Performance Analysis of a Passive Mixing Strategy assisted Heat-Pump-driven Liquid-Desiccant Air-Conditioning System

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Abstract. In liquid desiccant systems, an operating strategy of mixing small fractions of weak and strong solutions integrated with a closed-loop operating strategy has drawn attention for its ability to improve the system energy performance. This study proposed a passive mixing strategy integrated with the closed-loop strategy for a heat-pump-driven liquid-desiccant (HPLD) air-conditioning system and experimentally analysed its operating performances. Based on the density difference between the weak solution in the absorber sump after dehumidification process and the strong solution in the regenerator sump after regeneration process, the proposed passive mixing strategy can practically mix them without moving parts. The results showed that the passive mixing strategy was found to be feasible to properly maintain the solution temperatures and concentrations of both absorber and regenerator within the target range in the operation of the system. Therefore, the converged dehumidification rate was shown to be 4.3 g/kg and the converged cooling capacity was shown to be 5.4 kW, which satisfied the target performance. Consequently, the closed-loop and the proposed passive mixing strategy can be concluded to be applicable to the HPLD air-conditioning system.

1 Introduction

Over the past few decades, a liquid-desiccant-assisted air-conditioning system has drawn much attention for its ability to independently control the indoor temperature and humidity, thereby saving the energy consumption and improving the indoor air quality [1]. In the absorber, the liquid-desiccant (LD) solution absorbs moisture from the humid air based on the difference in vapour pressure between the desiccant-solution and the air (i.e., dehumidification process). Thereafter, in the regenerator, the diluted desiccant-solution should re-construct its concentration via the release of moisture to the scavenging air (i.e., regeneration process) [2]. In that case, the use of a heat pump capable of providing both cooling and heating has been regarded as one of the promising options for realizing the simultaneous cooling and heating of the LD solution [3]. Several studies have previously been conducted on the integration between the LD-assisted air-conditioning system and the heat pump, referred to as a heat-pump-driven liquid-desiccant (HPLD) air-conditioning system.

In the conventional operating strategy of the HPLD air-conditioning systems, the desiccant-solution was fully pumped from the sump of each tower (i.e., absorber or regenerator) into the opposite tower to take advantage of maintaining the solution concentrations [4, 5]. However, in recent years, some of the other previous studies [6, 7] have reported that the conventional operating strategy gave too much advantage in maintaining the solution concentrations, and gave disadvantage in reducing the solution thermal loads and saving the energy consumption even though a solution heat exchanger is used. Therefore, they adopted a new operating strategy that most of the desiccant-solution was circulated only within each tower to reduce the solution thermal loads. Then, a small fraction of the desiccant-solution from the opposite tower was mixed to maintain the solution concentration within an acceptable range.

However, the abovementioned new operating strategy requires more moving parts, such as pumps, valves, and pipelines, to not only circulate the solution but also mix the solution, which inevitably complicates the pipe structure. In addition, the moving parts would be the main danger factor that causes mechanical breakdown and makes long-term operation difficult, thereby requiring continuous maintenance and repair. Therefore, in this study, with the objective of improving the system practicality and commercialization, a novel solution mixing strategy was proposed which simply mixes the desiccant-solutions of different densities in the absorber and regenerator sumps without any moving parts. Then, the basic operating performance of the proposed mixing strategy was experimentally investigated to evaluate its workability and applicability.

2 System overview

The HPLD air-conditioning system in this study (Fig. 1) is composed of a LD unit to dehumidify the process air and a heat pump to control the temperature of the desiccant-solution and process air. In the absorber of the LD unit, the process air is dehumidified via the contact

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with the desiccant-solution which is cooled by a solution-side evaporator before entering the absorber. The dehumidified process air is then sensible cooled passing through an air-side evaporator. In the regenerator of the LD unit, the desiccant-solution which is heated by a solution-side condenser before entering the regenerator discharges its moisture to the scavenging air to increase the solution concentration.

The absorber sump has the cold and diluted solution because of the solution cooling process of solution-side evaporator and the dehumidification process. On the other hand, the regenerator sump has the hot and strong solution because of the solution heating process of solution-side condenser and the regeneration process. In this study, to reduce the solution cooling and heating loads, the desiccant-solution in each absorber sump and regenerator sump is circulated only within its dedicated tower. Then, a small fraction of the desiccant-solution from the sump of the opposite tower should be mixed to maintain the solution concentration. The proposed passive mixing strategy is based on the difference in solution densities in the absorber sump and the regenerator sump. The type of desiccant-solution chosen in this study is lithium-chloride (LiCl) solution, and its density is reported to change more sensitively according to the concentration than the temperature [8]. Accordingly, the cold and diluted solution in the absorber sump tends to rise due to its low density, whereas the hot and strong solution in the regenerator sump tends to sink due to its high density. On that basis, if a small hole is drilled up and down between the two sumps to form a slight solution flow-path, the desiccant-solution of low density in the absorber sump will move through the upper hole to the regenerator sump, whereas the desiccant-solution of high density in the regenerator sump will move through the lower hole to the absorber sump. Consequently, the proposed passive mixing strategy can naturally mix a small fraction of the diluted and strong solutions by using the difference in solution densities as a driving force and exclude the moving parts and complex pipe structure.

