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Theoretical study on volatile organic compound removal and energy performance of a novel heat pump assisted solid desiccant cooling system

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A B S T R A C T

A theoretical model was established for predicting the volatile organic compound (VOC) removal and energy performance of a novel heat pump assisted solid desiccant cooling system (HP-SDC). The HP-SDC was proposed based on the combination of desiccant rotor with heat pump, and was designed for cooling, dehumidification and indoor air cleaning in normal office, commercial or residential buildings. The desiccant rotor was used for dehumidification and indoor air cleaning; the heat pump provided sensible cooling and regeneration heat for the desiccant rotor. The theoretical model consisted of two sub-models. One sub-model was used to simulate the heat, moisture and VOC transfer in the desiccant rotor; the other sub-model was used to predict the energy performance of the heat pump. Combining the two sub-models, the energy performance and VOC removal effect of the HP-SDC could be simulated and predicted. The theoretical model was validated by experimental data. Validating results showed that the model could be used to predict the performance of HP-SDC. The results also showed that the HP-SDC could clean air borne contaminants effectively and could provide an energy efficient choice for ventilation.

1. Introduction

Great efforts [1–6] have been taken to do research on solid desiccant cooling system since Pennington acquired the first patent of solid desiccant cooling system in 1955 [7]. Studies showed that when the desiccant rotor was regenerated with thermal sustainable energy such as solar energy [8–10], energy from co-generators [11,12], and waste heat [13], energy conservation could be realized. But the using of solar energy, co-generator and waste heat is normally limited by regional and climate factors. To break the barrier, studies on heat pump assisted hybrid solid desiccant cooling system were brought forward [14–17], the studies of Jia et al. [14] and Hao et al. [15] used additional heateres before the desiccant rotor to get a high regeneration air temperature, but the additional heater decreased the energy efficiency of the overall system. The study of Zhang et al. [16] and Sheng et al. [17] used high temperature refrigerant to achieve high regeneration temperature, but the coefficient of performance (COP) of the heat pump was not high.

In addition to the research on cooling and dehumidification performance of solid desiccant cooling system, Fang et al. [18–20] and Zhang et al. [21] found the indoor air purification potential of desiccant rotor. In the study of Fang et al. [20], more than 80% of sensory air pollutants from building materials, human emissions and dosed chemicals were monitored to be removed by a silica gel desiccant rotor. These studies give new ideas to use desiccant rotors in ventilation systems as indoor air quality were found to have important influences on indoor occupants' health and working performance [22–24]. If silica gel rotor can be applied to clean indoor air and improve indoor air quality, then less outdoor fresh air could be used to control indoor air quality, and thus energy conservation for building ventilation could be realized. Based on the air

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purification capacity of silica gel rotor, Nie et al. [25] designed, developed and tested a unit called clean air heat pump. The clean air heat pump (CAHP) is termed as heat pump assisted solid desiccant cooling system (HP-SDC) in this paper. The HP-SDC combined silica gel rotor with heat pump and integrated indoor air purification, dehumidification and cooling in one unit. The testing results from Nie et al. [25] showed that to keep same indoor air quality, the clean air heat pump could save substantial amount of energy compared to conventional air source heat pump, but the energy saving varied greatly with the outdoor thermal climate conditions.

Though the study of Nie et al. [25] has tested the energy performance of the HP-SDC under different outdoor thermal conditions, it is difficult to predict its energy performance and indoor air purification effect under global conditions. With the variability of indoor thermal loads, indoor pollutant loads and outdoor thermal conditions, the energy and air purification performance of the HP-SDC are quite different, and it is impossible to test it in a lab under all climate conditions. A more realistic approach to predict the performance of the HP-SDC could be using numerical models.

In the study presented by this paper, a theoretical numerical model for the HP-SDC was established. The model consists of two sub-models including a one dimensional silica gel rotor sub-model for heat, moisture and VOC transfer simulation and a heat pump sub-model for energy prediction. The model was validated with experimental data. With the model, the effects of outdoor thermal environments to the air cleaning and energy performance of the HP-SDC were analyzed.

2. Principle of heat pump assisted solid desiccant cooling system

A typical HP-SDC consists of a silica gel rotor and a heat pump. The silica gel rotor was used to dehumidify and clean the ventilation air. The heat pump was used to cool the ventilation air and provide regeneration heat for the silica gel rotor. The principle of the HP-SDC is given in Fig. 1.

