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Research Paper

Modelling and dynamic simulation of a hybrid liquid desiccant system regenerated with solar energy

Adriana Coca-Ortegón *, Juan Prieto, Alberto Coronas

Department of Mechanical Engineering, CREVER, Universitat Rovira i Virgili, Av. Països Catalans 26, CP 43007 Tarragona, Spain

HIGHLIGHTS

- Modelling and dynamic simulation of an HLDS is presented.
- The regeneration process in the HLDS is carried out by solar energy.
- The HLDS is applied in an HVAC application with high latent loads.
- A sensitivity analysis of the HLDS for the main components is carried out.

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ABSTRACT

The combination of liquid desiccant systems with conventional vapour compression chillers, usually known as hybrid liquid desiccant systems (HLDS), is a promising alternative when temperature and humidity need to be controlled in air conditioning applications. One of the advantages of this technology is that different kinds of energy can be integrated, particularly low temperature solar thermal energy, which can reduce the electrical consumption of the system. These kinds of systems are typically analysed by discrete steady-state simulations, which show how the system behaves in design conditions. However, dynamic simulations can provide information about the seasonal performance and help to set an appropriate control strategy. This paper describes the modelling and dynamic simulation of an HLDS using TRNSYS. Because there are non-standard components for the main elements of a liquid desiccant subsystem (LDS), an alternative modelling method based on performance tables has been developed. The simulation is carried out for Kuala Lumpur, a city with high humidity and ambient temperatures, where air conditioning is required throughout the year. The control strategy is also defined. Finally a sensitivity analysis is performed for the case analysed.

1. Introduction

The combination of liquid desiccant systems with conventional vapour compression chillers, usually known as hybrid liquid desiccant systems (HLDS), is a promising alternative when temperature and humidity need to be controlled in air conditioning applications [1]. In contrast to conventional vapour compression systems (VCS), the dehumidification process using desiccant materials does not need to cool the air under the dew point and subsequently reheat it. Desiccants, then, make the air conditioning process more efficient, especially when latent loads are high [2–4].

Liquid desiccants are generally more able than solid desiccants to attract moisture and are more flexible. For example, the absorber and regenerator can be physically separated, it is easier to adapt to specific pumping conditions, and a liquid–liquid heat exchanger can be used to improve the efficiency of the system [4,5]. In addition, this technology can integrate different kinds of energy sources, particularly low temperature solar thermal energy [5–7], which may decrease the electrical consumption of the system.

Typically these systems are analysed by discrete steady-state simulations, which show how the system behaves in design conditions. One example of this kind of simulation is the study by Khalid Ahmed et al. [3], who simulate the performance of an HLDS made up of a vapour absorption chiller (VAC) with a liquid desiccant subsystem (LDS), and in which $H_2O/LiBr$ is used as a refrigerant/absorbent mixture. In this case a COP sensitivity analysis was carried out, which showed that in nominal conditions the COP of HLDS is about 50% higher than that of a conventional vapour compression chiller.

Dai et al. [8] did a similar simulation and validated the results with experiments. The HLDS analysed in this case was made up of an LDS, an indirect evaporative cooler and a vapour compression chiller. The sensitivity was analysed in terms of the electric coefficient of performance (ECOP), the thermal coefficient of performance (TCOP) and the general coefficient of performance of the system

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* Corresponding author. Tel.: +34 977 257887; fax: +34 977 559 691.
E-mail address: adriana.cocao@estudiants.urv.cat (A. Coca-Ortegón).

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(COP) as efficiency indicators. The results were also compared with the performance of a conventional vapour compression system.

Other researchers such as Tu et al. [9] also made a similar sensitivity analysis but using a more complex finite difference-based mathematical model for the packed columns of the LDS. Moreover, the system was optimised by using the exhaust air for heat recovery. The results show the influence of some key variables, such as the solution temperature, ambient temperature, ambient humidity and mass flow, on some performance variables (COP, cooling capacity and exergy capacity).

Yamaguchi et al. [10] carried out a simulation and experimental analysis of an HLDS, using the simulation tool Simulink. The system is a conventional heat pump whose evaporator and condenser are working at the same time as the absorber and the regenerator of the LDS respectively. They evaluated the sensitivity of the COP in different experimental conditions and the influence of key variables such as the humidity ratio, the isentropic efficiency of the compressor, and the efficiency of heat exchangers.

Despite the usefulness of these discrete steady-state studies, some research has concluded that the behaviour of liquid desiccant systems needs to be analysed in transient conditions, so more accurate transient simulation validated with experimental works are still expected [11,12].

Other studies have pointed out the importance of knowing the seasonal performance of the HLDS so that energy savings can be quantified more accurately and the feasibility of these systems determined, particularly for HLDS which uses solar energy in the regeneration process [13]. Dynamic simulations, which take into account the changing weather and load conditions, may help to understand better the HLDS performance in the long term and also to set an appropriate control strategy.

