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Design and Preliminary Test of a Heat Pump-driven Liquid Desiccant System for a Residential Building

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ABSTRACT

The purpose of this study is to suggest a heat pump-driven liquid desiccant (HPLD) air conditioning system for a residential building and preliminarily evaluate the cooling performance of the suggested system. The suggested HPLD system is composed of a liquid desiccant unit for the humidity control of process air with a liquid desiccant solution, and a heat pump unit for the temperature control of the desiccant solution and the process air. An experiment was conducted under operating parameters according to the design test conditions during summer operation mode based on a local standard of KS C 9306-Air Conditioners. From the test conditions, the performance indices of cooling and dehumidification capacity and system coefficient of performance (COP) were rated to evaluate the cooling performance. The experimental result showed that the suggested HPLD system acquired satisfactory supply air temperature (i.e., 15°C) and humidity ratio (i.e., 10 g/kg), and the mean cooling and dehumidification capacity of 5.14 kW met the evaluation standard of KS C 9306-Air Conditioners for a residential building. In addition, the mean system COP was 1.39 by using the compressor whose rated capacity was 3 hp.

INTRODUCTION

For the last decade, liquid desiccant-assisted air conditioning (LDAC) system has emerged as one of the promising options for realizing decoupled control of air temperature and humidity which is advantageous in energy efficiency and indoor air quality (Wang et al. 2013). In the liquid desiccant system, the strong desiccant solution should be cooled before entering the absorber and the diluted desiccant solution should be heated before entering the regenerator to improve dehumidification and regeneration performances, which are the key factors of energy consumption in the LDAC system operation. The use of a heat pump serving the solution cooling and heating simultaneously has been attracted as a practical choice. Therefore, several relevant heat pump-driven liquid desiccant (HPLD) systems have been researched in the open literatures (Abdel-Salam and Simonson 2015; Zhang et al. 2010; Niu et al. 2012).

Abdel-Salam and Simonson reported that the liquid desiccant system integrated with the heat pump used for the solution cooling and heating would be energy-efficient and economical approach (Abdel-Salam and Simonson 2015). Zhang et al. evaluated the coefficient of performance (COP) of a suggested reversible HPLD air conditioning system for both summer and winter operation modes. Their results showed that the total COP was enhanced by 20% in summer and 100% in winter operation compared to a conventional air conditioning system (Zhang et al. 2010). Niu et al. reported that an extra condenser should be considered in the HPLD system for maintaining the heat pump performance (Niu et al. 2012).

Despite of the verified benefits of the LDAC systems, they have been mostly applied to commercial or industrial buildings rather than residential buildings due to the system size and complexity. However, the integration of the heat pump with the liquid desiccant unit would make much compact LDAC system, which can be a solution for applying to a residential building (Rafique et al. 2016). Moreover, if a reversible heat pump is used, the LDAC system would be more attractive in that it can provide cooling and dehumidification in summer as well as heating and humidification in

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winter.

In this study, the workable design and operating strategies of a heat pump-driven liquid desiccant (HPLD) air conditioning system were suggested, and its experimental unit was constructed to evaluate actual air conditioning performance. Before a series of experiments under the variable operation modes, a cooling and dehumidification performance test under the design conditions according to a local standard of KS C 9306-Air Conditioners was preliminary conducted to evaluate whether the suggested HPLD air conditioning system meets the local standard.

EXPERIMENTAL SETUP

System overview

Figure 1 shows the schematic diagram of the experimental setup of the suggested heat pump-driven liquid desiccant (HPLD) system. The process air which is the outdoor air mixed with the room return air is dehumidified in the absorber at first. The desiccant solution should be cooled below 20°C by the solution-side evaporator before entering the absorber because the dehumidification process is exothermic (Nobrega and Brum 2013). Then, the dehumidified air leaving the absorber is cooled by the air-side evaporator to satisfy the supply air target temperature (i.e., 15°C). Meanwhile, the regenerator works for the solution regeneration. Because the regeneration process is endothermic, the desiccant solution should be heated above 40°C by the solution-side condenser before entering the regenerator for discharging moisture with the scavenging air which is the outdoor air. The desiccant solution in each sump is only circulated in its dedicated tower (i.e., absorber or regenerator) to reduce the solution cooling and heating loads treated by the heat pump. A small part of the weak and strong solutions in the separated sumps are mixed for adjusting the solution concentration as well as the solution level in both sumps by operating the solution mixing pumps located between the two sumps (Bergero and Chiari 2010). When the weak solution level in the absorber sump reaches the upper limit or the strong solution level in the regenerator sump reaches the lower limit, only the solution pump from the absorber sump to the regenerator sump was initially activated to adjust the solution levels in both sumps. After then, both solution mixing pumps were activated for a scheduled time (e.g., 10-15 minutes) to adjust the solution concentrations in both sumps. The extra condenser should be operated to maintain the condensing temperature of the heat pump (Niu et al. 2012). In addition, the proposed system can be simply manipulated flexibly handling the various operating modes. When only the sensible cooling is required, the solution circulation pumps are turned off to not provide the dehumidification of the process air. On the other hand, when only the latent cooling is required, the refrigerant flow of the heat-pump running to the air-side evaporator/condenser is by-passed using the refrigerant 3-way valve as shown in Fig. 1, thereby deactivating the air-side evaporator/condenser to not provide cooling of the process air.

