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Experimental evaluation on energy performance of innovative clean air heat pump for indoor environment control in summer and winter seasons

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ABSTRACT

Based on the air purification capacity of regenerative silica gel rotor, an innovative clean air heat pump (CAHP) was designed, developed and investigated through experimental studies. The CAHP integrated air purification, dehumidification and heating/cooling in one unit. A prototype of the CAHP was developed. Laboratory experimental studies were conducted to investigate its energy performance under different outdoor climates including cold, mild-cold, mild-hot and extremely hot and humid climates. The energy performance of the CAHP was then evaluated by comparing with a conventional air source heat pump. The results showed that to keep same indoor air quality, the CAHP could save substantial amount of energy. For example, compared to the conventional air source heat pump, the CAHP could save up to 59%, 40%, 30% of electricity for ventilation and air conditioning in a test room in summer of Copenhagen, Milan and Colombo, and could save 5%, 13% of electricity for ventilation and heating in the test room in winter of Copenhagen, Milan.

1. Introduction

Ventilation is essential for health and comfort of occupants indoor. Due to comfort and health concerns, the ventilation rates prescribed by the existing ventilation criteria and guidelines [1,2] are in the range from 9 to 36 m^3/h per standard person. However, many studies showed that even 36 m^3/h per person of outdoor airflow rate is not sufficient to remove indoor air pollutants which can lead to the risk of sick building syndrome (SBS) and short-term sick leaves [3]. A World Health Organization reported that up to 30% of new and remodeled buildings worldwide may have the risks of SBS [4,5]. An insufficient ventilation rate also leads to the decrease of working performance among the occupants in office buildings [6]. Increasing the outdoor air supply rate decreased concentrations of indoor air pollutants including those emitted by building materials, furnishing and human bio effluents [7]. However, further increases in ventilation rate are hardly acceptable due to the energy consumption concerns. Ventilation usually requires a substantial amount of energy. In most buildings, ventilation accounts for as much as 30% of energy consumption [8]. This proportion can be even higher in well-insulated and airproof low-energy buildings. Modern technologies of thermal insulation and airproof buildings have been highly developed to make it possible to limit the heat loss/gain between buildings and the outdoor environment. In contrast to thermal insulation and airproof technology, ventilation has become a bottleneck on reducing the total energy consumption in buildings.

On the other hand, the classical ventilation concept—which assumes that the outdoor air is clean maybe not valid any more in most modern cities. Toxic gases and ultra-fine particles emitted from vehicles and industries make outdoor air polluted, and they can be transmitted into indoors by ventilation. Positive correlations between mortality and particle concentrations (especially ultra-fine particle concentrations) have been found in epidemiological studies [9–11]. These studies showed the importance of controlling the concentration of indoor ultra-fine particles. Normal particle filters cannot prevent most of the ultra-fine particles from entering indoors through ventilation systems. Although high efficiency filters can be used to remove fine particles, they also produce high pressure drop, which result in much higher electric power consumption for the ventilation fans. On the other hand, overdue filters may constitute pollutants sources of particles [12–15]. In the study by Bekö et al. [15], dirty dust filters had been identified as pollution sources that emit gas phase pollutants due to the oxidation effect of outdoor ozone. Hence, the best solution to decrease

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energy consumption for ventilation and maintain a healthy and comfortable indoor environment is to develop energy efficient air purification technology to clean indoor air and use less outdoor air for ventilation.

The indoor air pollutants were normally considered to be from building materials, ventilation systems and human activities [16,17]. Different from outdoor air pollutants, indoor air pollutants are difficult to remove since most of them are volatile organic compounds (VOC) including formaldehyde, ethanol, toluene, 1,2-dichloroethane and so on. VOC can stimulate occupants' tissues and organs including the ocular mucosal, nasal, throat, skin, face, neck, hands, upper and lower respiratory tract [18]. The influence of VOC to humans belongs to acute response, and people tend to produce olfactory adaptation after a long time exposure [19]. But some sub-acute effects (such as headaches) will be more frequent and heavier with the increasing of exposure time to VOC pollutants [20]. Great efforts have been taken to do researches on removing VOC by means of air-cleaning devices, but major difficulties are encountered because of the wide range and low concentration of indoor air chemicals. Currently available air cleaners use sorption filtration, photo catalytic oxidation, ozone oxidation, air ionization, etc. Recent studies [21–23] have found that sorption filtration is more effective than other approaches. Desiccant materials are a subset of sorbents that are normally used for dehumidification, and they can also be used to remove gases other than water vapor from air in previous studies [24–29]. In the study of Fang et al. [28], the air cleaning efficiency of silica gel rotor was evaluated by PTR-MS and sensory assessment, and the results revealed that the measured VOCs were removed effectively by the desiccant wheel with an average efficiency of 94% or higher; more than 80% of the sensory pollution load was removed and the percentage dissatisfied with the air quality decreased from 70% to 20%. Great efforts and studies have been made to take the dehumidification capacity of silica gel rotor into ventilations systems [30–33]. However, the air cleaning capacity of regenerative silica gel rotor has not been combined to ventilation systems until now.

