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Simulation and energy saving analysis of high temperature heat pump coupling to desiccant wheel air conditioning system

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A B S T R A C T

The objective of this work is to investigate the energy saving potential of HTHP&DW (high temperature heat pump coupling to desiccant wheel) system by means of comparative analysis based on reference technologies. A complete numerical model of HTHP&DW system is established and the iterative algorithm is successfully applied and tested. The energy consumption, COP (coefficient of performance) and energy saving rate of HTHP&DW system are simulated under the different outdoor climates and indoor design conditions. The results show that energy saving rate of proposed system is 45.6% compared to CVC (conventional vapor compression) system and 30.5% compared to advanced HDC (hybrid desiccant cooling) system under the AHRI (Air-conditioning, Heating and Refrigeration Institute) design conditions. The impact of outside air humidity ratio is significant on the performance of HTHP&DW system. When the humidity is lower than 11 g/kg, the energy saving rate is up to 65% compared to CVC system. The lower indoor design temperature and higher indoor design humidity ratio are in favor of the energy saving of HTHP&DW system. Especially the energy consumption will decrease 20% when the indoor design humidity ratio increases 1.0 g/kg.

1. Introduction

The buildings in the developed countries account for about 40% of total energy consumption while this ratio is less in the developing countries [1]. On account of the rapid development of economy in the developing countries, the greater personal incomes allow people to enjoy higher standards of living and better comfort levels that results in the fast growth of building energy consumption. For example, the buildings in China consumed 1.9×10^7 GJ in 2008, which was 1.5 times that of 1998. This proportion was 25% of total energy consumption of the whole society [2]. Thus the energy for buildings in the developing countries will catch up soon along with the momentum of business boom. How to reduce the energy consumption for the buildings is an effective way to alleviate the pressure of the current worldwide energy resource shortage.

Desiccant cooling air conditioning system is attractive nowadays where depletion of energy resources and environmental degradation are worldwide concern. The biggest advantage of this system lies in the elimination of overcooling and reheating [3]. When the desiccant material is regenerated by means of “free” energy such as solar heat or waste thermal, the energy saving and the reduction of environmental impact are higher. However these applications are restricted for the local energy distribution, system structure, initial investment or operating cost. One common approach for desiccant cooling is to combine the vapor compression cooling system, desiccant component and regeneration heater together [8] (Hybrid desiccant cooling system referred as HDC system), which can be widely used for less limitation.

With the technology development of HTHP (high temperature heat pump), the released heat from the condenser of HTHP can satisfy the requirement of desiccant regeneration without additional heat. Hao et al. [4] explored the potential of integrating HTHP subsystem to the desiccant wheel (HTHP&DW system). Sheng et al. [5] introduced the mixture refrigerant BY-3 into the HTHP. The results showed that HTHP&DW system could be used in the extensive thermal hygrometric environment. Fang et al. [6] found that the desiccant wheel coated with silica gel could removal the air pollutants through recycling. The multi-stage desiccant system driven by heat pump was also studied by Tu et al. [7] and high *COP* (coefficient of performance) was obtained when the supply air

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humidity was over 10 g/kg. As aforementioned, the characteristics of removing air pollutants, less energy consumed and compact structure make the HTHP&DW system an appropriate technology for the development of air conditioning.

Energy analysis is the main method to evaluate the system performance. Some researches focus on the energy saving based on the annual operation data by means of theoretical analysis, numerical simulation and experimental investigation. Zhang [8] compared four independent air dehumidification systems with energy recovery strategies. Lee SH and Lee WL [9] calculated the energy saving rate of rotary desiccant cooling system in Hongkong on a basis of different ventilation rates. Kim et al. [10] showed that 51% less energy was consumed by liquid desiccant in the evaporative cooling assisted system compared to variable air volume system. Esen et al. [11] analyzed the *COP* of ground-coupled and air-coupled heat pump system on a basis of operation data in the cooling season.

Other researches evaluate the system energy saving under the specific conditions. Li et al. [12] reported the *COP* of HDC system based on primary energy usage and electricity usage under the hot humid weather. Niu et al. [13] investigated the energy saving potential of chilled-ceiling combined with desiccant cooling in hot and humid climates. The proposed system saved 44% of primary energy consumption in comparison with a conventional constant volume all-air system. The influences of specific parameters such as ventilation air flow rate, temperature and humidity of outdoor air, as well as regeneration-to-process air ratio on *COP* and energy consumption were also investigated [14]. Besides the effect of the composition of desiccant cooling system was studied. Antonellis et al. [15] analyzed seven HVAC (heating, ventilating and air conditioning system) configurations for product drying based on desiccant wheels. Simulations were carried out for different values of sensible to latent ambient load ratio and the effect of ambient and outside air conditions was evaluated for each configuration.

