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# A heat pump driven and hollow fiber membrane-based liquid desiccant air dehumidification system: Modeling and experimental validation

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ABSTRACT

A compression heat pump driven and membrane-based liquid desiccant air dehumidification system is presented. The dehumidifier and the regenerator are made of two hollow fiber membrane bundles packed in two shells. Water vapor can permeate through these membranes effectively, while the liquid desiccant droplets are prevented from cross-over. Simultaneous heating and cooling of the salt solution are realized with a heat pump system to improve energy efficiency. In this research, the system is built up and a complete modeling is performed for the system. Heat and mass transfer processes in the membrane modules, as well as in the evaporator, the condenser, and other key components are modeled in detail. The whole model is validated by experiment. The performances of SDP (specific dehumidification power), dehumidification efficiency, EER (energy efficiency ratio) of heat pump, and the COP (coefficient of performance) of the system are investigated numerically and experimentally. The results show that the model can predict the system accurately. The dehumidification capabilities and the energy efficiencies of the system are high. Further, it performs well even under the harsh hot and humid South China weather conditions.



## 1. Introduction

Liquid desiccant air dehumidification has gained much attention recently [1–6]. Compared to the traditional dehumidification method of cooling coils, liquid desiccant air dehumidification has many benefits: (1) the hygroscopic solution has large dehumidification capabilities even at moderate temperatures, thus a low evaporating temperature is not required anymore if cooled by a refrigeration system. Energy saving therefore can be realized. (2) The solution can be regenerated by low-grade waste heat, thus renewable energy sources like solar energy can be utilized. (3) The concentrated solution can be used as energy storage materials, thus it can be used to store the off-peak electricity. Operation costs can be reduced in this way.

Traditionally, packed-bed columns [5] are used as the equipments where the humid air and the liquid desiccant contact and exchange moisture with each other. The two fluids are well mixed. While this manner is efficient in heat and moisture exchange, it has a coherent adverse effect: the small corrosive liquid droplets may be carried over to rooms by the process air during the absorption processes. It is rather harmful to indoor environment and occupants. To solve this problem, in recent years, membranes, that are permeable to water vapor but impermeable to liquid desiccant, have been used to separate the process air from the liquid desiccant [6]. According to this concept, a bundle of hollow fiber membranes is packed in a shell to form a shell-and-tube like module. Liquid desiccant flows in tube side, and air flows in shell side. They exchange heat and moisture through the membranes, in a non-contacting way. In this manner, the problem of liquid droplets cross over is prevented. As seen, instead of packed-bed columns, the membrane modules are used as the dehumidifier or/and the regenerator in a desiccant system.

For a continuous operation, heating-regeneration and cooling-dehumidification processes of the salt solution are required simultaneously. Though an independent heater and an independent cooler are simple in installation, the overall energy use of the system is not optimized. Because a compression heat pump generates heating and cooling simultaneously with high efficiency, it

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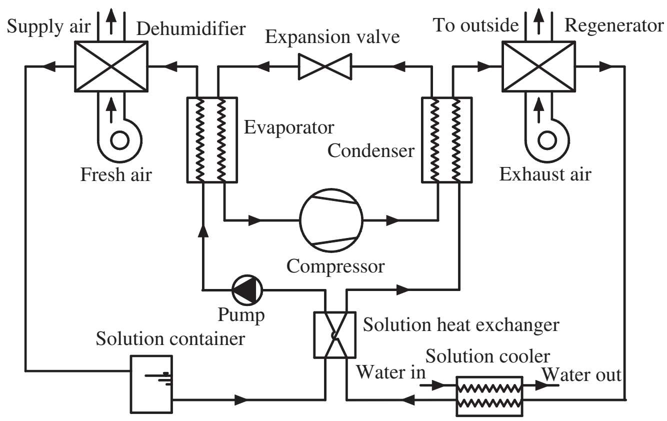


**Fig. 1.** Schematic of a heat pump driven, membrane based liquid desiccant air dehumidification system. Both the dehumidifier and the regenerator are hollow fiber membrane modules.

would be energy conservative if it is combined to a membrane-based liquid desiccant air dehumidification system. In this way, both the cooling and the heating energy from a heat pump can be utilized. The method to realize simultaneous heating and cooling with a heat pump has been practiced with traditional packed bed liquid desiccant systems [7,8]. However for a membrane system, previously it was only driven by a separate heater and a separate cooler [9,10], which are energy intensive. This study is a step forward to drive the membrane liquid desiccant system with a compression heat pump system.

