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An experimental evaluation on air purification performance of Clean-Air Heat Pump (CAHP) air cleaner

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ABSTRACT

The escalation of energy consumption in buildings and heightened concerns about acceptable indoor air quality stimulate interest in the usage of air cleaner as an adjunct for indoor environmental conditioning. A regenerative desiccant wheel integrated into a ventilation system termed Clean-Air Heat Pump (CAHP) can improve the air quality during the process of dehumidification without using additional energy. An experimental study in a field lab was performed to investigate the air cleaning performance of CAHP. Photoacoustic gas analyzer-INNOVA was used to characterize chemical removal of indoor air pollutants by the CAHP. The results revealed that all the detected VOCs were removed effectively by the CAHP with an average single pass efficiency of 82.7% when the regeneration temperature for desiccant wheel was 60 °C. The mass balance between adsorption and desorption of the desiccant wheel was 96.8%, which indicated that the most of gaseous pollutants were not accumulated in the CAHP. The regeneration temperature for the wheel could affect the air purification performance of CAHP. At 70 °C of regeneration temperature, the air-cleaning efficiency reached 96.7%. Up to 70% of the outdoor air ventilation can be saved with the operation of CAHP. The clean air deliver rate (CADR) was over threefold of the outdoor air supply rate when CAHP was in operation.

1. Introduction

Inevitable presence of chemical gas pollutants emitted from building materials, furniture, detergents, indoor facilities and people's activities in indoor environment has an adverse impact on human health and productivity. Some studies have reported that a higher ventilation rate, as high as over 20 L/s per person [1,2], can improve the indoor air quality and thus minimize prevalence of SBS symptoms [3,4]. However higher ventilation rate results in a significant increase in energy consumption in buildings, which opposes the current trend for sustainable buildings. Furthermore ventilation, although important, may not always provide a clean indoor environment, e.g. in areas with high outdoor pollution [5,6]. An alternative method by usage of air cleaning for pollutants control as an adjunction for ventilation has been much practical to attain acceptable indoor air quality and benefit for reducing energy cost for ventilation. Cho et al. [7] found that the energy use was reduced by nearly 20% when the air-cleaning unit was operated with demand control ventilation in an energy simulation using TRNSYS software. Han et al. [8] reported that an integration of ventilation and air cleaning technology was promising in achieving the indoor air quality constraints for major indoor compounds and the annual energy cost was reduced 11% in a mild climate, based on a numerical simulation. The study by Sidheswaran et al. [9] indicated that a combination of activated carbon fibre air cleaning with a 50% reduction in ventilation would still remove 60–80% of indoor VOCs. Ventilation combined with air-cleaning may maintain indoor air quality with a reduced consumption of energy.

However what type of air purification technology is the most effective method for pollutants removal and the most practical to be combined into a ventilation system still need be to studied. Photocatalytic oxidation (PCO) is regarded as one of the most promising methods. In fact, generation of by-products is one of the main concerns associated with the application of PCO technology in buildings since some of these by-products can be even more toxic than their parent compounds. For example, benzaldehyde, benzoic acid, benzyl alcohol, phenol and benzene were found to be the intermediates during photocatalytic oxidation of toluene [10–13]. Plasma air cleaners were reported to remove particles at high efficiency within the range of 76–99% but not efficient at removing gas-phase pollutants [14–16]. The production of secondary pollutants such as NOx and O_3 was also a main drawback of plasma technology [15,16]. Ozone could react with some indoor pollutants but ozone itself had harmful effect on human

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body [17,18].

Compared to these air purification technologies using oxidation principles, sorption technology is commonly used in the indoor environment and effective in removing the most of indoor pollutants. Activated carbon [7–9] is one of the most commonly used sorption techniques in practice. Some limitations of activated carbon as an absorbent are that the temperature must usually be higher than 150 °C to achieve adequate regeneration, that this requires abundant energy, and that the air-cleaning effectiveness for formaldehyde is relatively low [8,19]. Another adsorbent is silica gel. It is well known that the silica gel desiccant wheel was usually applied for dehumidification in a ventilation system. Great efforts have been taken on its dehumidification performance [20–22] and energy conservation [23–25]. Fang et al. [26] and Zhang et al. [27] accidentally found the indoor air purification potential of regenerative desiccant rotor. In Fang et al.'s study [26], more than 80% of sensory pollution loads from building materials, human emissions and dosed chemicals were removed by a silica gel rotor. These findings indicate a desiccant wheel as an air cleaner except for dehumidification. Based on air purification capacity of desiccant wheel, Nie et al. [28] designed, developed and tested a unit termed as Clean Air Heat Pump (CAHP). CAHP included a silica gel rotor and a heat pump. The recirculation air from the conditioned room was mixed with outdoor air to form process air, which was dehumidified and cleaned by the silica gel rotor, then cooled by the evaporator of the heat pump and delivered to the room. On the other side, the regeneration air taken from outside was heated up by the condenser of the heat pump, and then used to reactive the silica gel rotor. In the past decades, a substantial energy consumption for the regeneration of desiccant wheel limited the development of solid desiccant wheel technology. Although the energy conservation could be realized when the desiccant rotor was regenerated with thermal sustainable energy such as solar energy [29], energy from co-generators [30], and waste heat [31], their applications were normally limited by regional and climate factors. The proposed method of CAHP can regenerate the wheel by the condensing heat from the heat pump to save energy, which significantly improved the thermal performance of ventilation system and made a great progress in the development of desiccant cooling air conditioning system.