It can be observed in these literatures that the impacts of outside air conditions on the performance of HDC system in the previous works were investigated while the effects of indoor design conditions were scarcely mentioned, needless to say, quantitatively analyzed. The conventional vapor compression system was always chosen as the reference system. The advanced air conditioning system was rarely to be compared. The aim of this work is thus to study the performance of HTHP&DW system under the various outdoor air conditions and different indoor design conditions, as well as an evaluation of energy saving potential.

For the desiccant component, liquid desiccant and solid desiccant are the main patterns. Solid desiccant wheel attracts more attention for its compact, corrosion resistance and working continuous. Silica gel is always chosen as the desiccant material for high dehumidification efficiency [16] and easily obtained on the market. The silica gel is adopted as the adsorbent for the packed bed in the publications of Refs. [17,18], and positive results are achieved for the efficient dehumidification. Desiccant coated heat exchanger is proposed for the air dehumidification recently. The silica gel is also the first choice [19]. Another merit of silica gel is that it can be reactivated at the low regeneration temperature [20]. Therefore the desiccant wheel coated by silica gel is recommended in this paper.

In this work, the numerical model for HTHP&DW system is established and validated by the experimental data. Energy saving potential of HTHP&DW system is analyzed compared with reference technologies. Except the traditional vapor compression system, the HDC system is chosen as the reference system. The analysis is simulated under various outdoor air conditions which represent typical climate zones in China except the extreme weather. Indoor air design conditions are arranged based on the AHRI (Air-conditioning, Heating and Refrigeration Institute) design conditions (27 °C, 47% RH). In this way, the approaches for optimization of HTHP&DW system are discussed and some suggestions for system further development are provided.

2. HTHP&DW system and reference air conditioning systems

The schematic diagram of HTHP&DW system is shown in Fig. 1. There are two air flows entering the system:

Process air: Return air (N) and outdoor fresh air (W) are mixed to become the process air (C), dehumidified by the desiccant wheel (Cn for its compact, corrosion resistance and woto a comfortable level (E → O).

Regeneration air: Heated up by the condenser of HTHP (W → A) and expelled after regenerating the desiccant wheel (A → B).

Two reference systems are chosen, one is the CVC (conventional vapor compression) system and the other is HDC (hybrid desiccant cooling) system as presented in Fig. 1. The aim is to evaluate the energy saving potential under the different mechanisms of moisture removal (condensation dehumidification and adsorption dehumidification), as well as an analysis of the effect of HTHP by replacing the conventional heat pump (outlet air temperature usually no more than 50 °C) and regeneration heater.

3. Modeling

3.1. Desiccant wheel

One-dimensional coupled heat and mass transfer model is proposed based on the model by Zhang [21], and some corrections are made when the adsorbent is saturated as indicated in Eq. (2). The following assumptions are set before building the model:

- All ducts in the desiccant wheel are made of the same material and are of the same configuration.
- All ducts are assumed to be adiabatic.
- The rotary speed is uniform and is low enough to be reasonable to assume the rotary wheel as an inertia system.
- Axial heat conduction and mass diffusion in both the air stream and the desiccant wall are negligible.
- The effects of adsorption and desorption on the heat and mass boundary layer are negligible.
- The hygroscopic capacity of matrix material is negligible.
- The thermodynamic properties of dry air, vapor and desiccant are constants.
- The heat and mass transfer coefficient between the air stream and the desiccant wall is constant along the air channel.

Within the differential element *dz*, the following conservation and transfer equations are derived.

Mass conservation between air stream and desiccant wall:

$$\frac{\partial Y}{\partial t}+v\frac{\partial Y}{\partial z}+w_1\frac{\partial W}{\partial t}=0 \tag{1}$$

Mass transfer on the desiccant wall:

$$\frac{\partial W}{\partial t}=\begin{cases} w_2(Y-Y_d), \ when\ W<W_{\max} or\ W=W_{\max},\ and\ Y<Y_d \\ 0,\ when W=W_{\max}\ and\ Y>Y_d \end{cases} \tag{2}$$

When $W = W_{max}$ and$Y > Y_{d,}$ the water concentration in the air is higher than the equilibrium adsorption concentration, however, no adsorption occurs in this case for the saturation of adsorbent.

Energy conservation between air stream and desiccant wall: