of the cooling heat pump.

III. Results and Discussions

The performances of the four membrane LDAC systems are presented in this section in terms of their coefficients of performance (COPs). In addition, the COPs of the cooling, heating and hybrid heat pumps are evaluated. A parametric study is conducted under wide ranges of six design/operating parameters as follows: ambient air temperature (T_{amb}) and humidity ratio (W_{amb}), solution inlet temperature to dehumidifier ($T_{sol,deh,in}$) and regenerator ($T_{sol,reg,in}$), number of heat transfer units (NTU), and solution-to-air heat capacity ratio (Cr^*). Table I shows the reference value and variation range for each of the aforementioned design/operating parameters.

TABLE 1

REFERENCE VALUES AND INVESTIGATED RANGES FOR THE SIX DESIGN/OPERATING PARAMETERS STUDIED.

Parameter	Reference	Min	Max	Increment
$T_{sol,deh,in}$ [ºC]	20	14	26	2
$T_{sol,reg,in}$ [ºC]	50	41	59	3
T_{amb} [ºC]	35	26	41	3
W_{amb} [g/kg]	17.5	10	25	2.5
NTU	5	1	13	2
Cr^*	4	2	6	1
Air flow rate [kg/s]	0.31	-	-	-

Fig. 4 shows the influences of ambient air temperature (T_{amb}) and humidity ratio (W_{amb}) on the performances of the four membrane LDAC systems. Figs. 4(a) and 4(b) show that the COP of the system which uses a hybrid heat pump is higher than the COPs for the other systems studied under the entire range of W_{amb} and high values of T_{amb}. While at low T_{amb}, the COP of the solar membrane LDAC system is higher than the COP of the membrane LDAC system which uses a hybrid heat pump.

The COPs of the heating and cooling heat pumps experience more significant variations with T_{amb} than the COP of the hybrid heat pumps as shown in Fig. 4(c). This is because the condensing and evaporating temperatures of the cooling and heating heat pumps increase with the increase of T_{amb}. On the other hand, the condensing and evaporating temperatures of the hybrid heat pump remain almost constant with T_{amb} because they are dependent on the solution inlet temperatures to the dehumidifier ($T_{sol,deh,in}$) and regenerator ($T_{sol,reg,in}$) which only slightly change with T_{amb}. The operating mode of the hybrid heat pump changes from the auxiliary evaporator mode to the auxiliary condenser mode when T_{amb} becomes equal to or greater than 32°C. This results in the observed trends for the COPs of the membrane LDAC system which uses a hybrid heat pump.