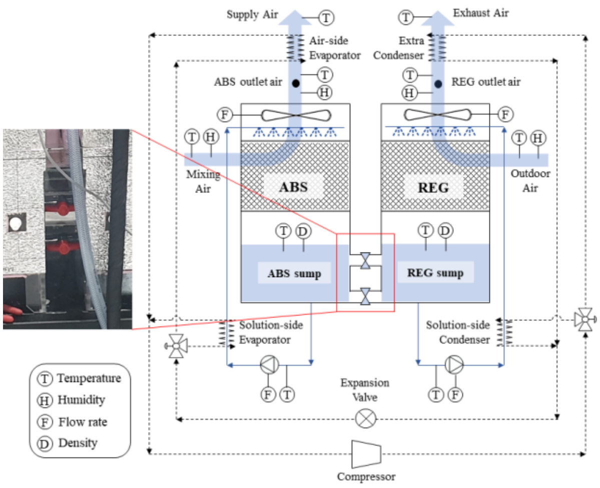

Fig. 1. HPLD air-conditioning system with proposed passive mixing strategy

3 Experimental overview

To evaluate the workability and applicability of the proposed passive mixing strategy, its operating behaviours and dehumidification and regeneration performances are experimentally investigated. The inlet air conditions of the absorber (i.e., mixing air) and regenerator (i.e., outdoor air) were set (Table 1) under the summer standard condition using an environmental chamber. The initial solution concentration was set to 30 %. The volume of each solution sump is 15 L (0.32 m (width), 0.38 m (depth), 0.12 m (height)), and the diameter and length of the solution-mixing flow-path are 3 cm and 7 cm, respectively. The solution mixing valve was opened after 30 min of system operation, and the experiments were continued until their convergence were reached.

Table 1. Test conditions.

Component	Air conditions		
	Dry-bulb temperature	Humidity ratio	Flow rate
Absorber	29.1°C	13.5 g/kg	800 m3/h (0.27 kg/s)
Regenerator	33.0°C	15.4 g/kg	900 m3/h (0.3 kg/s)

4 Results and discussion

The solution temperature and concentration behaviours of each sump are presented in Fig. 2(a) and (b), respectively, and the solution density behaviour of each sump is also presented in Fig. 2(c). According to the operating behaviours, the passive mixing process based on the solution density difference between the absorber and regenerator sumps was shown to be clearly realized. When the solution mixing valve was opened 30 min after system operation, the solution temperature of the absorber sump was slightly increased due to the mixing of high-temperature solution from the regenerator sump. Similarly, the solution temperature of the regenerator sump was slightly decreased due to the mixing of low-temperature solution from the absorber sump (Fig. 2(a)). However, only small fractions of hot and cold solutions were mixed, therefore any damage to the solution cooling and heating loads did not occur. The solution concentration of absorber sump was continuously decreased to 28.2 % due to the dehumidification process (Fig. 2(b)). However, when the mixing valve was opened, the solution concentration of absorber sump was increased due to the mixing of high-concentration solution from the regenerator sump and then converged to 30.3 %. Similarly, the solution concentration of regenerator sump was rapidly increased to 32.2 % due to the regeneration process. However, when the mixing valve was opened, the degree of increase in the solution concentration of regenerator sump was alleviated due to the mixing of low-concentration solution from the absorber sump, and finally the concentration was converged to 33.6 %. Accordingly, in the solution density behaviour (Fig. 2(c)), the solution density of

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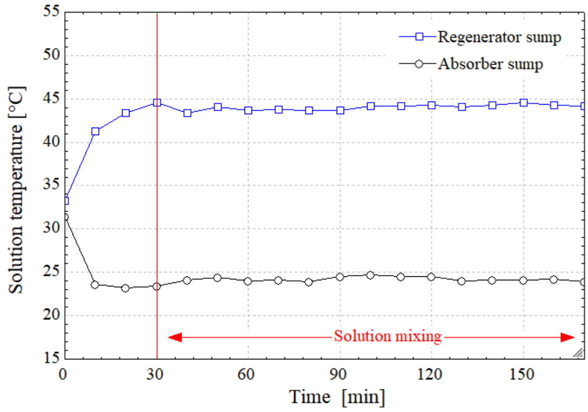
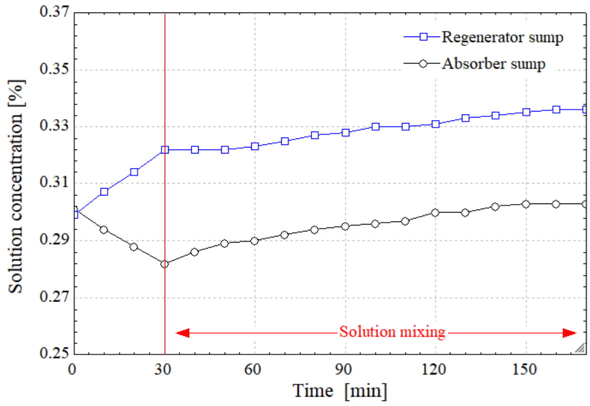
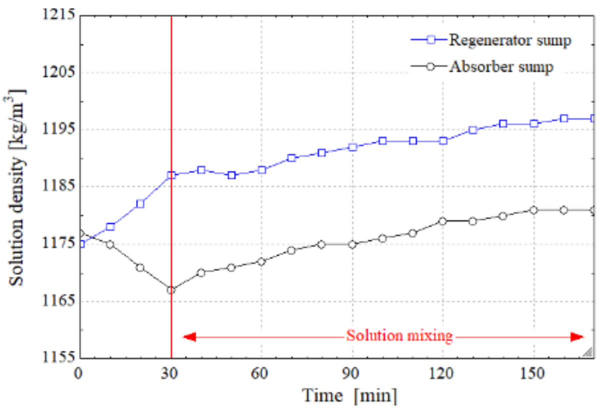
absorber sump was low due to the low concentration, and that of regenerator sump was high due to the high concentration. Consequently, in the proposed passive mixing strategy, the low-density solution of absorber sump was indicated to be moved through the upper hole to the regenerator sump, whereas the high-density solution of regenerator sump was indicated to be moved through the lower hole to the absorber sump.



