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Model-based optimization strategy of chiller driven liquid desiccant dehumidifier with genetic algorithm

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ABSTRACT

This study presents a model-based optimization strategy for an actual chiller driven dehumidifier of liquid desiccant dehumidification system operating with lithium chloride solution. By analyzing the characteristics of the components, energy predictive models for the components in the dehumidifier are developed. To minimize the energy usage while maintaining the outlet air conditions at the pre-specified set-points, an optimization problem is formulated with an objective function, the constraints of mechanical limitations and components interactions. Model-based optimization strategy using genetic algorithm is proposed to obtain the optimal set-points for desiccant solution temperature and flow rate, to minimize the energy usage in the dehumidifier. Experimental studies on an actual system are carried out to compare energy consumption between the proposed optimization and the conventional strategies. The results demonstrate that energy consumption using the proposed optimization strategy can be reduced by 12.2% in the dehumidifier operation.

1. Introduction

During the past decade, LDDS (Liquid Desiccant Dehumidification System) has gained a significant popularity for building latent load handling due to its ability to improve energy efficiency by shifting the energy use away from electricity toward renewable or low grade energy such as solar energy, geothermal energy and waste energy from industrial processes in providing better indoor thermal comfort and indoor air quality with the employment of environment friendly working fluids which do not contribute to ozone depletion [1].

Among many schemes, chiller driven LDDS has drawn growing interests in the research society as chiller can provide colder environment in the dehumidifier to make it more efficiently. A great deal of research has been carried out on the system design [2], experimental investigation [3,4], performance analysis coupled with heat mass transfer model development [5,6]. Zhao et al. [7] proposed a chiller driven LDDS to remove the entire latent load of fresh air in an office building. The experiment results showed that the system can achieve magnificent energy saving compared with the conventional air conditioning system and provide comfortable indoor environment as well. Bakhtiar [8] developed a chiller driven LDDS to investigate efficiency of the system by a novel method verified by experimental studies. Mohammad et al. [9] carried out experimental study on a hybrid LDDS driven by a chiller and solar energy to analyze the performance of the dehumidifier by employing an ANN (Artificial Neural Network). The heat and mass transfer process is also analyzed and discussed by finite difference model [10], NTU model [11,12] and data driven model [13].

As an important component of the LDDS, optimization of chiller system has been widely investigated and many optimal strategies have been proposed. Kusiak et al. carried out studies on model development and optimization of HVAC (heating ventilating and air conditioning) by employing a data-driven approach [14], dynamic neural network [15] and PSO (particle swarm optimization) [16]. The results showed that the proposed optimal strategy can save up to 30% of the total energy consumption of the HVAC compared with a traditional strategy. Zhao et al. developed models of the components in chiller system and formulated the overall system optimization problem solved by using a modified genetic algorithm [17] and decentralized optimization method [18]. The simulation and experiment results showed that both the modified genetic algorithm and decentralized optimization can reduce the energy consumption of the system by 8.45% and 6.5%, respectively.

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Decentralized optimization outperforms the modified genetic algorithm with much less computation time and with only 1.05% more energy consumption.

However, very little attention has been paid on the LDDS optimization. Most of studies on model development and optimization of LDDS focused on the optimal system design and simulation. Among the few, Audah et al. [19] formulated an optimization problem for selection and operation of a LDDS powered by solar energy when they studied the feasibility to meet both building cooling load and fresh water needs in Beirut with minimal energy cost. Optimal control strategy of LDDS was developed to maintain the multi-zone space thermal comfort with minimized total energy consumption by simulation methods. Air supply temperature and relative humidity were selected as the two set-points to be optimized and then a Genetic algorithm was employed to search the optimal set-points [20,21]. Zhang et al. [22] proposed a heat pump driven LDDS and carried out investigation on performance optimization of the system. Ge et al. [23] studied the optimization control on the solution flow rate on the annual energy recovery for the liquid desiccant run-around membrane energy exchanger systems. Kim et al. studied the annual operating energy savings of a liquid desiccant evaporative cooling DOAS (dedicated outdoor air system) by using TRNSYS simulation software [24,25]. Qi and Lu simulated and optimized the operation performance of internally cooled/heated LDDS in a case study of Hong Kong [26]. Most of the papers carried out the researches by simulation methods and liquid desiccant dehumidifier is only a small component in the systems they studied. Characteristics and model of liquid desiccant dehumidifier have not been addressed and described in details.