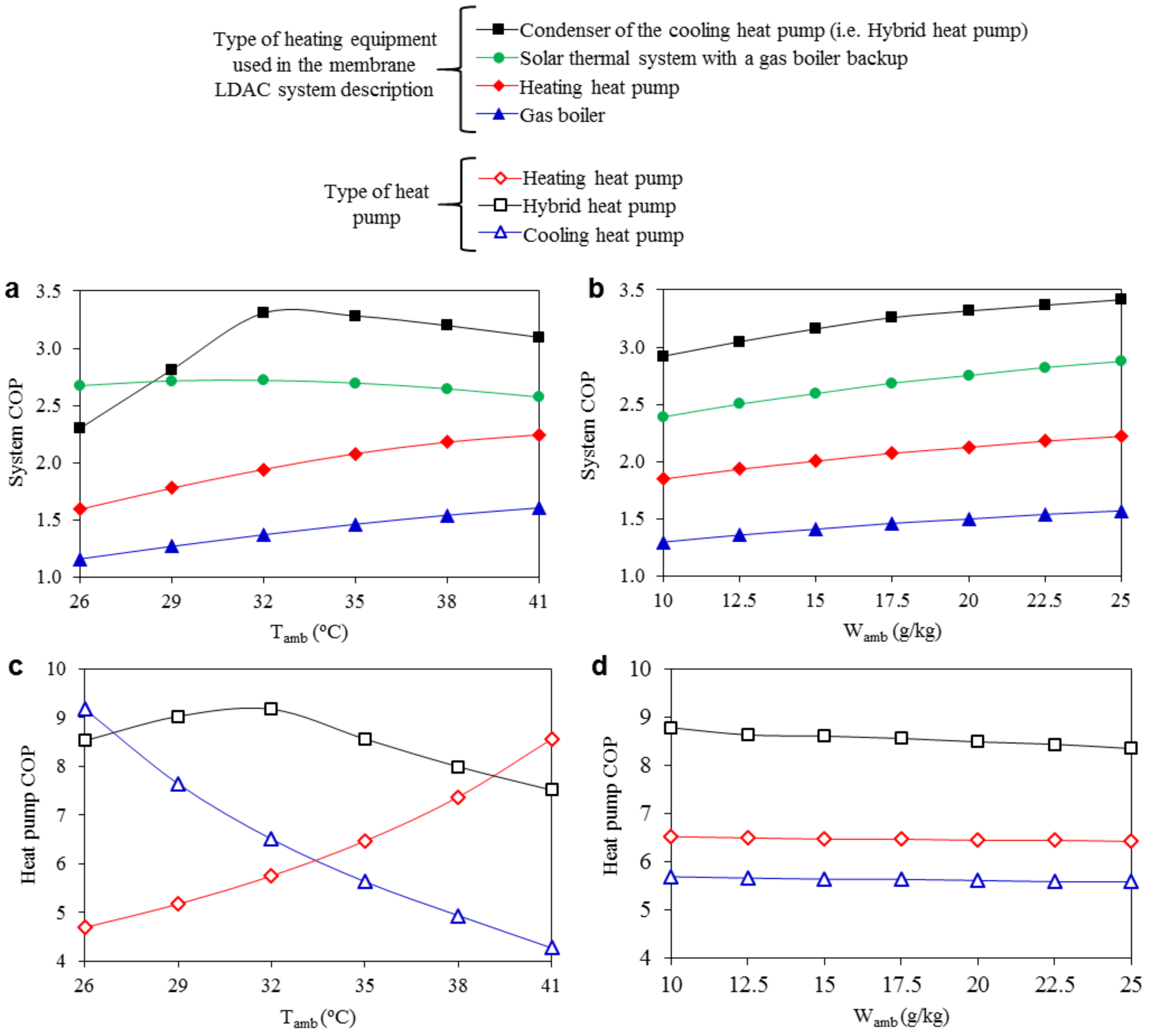

Fig. 4. The influences of ambient air temperature (T_{amb}) and humidity ratio (W_{amb}) on the COPs of the four membrane LDAC systems and the COPs of cooling, heating and hybrid heat pumps.

Fig. 4(d) shows that the COPs of the cooling and heating heat pumps remain nearly constant under the entire range of W_{amb} studied. Similarly, the COP of the hybrid heat pump remains nearly constant with the increase of W_{amb}. This is because the increase of W_{amb} increases both the solution heating and cooling loads, as well as compressor power of the heat pumps by similar rates. Also, the condensing and evaporating temperatures remains nearly constant with the increase of W_{amb}.

Fig. 5 shows the influences of the solution-to-air heat capacity ratio (Cr^*) and number of heat transfer units (NTU) on the performances of the four membrane LDAC systems. As shown in Figs. 5(a) and 5(b), the COPs of the four membrane LDAC systems decrease and increase with the increase of Cr* and NTU, respectively. The COP of the system which uses a hybrid heat pump is the highest compared to the other systems studied, followed by the system which uses solar thermal energy. Figs. 5(c) and (d) show that COPs of the cooling, heating and hybrid heat pumps are slightly influenced by Cr* and NTU, with more significant influence in the hybrid heat pump.