To evaluate the cooling performance of the suggested HPLD system, the measuring parameters for the experimental test were the dry-bulb temperatures and humidity ratios of the absorber inlet and outlet air, supply air temperature, supply air volume flow rate, solution temperature before entering and after leaving the solution-side evaporator, absorber solution density, and absorber solution volume flow rate. In addition, to check the regeneration performance and maintenance of the heat pump, the dry-bulb temperatures and humidity ratios of the regenerator inlet and outlet air, scavenging air flow rate, solution temperature before entering and after leaving the solution-side condenser, regenerator solution density, and regenerator solution volume flow rate were measured.

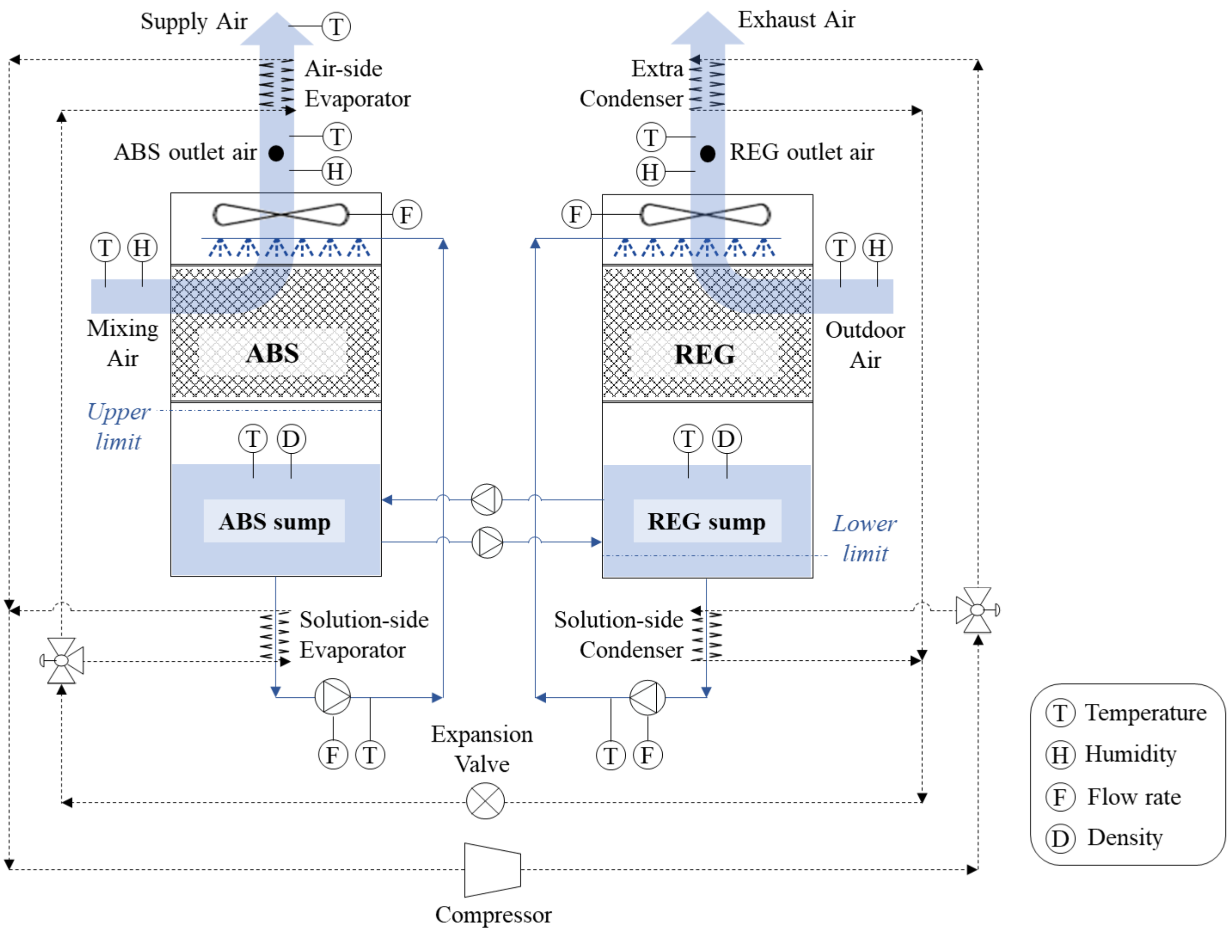
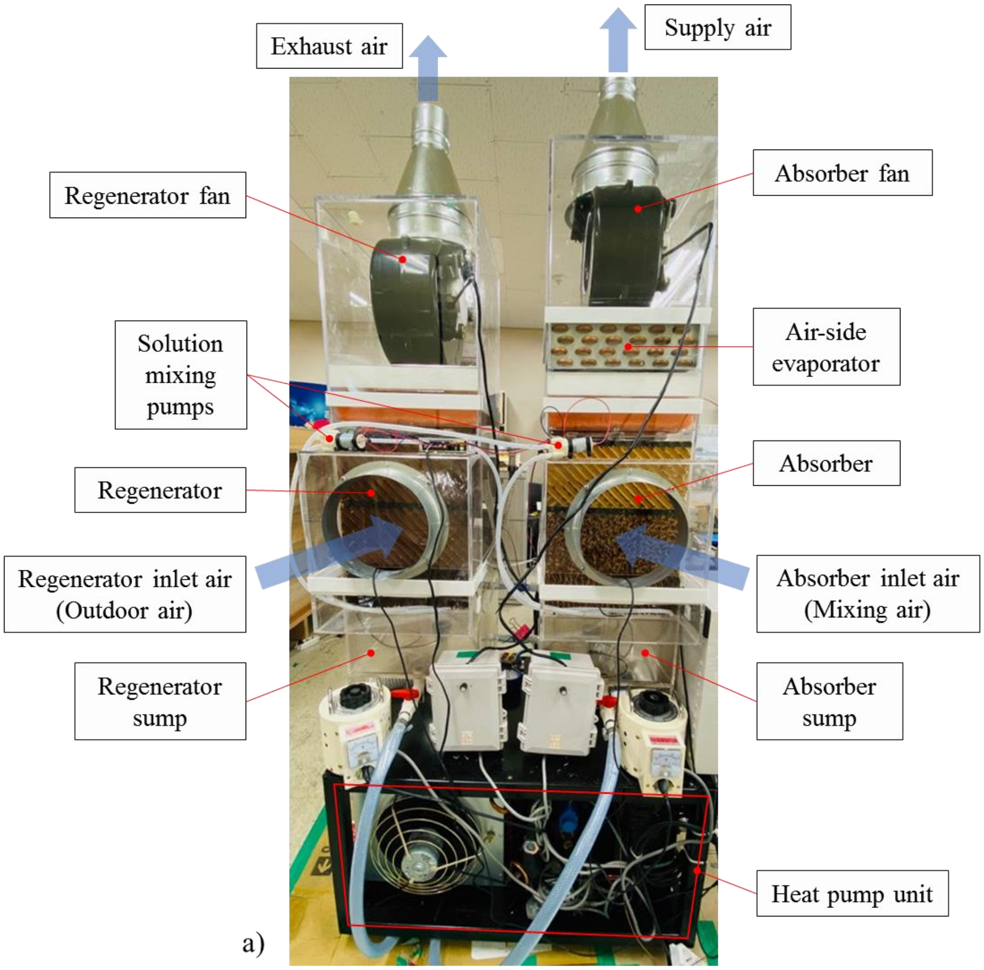