In this research, a heat pump driven and hollow fiber membrane based liquid desiccant air dehumidification system is presented. The heat pump system is comprised of a compressor, an evaporator, a condenser and an expansion valve. The salt solution is cooled by the evaporator before it goes to the membrane dehumidifier. Simultaneously, the solution is heated by the condenser before it goes to the membrane regenerator. To study the system performance, a mathematical model for the whole system is proposed. After model validation, the performances of the novel system, including the SDP (specific dehumidification power), dehumidification efficiency, EER (energy efficiency ratio) of heat pump, and the COP (coefficient of performance) are investigated. The results are helpful for future system design and optimization.

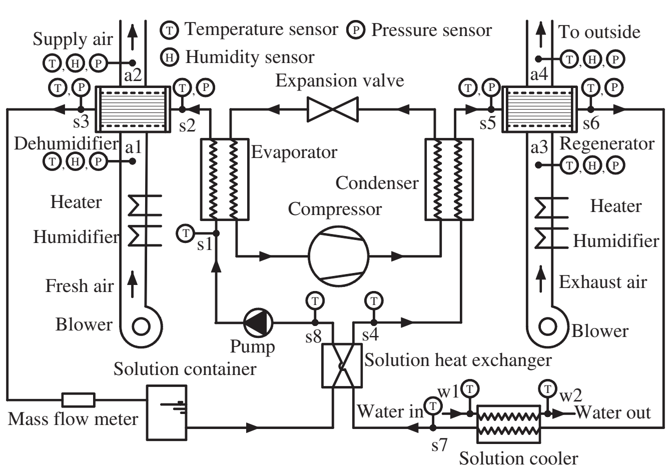


**Fig. 2.** Experimental set up of the heat pump driven and membrane-based liquid desiccant air dehumidification system, with instrumentation. The state points for the air, solution, and water streams are also plotted.

## 2. System description and experimental set up

### 2.1. System description

Fig. 1 shows the schematic diagram of the heat pump driven and membrane-based liquid desiccant air dehumidification system. It mainly consists of an air dehumidification module, a solution regeneration module and a compression heat pump system. Both the dehumidification module and the regeneration module are novel cross-flow hollow fiber membrane modules developed in SCUT [10]. Fresh air flows in the shell side of the module. It is dehumidified and cooled by the concentrated LiCl salt solution flowing in tube side. After cooling and dehumidification, the fresh air is supplied to indoors. At the same time, exhaust air flows through the shell side of the membrane regenerator. The diluted and heated salt solution is cooled and regenerated. The solution circulates for another cycle.

The heat pump system provides simultaneous cooling and heating for the solution, for the dehumidification and regeneration processes respectively. It has a compressor, an evaporator, a condenser and a thermal expansion valve. R134a is used as the refrigerant. Generally, the heating power is larger than the cooling power of a heat pump. To balance the energy output of the system, an auxiliary solution cooler is used to absorb the surplus heat by cooling water. Moreover, a solution heat exchanger is installed for energy recovery between the two fluids going to the condenser and to the evaporator respectively. Both the solution heat exchanger and the auxiliary solution cooler are shell-and-tube type plastic heat exchanger. For the range of mass flow rates in operation (220–340 L $h^{-1}$), heat transfer coefficients in these plastic heat exchangers are insensitive to flow rates. Therefore constant heat transfer coefficients are used in simulations.

### 2.2. Experimental set up

The real test prototype is shown in Fig. 2 with air ducting work and instrumentation. The state points of the fluids, including the air, the solution, and the cooling water, are also plotted in the figure. Air streams, for both the fresh air and the regeneration air, are driven by two wind tunnels from indoors. The inlet temperature and humidity are adjusted to the design points before they flow to the membrane modules. Air flow rates are varied by two variable speed blowers and are measured by hot-wire anemometers with accuracies of ±0.15%. Solution flow rate is measured by a mass flow meter with an accuracy of ±0.5%. Heaters and humidifiers are installed in air ducts to adjust temperature and humidity of air streams. Temperature is measured by temperature sensors (PT100) with an accuracy of ±0.1 °C. Relative humidity is measured by humidity sensors (center 313) with an accuracy of ±2.5%. Fluid pressures are detected by pressure sensors with an accuracy of 0.5 Pa. The power consumptions of the compressor, pump and fan are measured by an electrical power meter with an accuracy of ±0.1%. Temperatures of solution are measured before and after the dehumidifier, the regenerator, the solution cooler and the solution heat exchanger. Solution along the flow is sampled and the concentration is analyzed by density measurement. Temperature, humidity and pressure of solution are measured before and after the dehumidifier and regenerator. Inlet and outlet temperatures of cooling water are also measured.

The physical and design parameters of the main components of the system are listed in Table 1.