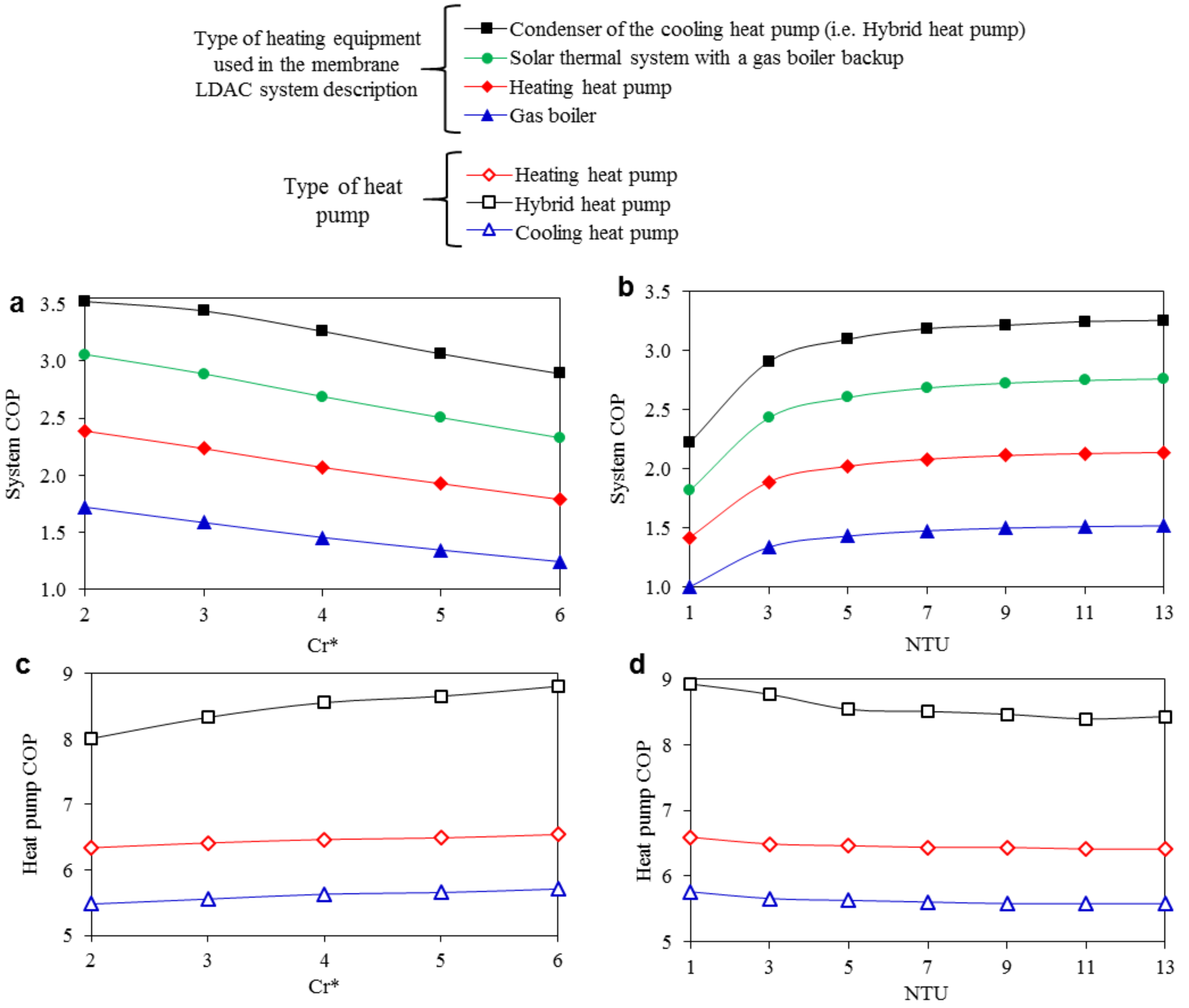

Fig. 5. The influences of solution-to-air heat capacity ratio (Cr*) and number of heat transfer units (NTU) on the COPs of the four membrane LDAC systems and the COPs of cooling, heating and hybrid heat pumps.