Nie et al. [28] has made a numerical model to evaluate the air cleaning performance of CAHP and showed that CAHP could clean indoor air with a VOCs removal efficiency of at least 65%. However its real air purification performance in a complex indoor environment is difficult to be predicted by the numerical simulation. The acquisition of field performance data of CAHP for pollutants removal is indispensable to help the development of CAHP system.

The inlet states of process air and regeneration air for the wheel (air temperature, humidity and air flow rate) may affect the adsorption performance of a desiccant wheel to certain extent. Among these parameters, regeneration air temperature has a significant impact on the adsorption. Angrisani et al. [32] evaluated the dehumidification performance as a function of the regeneration temperature, the inlet process air humidity and temperature and the ratio between the regeneration and process air flows. It showed that the regeneration temperature influenced the desiccant wheel performance more than other parameters. Many researches [33–37] also obtained similar results that higher regeneration air temperature would lead to an increase in dehumidification efficiency. Since the process of pollutants removal takes place in parallel with moisture removal, the regeneration air temperature may also have an impact on the pollutants removal.

In this study, the effect of regeneration air temperature on the air cleaning performance of the silica gel rotor will be focused and analyzed. A CAHP system was designed and installed in a field lab. The air cleaning performance of CAHP on indoor air quality improvement was examined by means of chemical measurement when a field lab was polluted by the building decoration materials and pure chemical compounds.

2. Method

2.1. Approach

The indoor pollution sources adapted from ordinary office combined with some chemical compounds were placed in a test room which was ventilated at a low outdoor air supply rate. Recirculated air was purified by a CAHP air purification system. Air pollutants removal capacity of the CAHP was monitored by Photoacoustic Gas Monitor-INNOVA 1312. The regeneration air temperature (T_{reg}) for the silica gel rotor in the CAHP was in the range of 25–70 °C.When the CAHP was operated at T_{reg} = 60 °C, air-cleaning performance of CAHP was emphatically analyzed. (The indoor latent load can be removed at the most climate zones when the silica gel rotor was regenerated at 60 °C based on our previous study [38]. Therefore it was selected as a typical case for an independent analysis).

2.2. Experimental facility

The present investigation was carried out in a field lab located in Technology University of Denmark. This field lab was separated into two zones by a wall made of low emitted construction material as presented in Fig. 1. The space in front of the wall was used as a test room and the space behind the wall was used to accommodate the experimental facility. The test room had a floor area of 72 m^2 and a volume of 216 m^3.

A commercially-available silica gel rotor and a double-condenser heat pump were incorporated in a ventilation system to constitute the Clean Air Heat Pump, namely CAHP system. The silica gel rotor was produced by Munters A/S and its main physical properties are given in Table 1. A piston compressor "2GC-2.2" branded with Bitzer was used with the max power consumption of 2.7 kW. The type of evaporator and condenser was air source chip tubular. An electronic expansion valve "AKV10-6" produced by Danfoss was selected to be the throttle device in the heat pump. The R134a was chosen as the refrigerant.

In the operation mode, the return air was mixed with a small amount of outdoor air (process 1,8 → 2) and then processed by the silica gel rotor where a large amount of moisture and indoor pollutants were expectedly removed (process 2 → 3). In this process, the mixed air is dehumidified, cleaned and warmed up. The mixed air will then be cooled by the evaporator of the heat pump (process 3 → 4). Finally, the cool, dry and clean air is delivered into the test room to keep a healthy and comfortable indoor environment (process 4 → 5). On the other side of the heat pump, one stream of outdoor air was heated up by Condenser 1 of heat pump was used to regenerate the rotor (process 7 → 9→10 → 11→13). The other stream passed through Condenser 2 and was used to reject the extra heat generated by the heat pump (process 7 → 12→13). This dual-condenser configuration was required to avoid overheating the silica gel rotor (see Ref. [38] for details). Finally some exhaust air from the test room and the regeneration air after regenerating the rotor together with the air carrying the extra heat were rejected to the outdoor ambient (process 6,13 → 14).

For the air system of the CAHP, one heat pump was designed and its schematic diagram is given in Fig. 2. As mentioned above, there were two condensers in the heat pump. The Condenser 1 was used for heating the air to regenerate the silica gel rotor, and the Condenser 2 was used to reject the extra heat generated by heat pump to avoid the over dehumidification of the wheel. A variable speed piston compressor was used in the heat pump of the CAHP prototype. The variable speed control of the compressor ensured that the heat pump can adapt to different heating and cooling demand. With the speed variable piston compressor, an electronic expansion valve was used to control the superheat degree of the refrigerant in the evaporator of the heat pump.