In operation mode of the HP-SDC, indoor air is taken from the ventilated room. A small part of the indoor air is expelled outside, and the rest is used as recirculation air. The recirculation air is mixed with outdoor fresh air to form process air. The process air is dehumidified and cleaned by the silica gel rotor, and then cooled by the evaporator of the heat pump. After being cleaned, dehumidified and cooled, the process air is delivered into the ventilated room to keep a comfortable and healthy indoor environment. On the other side, the regeneration air taken from outside is heated up by one condenser of the heat pump, and then used to reactive the silica gel rotor. Calculation work before the system design found that, in most cases of summer, the condensing heat is more than what is required for regenerating the rotor. Dual-condensers were thus designed in the heat pump to expel extra heat generated from the heat pump and control the heating for the regeneration air at the exact amount demanded by dehumidification. The air taking extra heat from the heat pump is finally mixed with regeneration air (after regeneration), exhausted air from the ventilated room and finally expelled to outdoor ambient. The expelled air carries sensible, latent heat and the concentrated indoor air pollutants away from the ventilated room.

The advantages of such a design are the following:

1) Energy on both sides of the heat pump is fully used and contributed to the cooling, dehumidification and air cleaning process. The condensing heat from the condenser is used to regenerate the rotor (removing moisture and indoor air pollutants from the process air). The cooling from the evaporator is used to cool the recirculation air (removing sensible heat from the process air).
2) The system is working in a completely dry environment (no water condensation occurs on the evaporator of the heat pump since moisture is removed by the silica gel rotor). This can effectively prevent the growth of bacteria and mold in the system.
3) The system can process large quantities of recirculation air and remove pollutants from the air, which will be equivalent to a high outdoor air ventilation rate. The air cleaning by the silica gel rotor takes place together with the dehumidification. Therefore, the air cleaning does not consume extra energy.

Thus, such a system devoting to indoor air cleaning can provide a large quantity of effective ventilation air without a significant amount of energy consumption.

3. Theoretical model for heat pump assisted solid desiccant cooling system

To predict the performance of the HP-SDC under different climate conditions, a theoretical model for the HP-SDC was

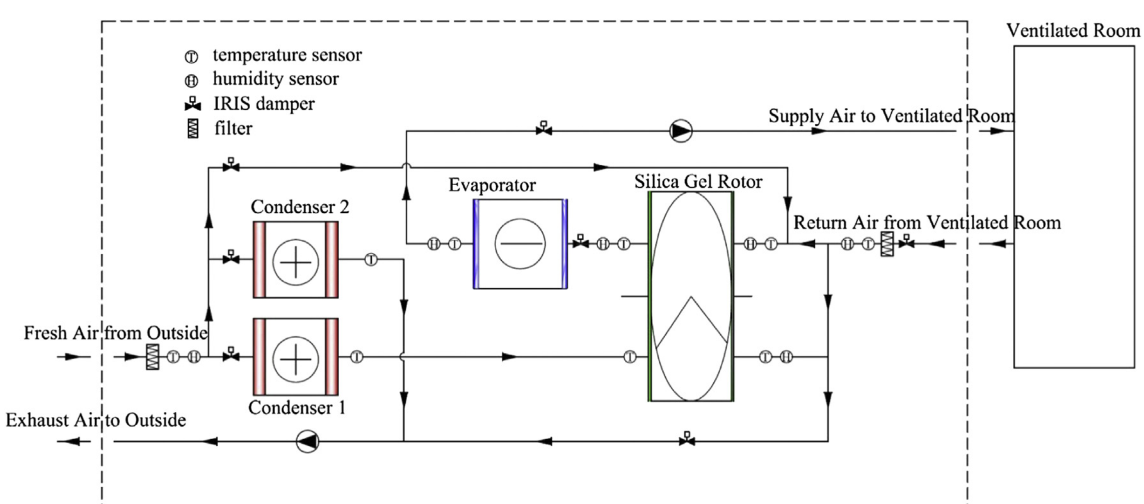

Fig. 1. Schematic diagram of the heat pump assisted solid desiccant cooling system.