As far as this kind of dynamic simulation is concerned, Liu et al. [14] analyse the annual performance of an HLDS with a spray dehumidifier using the Equation Engineers Solver (EES) and the Fchart method. The study compares the system's behaviour in summer and winter seasons, and the results show that it performs better in summer. In comparison with a conventional vapour compression system, the energy consumption of the HLDS was about 78% during the summer and 62% during the winter for the case analysed in Beijing.

Zhang et al. [15] analysed the summer and winter performance of an HLDS consisting of a vapour compression heat pump to treat the sensible load and an LDS to treat the latent load. The system also uses the heat pump to pre-cool the liquid desiccant, and the exhaust air of the regeneration process to prevent the heat pump from frosting during the winter.

Lee and Lam made a more complex analysis [16]: a dynamic simulation of an HLDS made up of a ground heat pump subsystem and the LDS. All the components were modelled and programmed to solve the system by iterations using the Newton–Raphson method for the refrigerant system, and the Gauss–Seidel method for the LDS. The advantage of this methodology is that the results are very accurate, but the disadvantage is that the simulation takes a long time (in this case it was completed in 9 days).

More recently special tools have been used to develop dynamic simulations of HLDS, but even so very little work has been carried out in this line. The work done by Crofoot [17] is one example of this kind of study: an existing HLDS regenerated using evacuated tube solar collectors was simulated in TRNSYS software, and specific components for the LDS were programmed in Fortran. The results show the annual performance of the system, and these were compared with the measurements of an experimental facility, but did not analyse the control strategy using the seasonal results.

This paper presents a dynamic simulation of an HLDS using TRNSYS. An alternative method based on performance tables is applied to model the LDS components (absorber and regenerator). In addition, the control strategy has been defined and the seasonal performance evaluated for a specific case with high internal latent loads and environment humidity.

Table 1
Summary of design conditions.

Description	Ambient conditions	Zone conditions	Supply conditions
Pressure [Pa]	99.77	99.77	99.77
Dry bulb temperature [°C]	33.9	25.0	17.2
Relative humidity [%]	62.4	60.0	85.0
Humidity ratio [kg_w/kg_{da}]	0.02130	0.01208	0.01058

2. Case study

2.1. System description

Öberg and Goswani [5] published an extensive review of the HLDS that uses solar energy in the regeneration process, and more recently it was complemented by Mei and Dai [1]. According to these studies, HLDS usually consists of a liquid desiccant subsystem (LDS) that treats the latent load and a cooling subsystem (CS) that handles the sensible load.

In the LDS, the regeneration process with solar energy is carried out directly by solar regenerators (open or closed) or indirectly by conventional solar collectors; the absorbers and the regenerator use technologies such as packed beds, internally cooled packed beds, falling film plates, falling film extruded plates, and falling film tubes, and the most commonly used liquid desiccant material recently has been LiCl.

The CS can also incorporate such technologies as conventional vapour compression chillers, vapour absorption chillers, and evaporative coolers. The conditioning process can also be optimised using different configurations for heat recovery in the air subsystem (AS), as Das and Jain point out [18].

Taking these options into account, the proposed HLDS consists of four main subsystems: the liquid desiccant subsystem (LDS) with LiCl-H_2O solution, in which the supply air is dehumidified; the solar subsystem (SS) with conventional flat plate collectors, which supplies heat to the regeneration process; the cooling subsystem (CS), which handles the sensible load, with a water–water vapour compression chiller; and the air subsystem (AS) with two air-to-air heat exchangers, an evaporative cooler and a cooling coil. The LDS consists of an absorber, a regenerator, a solution exchanger, and such other elements as valves and pumps. Its operation is described in several previous publications [5,6,19].

The LDS is dimensioned in the design conditions (Table 1), which means that in different ambient and/or zone conditions, humidity after the absorber may be below the required supply humidity conditions. In order to reach the required supply air humidity and decrease the air temperature, an evaporative cooler is added after the absorber, as Öberg and Goswani explained [5] in their review of the studies by Griffiths [20], Chebbah [21] and Gandhidasan [22]. After the evaporative cooler, a cooling coil, which is provided with cold water by the vapour compression chiller, makes the final adjustment to the air temperature. Finally, the treated air is driven to the conditioning zone.

The return air from the conditioning zone is used as regeneration air, because it is less humid than the environment air. The temperature of the regeneration air is first increased in the air subsystem (AS) through two air heat exchangers: one located after the absorber and the other located after the regenerator.

The aim of this system is to use solar energy as the main resource, so the configuration incorporates the mentioned evaporative cooling to minimise the use of conventional energies and a cooling