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Investigation of liquid desiccant regenerator with fixed-plate heat recovery system

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ABSTRACT

In this paper, performance analysis has been conducted to evaluate the regenerator with heat recovery in Liquid Desiccant Dehumidification System (LDDS) under different air mass flow rate. The waste heat of the exhausted regenerating air is recovered by a fixed-plate heat exchanger (FPHE). A hybrid model has been proposed for the heat recovery process and combined with the regenerating heat and mass transfer hybrid model, the heat recovery performance of FPHE and its effects on the regenerating performance have been evaluated. The comparison of the experimental and numerical results show that the numerical computation is accurate and effective for prediction, control and optimization of regenerator with heat recovery. The largest relative error is only 10.03%. With heat recovery, the regenerating performance is improved with high regenerating rate, effectiveness and thermal efficiency. FPHE recovers 16–19% of the waste energy and compared with regenerator without heat recovery, its employment in regenerator contributes to 14–18% energy saving.

1. Introduction

Energy saving technologies and their deployment have a great potentiality for large-scale reduction in energy demand. Kim [1] presented an economic analysis on energy saving technologies in a complex manufacturing building and his results indicated that with energy saving technologies, i.e., high efficiency HVAC equipment and advanced fluorescent lighting systems, the total energy cost could be saved by 14%. Oh et al. [2] evolved an innovative adsorbent-based dehumidifier and an indirect evaporative cooling technology and concluded that this technology could save 21,096 GWh electricity till 2030. As one of the energy saving technology, waste heat recovery system can reutilize a fraction of waste heat. Instead of creating heat, this system reduces heat waste and makes energy consumption more cost-effective. It can reuse the exhausted heat sources to preheat the incoming gas and hence, decrease the heating load and energy demand. Heat recovery system can recover about 60–95% heat from the waste heat and can dramatically increase the energy consumption efficiency [3].

Singapore is a tropical country. Due to the all-year round hot and humid tropical climate, Air Conditioning and Mechanical Ventilation (ACMV) systems consume 40–50% of energy in commercial buildings [4]. Reducing ACMV system energy consumption without compromising occupancy comfort would benefit both environmentally and financially. Compared with conventional mechanical based air dehumidification schemes, liquid desiccant dehumidification system (LDDS) exhibits many advantages, such as efficient humidity-removal process, the potential to use low-grade energy and high-quality of supplied air. Researchers developed many types of LDDS, such as internally heated/cooled LDDS [5–7], membrane LDDS [8–12], low-grade energy driven LDDS [13] and electro dialysis LDDS [14,15].

LDDS uses the vapor pressure difference between process air and liquid desiccant as the driven force to achieve heat and mass transfer, consequently, dehumidifying the process air. Dehumidifier and regenerator are two major parts in LDDS, where heat and mass transfer take place. For re-concentrating the liquid desiccant and applying it repeatedly, the regenerator consumes major energy in LDDS. The improvement of energy efficiency in regenerator could reduce the amount of energy required to attain demanding regenerating performance. Many techniques are proposed to improve the regenerator performance. As proposed in

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Refs. [16–18], keeping the solution temperature constant inside the regenerator can improve the regenerator efficiency. To maintain the temperature, internally heated technique is one way. However, additional energy is consumed. Heat recovery technique can preheat the incoming air by using the waste heat and therefore, the sensible heat transferred from the liquid to the air is reduced.

Riffat et al. [3,19] made a detailed review of the heat recovery systems for building applications. They categorized the heat recovery devices into four types considering the construction type of heat exchanger, namely fixed-plate heat exchanger [20], heat pipe heat exchanger [21], rotary thermal wheel [22] and run-around [23]. Heat pipe heat exchanger is expensive, rotary wheel needs additional power input and run-round has the lowest heat recovery efficiency. Therefore, using fixed-plate heat exchanger to recover waste heat in regenerator of LDDS will be a better choice.