With the increasing popularity of the chiller driven LDDS in building applications, it is imperative to study an optimal strategy to reduce the energy cost of LDDS and to verify the energy savings in an actual operating system. Large amount of cooling energy will be consumed by the dehumidifier during the process of air dehumidification and the dehumidifier is the key part that supplies required air conditions to maintain the indoor thermal comfort. Therefore, this paper will analyze the characteristics of dehumidifier and address model-based optimization problem for the dehumidifier part in an actual operating LDDS based on our previous hybrid heat and mass transfer model in chiller driven LDDS [27]. Energy models of the components including chiller, pump and fan, as well as the interactions between them are presented. The optimization strategy is developed to minimize the energy consumption while maintaining the corresponding indoor thermal comfort within an acceptable range. Then genetic algorithm which is an effective method to solve large scale optimization problem is adopted to search the optimal setting points. Finally, an experiment is carried out on an existing LDDS to show energy saving potential of the proposed optimization strategy.

2. LDDS working principle

A schematic diagram of a typical LDDS is shown in Fig. 1 that mainly consists of five components, namely a dehumidifier, a regenerator, a heater powered by hot water, a chiller with vapor compression cycle and an internal heat exchanger. The dehumidifier is to remove the water vapor from the process air and the regenerator is to concentrate the diluted solution from the dehumidifier to an acceptable concentration. The chiller and the heater are equipped to cool and heat the desiccant solution in the dehumidifier and regenerator, respectively. The internal heat exchanger is used to recover the energy when desiccant solutions with different temperatures from the two columns are communicating with each other. Fig. 2 illustrates the change of desiccant water vapor pressure during the operating process accordingly. The working principle description is given as follows:

- In the dehumidifier, the strong desiccant solution which is cooled by the chiller in state A is sprayed on top of the dehumidifier. The process air is drawn by a fan from the bottom of the column to directly contact with the falling desiccant solution in a counter-flow configuration. The water vapor pressure of strong cooled desiccant solution is lower than that of process air and the water vapor is forced to migrate from process air towards to the solution. Water vapor pressure difference between desiccant solution and process air acts as the driving force for the mass transfer. This process is represented by line A-B in the figure.
- To recover the diluted solution back to strong affiliation to moisture, desiccant solution is heated (B–C) by a heater before it is pumped into the regenerator to contact with regenerating air with a higher water vapor pressure.
- Since the desiccant solution has higher water vapor pressure than that of regenerating air, mass transfer takes place in the opposite direction to that which occurs in the dehumidifier and the moisture absorbed in dehumidification progress can be transferred from the desiccant solution to regenerating air as indicated by line C–D.
- Even desiccant solution is concentrated; it still has high surface vapor pressure due to its high temperature. Therefore, cooling (D–A) is needed to cool down the solution so that the desiccant can reach to state A to complete the cycle.

3. Components models

Effective and valid physical components models at low computational cost are important for online optimization procedure. It is difficult to accurately represent the inherent nonlinearity and complexity of a typical dehumidifier by mathematical or physics-based models. However it can be easily captured by the hybrid model which is developed by lumping the variables as constant parameters based on theoretical analysis. In chiller driven liquid desiccant dehumidifier, chiller, pump and fan are the three energy-consuming components, and the outlet air conditions are determined by heat mass transfer process. The models of the components and process are given as follows:

3.1. Chiller model

The power consumption of a chiller system is estimated in terms of the part load ratio which is defined by the ratio of the current load and the designed capacity of the chiller. The current load is determined by the cooling requirement of the desiccant solution which can be expressed as follows:

$$Q_{c,cur} = c_s \dot{m}_s (T_{s,in,c} - T_{s,o,c}) \tag{1}$$

where $Q_{c,cur}$ is the current load of the chiller, c_s is the specific heat of desiccant solution, $\dot{m}_s$ is the desiccant solution flow rate, and $T_{s,in,c}$, $T_{s,o,c}$ are the solution temperatures of inlet and outlet of the chiller, respectively. Therefore, the part load ratio can be found from the following equation:

$$PLR_c = \frac{Q_{c,cur}}{Q_{c,nom}} \tag{2}$$

where PLR_c is the part load ratio of chiller, $Q_{c,nom}$ is the nominal chiller capacity. The chiller power consumption E_c can be presented in terms of part load ratio PLR_c as [28],

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