(a) Solution temperature behaviour of each sump



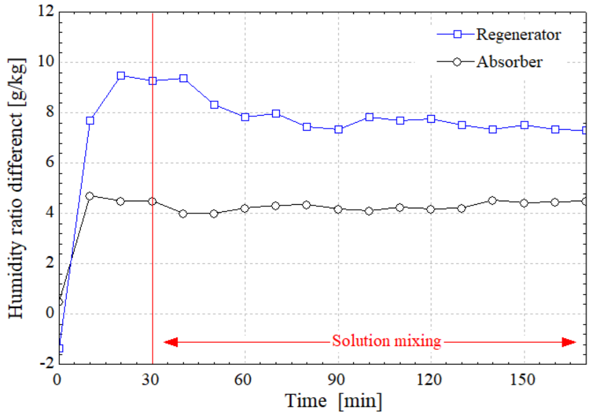
(b) Solution concentration behaviour of each sump



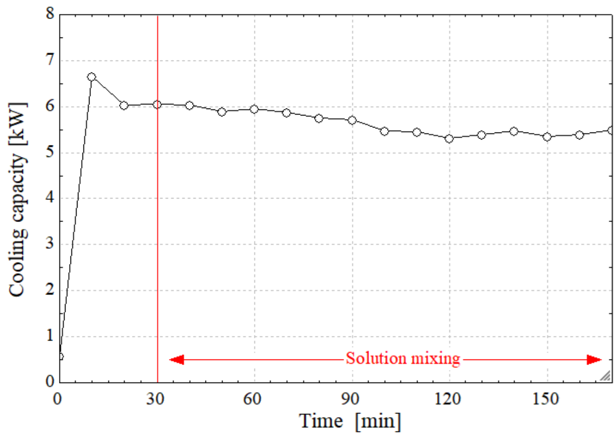
(c) Solution density behaviour of each sump

Fig. 2. Operating behaviours of desiccant-solution in each sump

The experimental cooling and dehumidification and regeneration performances are presented in Fig. 3. Because the solution temperature and concentration were properly maintained within the target range, the dehumidification rate was maintained at 4.3 g/kg. In addition, when the solution concentration is reached to convergence, the cooling capacity (i.e., cooling and dehumidification performance) could be stabilized and then maintained 5.4 kW. The regeneration rate was shown to be always higher than the dehumidification rate. This is because the inlet air conditions of the regenerator are advantageous to the regenerator performance and the initial solution concentration (i.e., 30 %) was also favourable to the regenerator performance. The regeneration rate was significantly high at the beginning of system operation, however the solution concentration was accordingly increased, therefore the regeneration rate was gradually decreased and then converged to 7.3 g/kg.



(a) Dehumidification and regeneration rates



(b) Cooling capacity

Fig. 3. System operating performances

5 Conclusion

In this study, with the objective of improving the system practicality and commercialization, a passive mixing strategy which can naturally mix the desiccant desiccant-solutions of different densities in the absorber and regenerator sumps without any moving parts was proposed, and its basic operating performance was experimentally investigated. Based on the experimental results, the solution density difference occurred between the absorber sump containing low-concentration and low-density solution and the regenerator sump containing high concentration and high-density solution. Therefore, the proposed passive mixing process wherein the low-density solution of the absorber sump was moved through the upper hole while the high-density solution of the regenerator sump was moved through the lower hole was shown to be clearly realized. Accordingly, the solution temperature and concentration were maintained within the target conditions, thereby satisfying the system operating performances under the summer standard mode. Consequently, the proposed passive mixing strategy can be concluded to be applicable to the HPLD air-conditioning system and also contribute to improving its practicality and commercialization. In future, the geometry and structure of the solution-mixing flow-path should be optimized in terms of the system energy performance.

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