It is worth mentioning that the change in the solution temperature as it passes through the dehumidifier and regenerator varies with Cr* and NTU. For instance, the higher the Cr*, the lower the variation in the solution temperature as it passes through the dehumidifier and regenerator, which results in the decrease of the condensing temperature and the increase of evaporating temperature (i.e. decrease of temperature lift of the heat pump). The change in temperature lift, accompanied with the change of the cooling capacity and the solution heating and cooling loads, result in the aforementioned variation in the COPs. The COP of the hybrid heat pump is the most influenced because the aforementioned variation in solution temperatures simultaneously affects the evaporating and condensing temperatures of the hybrid heat pump, and thus has large influence on its temperature lift. On the other hand, only the evaporating temperature of the cooling heat pump is affected and only the condensing temperature of the heating heat pump is influenced, and thus there temperature lifts do not vary significantly.

The influences of solution inlet temperatures to dehumidifier ($T_{sol,deh,in}$) and regenerator ($T_{sol,reg,in}$) on the performances of the four membrane LDAC systems are presented in Fig. 6. As shown in Figs. 6(a) and 6(b), the COP of the system which uses a hybrid heat pump is the most influenced by $T_{sol,deh,in}$ and $T_{sol,reg,in}$ compared to the other systems studied. The higher $T_{sol,reg,in}$, the lower its COP, and vice versa with $T_{sol,deh,in}$. The

COP of the system which uses a hybrid heat pump remains higher than the COPs of the other systems under the entire range of $T_{sol,deh,in}$ and low values of $T_{sol,reg,in}$, while the COP of the system which uses solar thermal energy becomes the highest at high $T_{sol,reg,in}$.