In the study presented by this paper, an innovative clean air heat pump (CAHP) was designed and developed based on the air cleaning capacity of silica gel desiccant wheel. It has integrated air purification, dehumidification and cooling in one unit. Experimental studies were conducted to investigate the energy performance of the CAHP operating in different climate conditions.

2. Methodologies

The principle of the clean air heat pump (CAHP), the prototype development, the experimental setup, the experimental design and the data analyzing methods are stated in this section.

2.1. Principle of CAHP

The clean air heat pump was proposed based on the adsorption capacity of regenerative silica gel rotor. Previous studies [28,29] showed that the regenerative silica gel rotor has high air purification efficiency, and it doesn't produce any by-product during the air purification process. To allow this air cleaning technology to be applicable in ventilation system, silica gel rotor was designed to be cooperated with heat pump in the proposed CAHP ventilation technology. The CAHP was designed to be used for both summer and winter seasons when the thermal load of a ventilation system can be dehumidification, cooling or heating. The air system schematic diagram of the CAHP is given in Fig. 1. In the CAHP, two evaporators are used in one heat pump, one is used in summer and the other is used in winter. There are dual-condensers as well in the heat pump, one is used for heating the regeneration air, and the other is used to take away the excess heat generated from the heat pump (in summer) or used to heat up the fresh air (in winter). Outdoor fresh air supplied to the ventilated room is switched by dampers to select whether it is heated by the condenser or not. In summer, it is taken directly from outside without heating, while in winter it is heated up by a condenser of the heat pump. Temperature and humidity sensors were installed in various locations of the CAHP prototype for monitoring the air thermal conditions during the treatment process.

In summer operation mode of the CAHP, ventilation system supplies minimum levels of outdoor airflow and recirculates a large quantity of indoor air. The recirculated air is mixed with the outdoor fresh air and then processed by the silica gel rotor where a large amount of moisture and indoor air pollutants are removed by the rotor. 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. Finally, the cool, dry and clean air is delivered into the ventilated room to keep a healthy and comfortable indoor environment. On the other side of the heat pump, the regeneration air from outdoor is heated up by one condenser of the heat pump and used to regenerate the silica gel rotor. After the regenerating work, the regeneration air is mixed with some indoor exhaust air and carries both sensible, latent heat and indoor air pollutants out of the ventilated room. Calculation work before the experimental studies found that, in most cases of summer, the condensing heat is more than what is required for regenerating the rotor. If all the condensing heat is used to regenerate the rotor, it may over dry the ventilation air and increase the cooling load of the evaporator and, in turn, increase the speed of the compressor which results in a higher energy consumption. The dual-condensers design was adopted to control the heating for the regeneration air at the exact amount as demanded by dehumidification. In this dual-condensers design, the extra condensing heat is rejected directly by the second condenser without feedback to the evaporator.

From this design, energy on both sides of the heat pump is used and contributed for air purification, dehumidification and cooling. The condensing heat is used to regenerate the rotor (removing latent heat and pollutants). The evaporating cooling is used to cool the process air (removing sensible heat). The system is working in a completely dry environment, no water condensation occurs on the evaporator of the heat pump since the moisture was removed by the silica gel rotor. This could effectively prevent the growth of mold and bacteria in the air-conditioning system. The CAHP system cleans a large quantity of recirculation air and removed pollutants from the air, which could be equivalent to a high outdoor air ventilation rate. In the study of Fang et al. [28], 80% of the cleaned recirculation air by silica gel rotor could be used as outdoor fresh air. Meanwhile, the air cleaning by the silica gel rotor takes place together with dehumidification, and it doesn't consume extra energy. Therefore, such a system devoted to air cleaning can provide a large quantity of effective ventilation air without significantly extra energy consumption.

In winter operation mode of the CAHP, the recirculation air is cleaned by the silica gel rotor as well. Different from the summer mode, the regeneration air temperature could be much lower than it is in the summer mode since much less moisture needs to be removed from indoor air in winter time. However, in previous study [28], it was found the low regeneration temperature does not affect the air purification efficiency of the silica gel rotor. The recirculation air is, therefore, cleaned and slightly heated by the rotor in the winter operation mode. The heating effect of the rotor is also favorable for winter use. The recirculation air – after being cleaned, slightly dehumidified and heated by the rotor – is mixed with the heated outdoor air and then delivered into the room. The regeneration air for the silica gel rotor is outdoor air which is heated by the condenser of the heat pump. After regenerating the rotor, the warm