Figure 1 Schematic diagram of the HPLD experimental setup

As shown in Figure 2, the experimental setup consisted of the variable speed air fans, absorber and regenerator packings, absorber and regenerator sumps, variable speed solution circulating pumps, solution mixing pumps, and the heat pump unit including the solution-side evaporator, air-side evaporator, solution-side condenser, extra condenser, compressor, and the expansion valve. Two environmental chambers which were filled with a uniform temperature and humidity unit were used for maintaining the absorber and regenerator inlet air target conditions. Both absorber and regenerator packings adopted the CELdek structured material. Considering the design air flow rate (e.g., 0.22 m^3/s) and the recommended air face velocity (e.g., below 2 m/s) (Elsarrag et al. 2005), the packing dimension was 0.32 m (width) × 0.38 m (depth) × 0.4 m (height) with a specific surface area of 284.4 m^2/m^3. The dimension of the absorber and regenerator sumps was 0.32 m (width) × 0.38 m (depth) × 0.16 m (height) with a capacity of 20 L. The refrigerant of heat pump selected in this experiment was R410A. By calculating the heat balance under the design conditions, a rotary compressor was used whose rated capacity was 3 hp that provided the required cooling capacity of the evaporator and heating capacity of the condenser.



a)

b)

Figure 2 (a) Photo of the HPLD experimental setup (b) Environmental chamber

Operating conditions

Table 1 summarizes the experimental test conditions. The experimental test was conducted under the design conditions during the summer operation mode based on a local standard of KS C 9306-Air Conditioners. Referred to the KS C 9306, the outdoor air set conditions were 35°C and 14.2 g/kg, and the room air set conditions were 27°C and 10.4 g/kg. The absorber inlet air was set to the mixing air conditions composed of the 30% outdoor air and 70% room return air. The regenerator inlet air was set to the outdoor air conditions. The air flow rate was set to 0.26 kg/s according to the design air flow rate for the target space of a household of 80 square meters in area. The desiccant solution selected in this experiment was lithium Chloride (LiCl) solution, and the solution concentration was set to 30% for both the dehumidification and regeneration performance. The absorber solution flow rate was set to 0.117 kg/s according to the recommended liquid-to-gas ratio (i.e., 0.5) for the dehumidification process (Jain and Bansal 2007). The regenerator solution flow rate was set to 0.39 kg/s for the removal of the condensing load.

Table 1. Test conditions

Parameter		Absorber	Regenerator
Air	Temperature	29.5°C	35°C
	Humidity ratio	11.54 g/kg	14.2 g/kg
	Mass flow rate	0.26 kg/s	
Solution	Type	Lithium Chloride (LiCl) solution	
	Concentration	30%	
	Mass flow rate	0.117 kg/s	0.39 kg/s

Performance indices

The cooling and dehumidification capacity and system coefficient of performance (COP) were adopted as the performance indices of the experimental test for evaluating the cooling performance of the suggested HPLD system. The cooling and dehumidification capacity was defined by multiplying the supply air flow rate with the enthalpy difference between the conditioned room enthalpy and the cooled and dehumidified supply air enthalpy, as shown in Eq. (1). The system COP was defined as the ratio of the cooling and dehumidification capacity to the sum of the operating energy consumption including the compressor, fans, and pumps, as shown in Eq. (2).

$$\dot{Q}_{cooling} = \dot{m}_{sa} \times (h_{ra} - h_{sa}) \tag{1}$$

$$COP_{sys} = \frac{\dot{Q}_{cooling}}{\dot{W}_{comp} + \dot{W}_{fan} + \dot{W}_{pump}} \tag{2}$$

EXPERIMENTAL RESULTS

Figure 3 shows the experimental data of the cooling and dehumidification capacity and system COP. According to the test procedure of KS C 9306, the experimental data was measured 6 times at 10 minutes intervals for 1 hour. The experimental data of both performance indices was almost uniform during the system operation for 1 hour because the supply air conditions were maintained by the heat pump and desiccant solution whose temperature and concentration were also adjusted. The mean cooling and dehumidification capacity was 5.14 kW and the mean system COP was 1.39 which met the evaluation standard of KS C 9306-Air Conditioners for the target space of a household of 80 square meters in area (KS 2017). Therefore, it was concluded that the suggested HPLD system has a potential to be applied to the residential building as a novel air conditioning system.