Fixed-plate heat exchanger (FPHE) has been investigated experimentally and numerically by many researchers. S. Anisimov et al. [20] presented theoretical analyses of heat and mass transfer process in the plate heat exchanger used for energy recovery. The heat recovery exchanger was operated under ice formation condition. The most unfavorable operating conditions were established. The impacting factors on temperature effectiveness were evaluated. O.P. Arsenyeva et al. [24] discussed the optimal design of plate heat exchanger, which was a tool to increase heat recovery and efficiency of energy utilization. A mathematic model was firstly developed, the number of passes and plates were optimized and the plate type and size were discussed. The optimized plate heat exchanger exhibited better thermal and hydraulic performance. S. Gendebien et al. [25] developed a model of air-to-air heat exchanger that described both dry and partially wet regimes. The experimental investigation was conducted for the validation of the proposed model. The influence of the humidity on the latent and sensible heat recovery rate and strategies to avoid freezing have also been studied. X.P. Liu et al. [26] proposed a new analysis method to minimize the material cost and the fan energy consumption at any given operating condition for different geometric parameters. Based on their study, the manufacturing and operating cost could be synthetically optimized. T.C. Wang et al. [27] constructed experimental prototype and tested a new type metal foam-filled plate heat exchanger for using low grade waste heat. The results achieved high heat exchange efficiency. The authors also proposed some methods to improve heat exchange performance.

In order to investigate the regenerating performance in LDDS, researchers have developed several numerical models to describe the regeneration process. Kim et al. [28] developed a simple empirical model for regenerator by using statistical analysis of data operated under different conditions. The operating parameters were identified by response surface methodology. The proposed model has been verified by experimental data and other existing models. By using this model, the regenerating performance could be predicted and optimized. However, the authors applied a simple first-order polynomial formula to estimate the heat and mass transfer of the regenerating process. Liu et al. [29] proposed a finite difference model to study the heat and mass transfer process of regenerator in liquid desiccant. The regenerating performance of different regenerating heat source and different configuration of the air and desiccant flow have been compared. Their study was helpful for the design and optimization of regenerator. Yin et al. [30] derived a validated mathematical model to analyze the performance of a desiccant solution regenerator using hot air as the regenerating heat source. The effects of main operating parameters and dimensions of the regenerator on the regenerating performance have been discussed. The models proposed by Liu and Yin could present the regenerating process in detail, yet their deriving and resolving procedure are very complicated and are not suitable for online optimization. Wang et al. [31] evaluated the packed column regenerator in LDDS by a simple yet accurate hybrid model, which has been widely used in liquid desiccant dehumidifier [32], cooling coils [33,34], heat pipe heat exchanger [35] evaporator and condenser [36,37]. This kind of model treated the thermodynamic and geometric parameters as constant, lumped them together and identify them by Levenberg-Marquardt method. The experimental validation proved the accuracy and availability of the hybrid models.

In this paper, fix-plate heat recovery exchanger (FPHE) in regenerator of LDDS is investigated. To evaluate the regenerating performance, a simple yet accurate hybrid model is developed for the heat recovery process and combined with the regenerating heat and mass transfer hybrid model, the regenerating and heat recovery performance are predicted. The effects of air flow rate on the heat recovery and reemerging performance are also analyzed. The predicted results are validated by the experimental data.

2. Working principle of regenerator with heat recovery

Fig. 1 is the schematic diagram of LDDS. Dehumidifier and regenerator are two main components of LDDS. In dehumidifier, the liquid desiccant solution is cooled by the cooler and is sprayed into the tower from the top. The ambient air enters the dehumidifier tower from the bottom. They contact with each other on the surface of structured packing. After dehumidification, the air becomes cool and dry and is supplied to the room. The liquid desiccant solution absorbs the extra moisture of air and is diluted. Regenerator can recover the concentration of the solution and make sure its recirculation to dehumidifier. After heat and mass transfer between air and liquid desiccant in regenerator, the liquid desiccant drops down to the tank beneath regenerating tower and the warm regenerating air flows to the heat recovery device, which reutilize the waste heat of regenerating air to preheat the incoming fresh air.

The schematic diagram of regenerator with FPHE in LDDS is presented in Fig. 2. As shown in the figure, the regenerator with heat recovery consists of four components, namely regenerator tower, structured packing, heater and FPHE. In the FPHE, the hexagonal plate stacks with each other to shape alternating channel for two air stream.

The operating procedure of regenerator with heat recovery is briefly described below:

1. Driven by the temperature difference and water vapor partial pressure difference, both heat and mass transfer takes place in regenerator. The heat and mass continuously transfer from the liquid desiccant to the regenerating air. And finally, the liquid desiccant is cooled down and concentrated while the air is heated up and humidified to state A.
2. The warm regenerating air (state A) is exhausted from the regenerator and enters to FPHE, where it releases its thermal energy to preheat the incoming fresh air (state C). After being heat recovered, the temperature of warm regenerating air decreases and it is exhausted directly to the environment (state B).
3. Preheated by the recovered heat, the incoming air (state C) changes to state D with higher temperature and lower relative