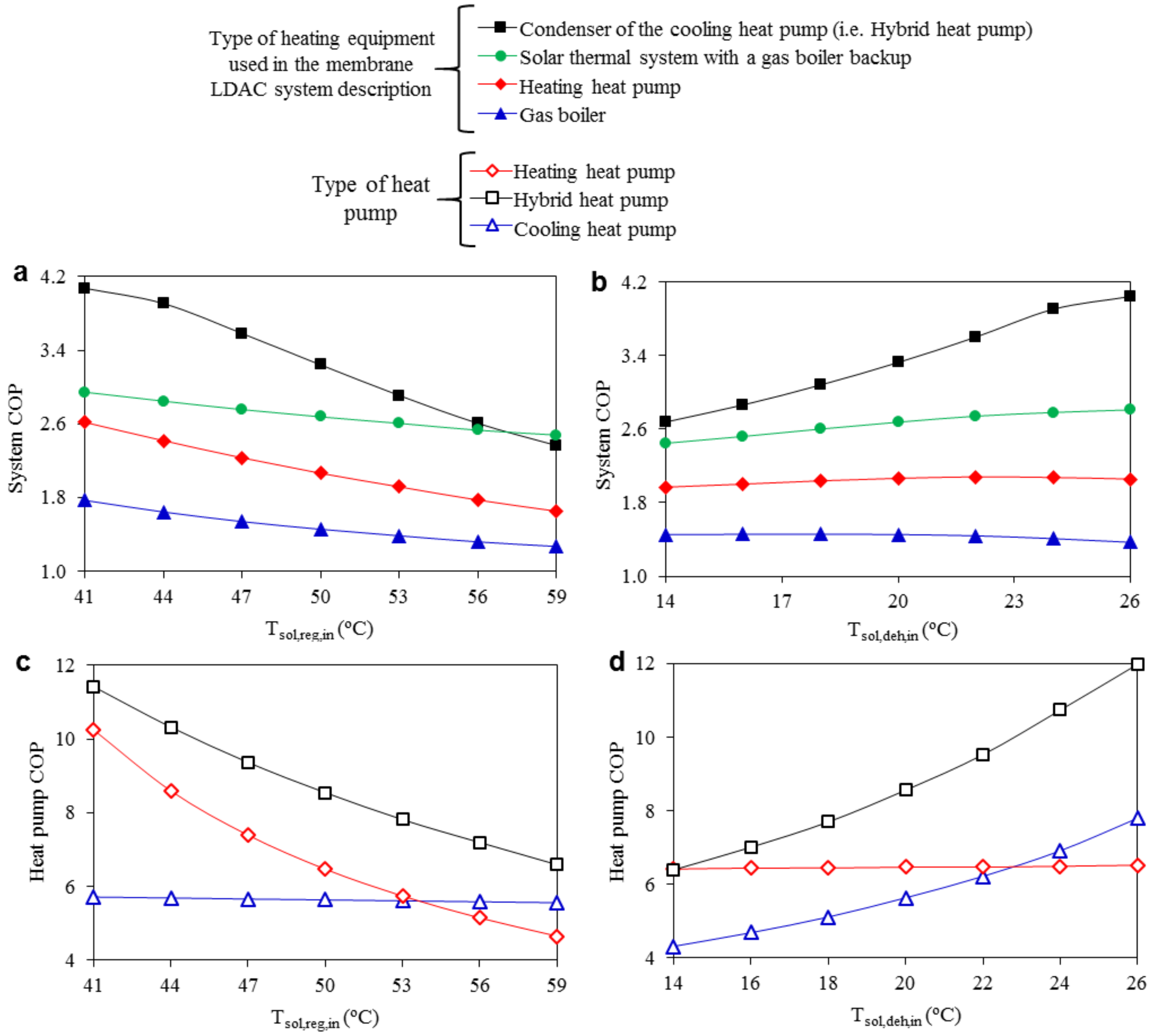

Fig. 6. The influences of solution inlet temperatures to the dehumidifier ($T_{sol,deh,in}$) and regenerator ($T_{sol,reg,in}$) on the COPs of the four membrane LDAC systems and the COPs of cooling, heating and hybrid heat pumps.

Fig. 6(c) shows that COPs of the heating and hybrid heat pumps decrease with the increase of $T_{sol,reg,in}$, and the COP of the cooling heat pump remains nearly constant. While Fig. 6(d) shows that the COPs of the cooling and hybrid heat pumps increase with the increase of $T_{sol,deh,in}$, and the COP of the heating heat pump remains nearly constant. The observed variations in the COPs are because $T_{sol,reg,in}$ and $T_{sol,deh,in}$ have significant influences on the condensing and evaporating temperatures, respectively, as well as on the cooling capacity and the solution heating and cooling loads

IV. CONCLUSIONS AND FUTURE WORK

The COP of four membrane LDAC systems are evaluated in this paper under wide ranges of six key design/operating parameters. The dehumidifiers and regenerators in the membrane LDAC systems studied are liquid-to-air membrane energy exchangers (LAMEEs), which are characterized by their ability to eliminate the problem of desiccant droplets carryover in air streams. The solution cooling loads are covered in the four systems studied using cooling heat pumps, while four different equipment are used to cover solution heating loads as follows: a gas boiler, a solar thermal system with a gas boiler backup, a heating heat pump, and the condenser of the cooling heat pump (i.e. hybrid heat pump). TRNSYS and CYCLE_D programs are used to evaluate the COPs of the systems studied.

The use of a gas boiler to cover the solution heating loads is not recommended as it results in low COP for the membrane LDAC systems in the range of 1.0 to 1.8. The performance of the membrane LDAC system improves when a heating heat pump is used compared to when a gas boiler is used, where the COP increases to the range of 1.4 to 2.6. The solar membrane LDAC system has high COPs in the range of 1.8 to 3.1;

however, the achieved improvement in the COP would be accompanied with higher capital costs, maintenance costs, and complexity. The membrane LDAC system which uses a hybrid heat pump has the highest COPs, range from 2.2 to 4.1, compared to the other systems studied except that the solar membrane LDAC system has higher COPs at low ambient air temperature and high solution inlet temperature to the regenerator.

The higher COP of the membrane LDAC system with a hybrid heat pump than the solar membrane LDAC system shows that future research on LDAC systems should be focused on the use of the same heat pump to simultaneously cover the solution heating and cooling loads in LDAC systems. In particular, novel control strategies are required to optimize the COP of the system and to match the capacities of the condenser and evaporator with the solution heating and cooling loads.

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