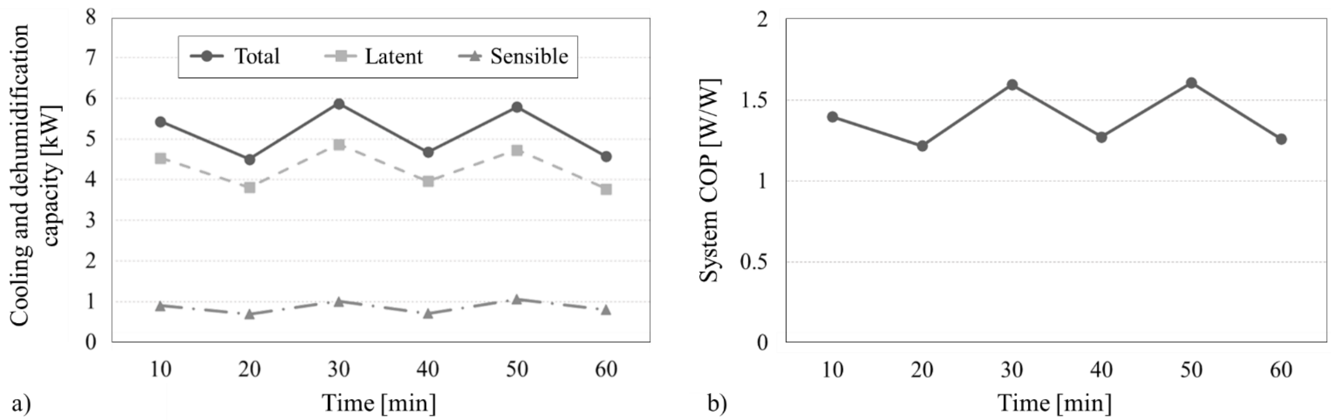


Figure 3 (a) Experimental result of cooling and dehumidification capacity (b) System COP

CONCLUSION

In this study, the workable design and operating strategies of the HPLD air conditioning system were suggested and its experimental unit was constructed to preliminarily evaluate the cooling performance under the design test conditions during summer operation mode based on a local standard of KS C 9306-Air Conditioners. As a result, the HPLD system offered reliable cooling performance during the system operation for 1 hour. In addition, the mean cooling and dehumidification capacity of 5.14 kW and the mean system COP of 1.39 satisfied the evaluation standard of KS C 9306. Therefore, it was concluded that the preliminary test results verified the applicability of the suggested HPLD air conditioning system for a residential building.

In order to make the HPLD air conditioning system more feasible and attractive to a residential building, the heating and humidification performance during the winter operation mode should be evaluated by reversing the heat pump. In addition, the energy performance at the part-load operation mode should be analyzed by using an inverter compressor. Therefore, in the future works, a series of experiments will be conducted under the variable operation modes to analyze the annual air conditioning performance and energy consumption of the suggested HPLD system. Moreover, the energy saving potential of the proposed system will be empirically compared with the conventional air-conditioning system.

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NOMENCLATURE

$\dot{Q}$ = capacity
$\dot{m}$ = mass flow rate
h = enthalpy
$\dot{W}$ = input power

Subscripts

cooling = cooling and dehumidification

sa	=	supply air
ra	=	room air
sys	=	system
comp	=	compressor
fan	=	fan
pump	=	pump

REFERENCES

Wang, R.Z., Yu, X., Ge, T.S., and T.X. Li. 2013. The present and future of residential refrigeration, power generation and energy storage. *Applied Thermal Engineering* 53(2):256–70.

Abdel-Salam, A., and C. Simonson. 2015. COP evaluation for a membrane liquid desiccant air conditioning system using four different heating equipment. *Proceedings of REHVA Annual Conference "Advanced HVAC and Natural Gas Technologies"* 125–31.

Zhang, L., Dang, C., and E. Hihara. 2010. Performance analysis of a no-frost hybrid air conditioning system with integrated liquid desiccant dehumidification. *International Journal of Refrigeration* 33(1):116–24.

Niu, X., Xiao, F., and Z. Ma. 2012. Investigation on capacity matching in liquid desiccant and heat pump hybrid air-conditioning systems. *International Journal of Refrigeration* 35(1):160–70.

Rafique, M.M., Gandhidasan, P., and H.M.S. Bahaidarah. 2016. Liquid desiccant materials and dehumidifiers - A review. *Renewable and Sustainable Energy Reviews* 56:179–95.

Nóbrega, C.E.L., and N.C.L. Brum. 2013. *Desiccant-Assisted Cooling: Fundamentals and Applications*. Springer.

Bergero, S., and A. Chiari. 2010. Performance analysis of a liquid desiccant and membrane contactor hybrid air-conditioning system. *Energy and Buildings* 42(11):1976–86.

Elsarrang, E., Ali, E., and S. Jain. 2005. Design guidelines and performance study on a structured packed liquid desiccant air-conditioning system. *HVAC and R Research* 11(2):319–37.

Jain, S., and P. Bansal. 2007. Performance analysis of liquid desiccant dehumidification systems. *International Journal of Refrigeration* 30(5):661–72.

KS. 2017. KS C 9306, *Air conditioners*. Korean Standards & Certifications.