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Energy-efficient air conditioning system with combination of radiant cooling and periodic total heat exchanger

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ABSTRACT

The main thrust of this paper is directed toward a novel air conditioning system that can maintain a healthy indoor environment and be energy-efficient. This system consists of a low-temperature regenerative periodic total heat exchanger, radiant ceiling-cooling coil, and conventional air conditioner. The natural cold energy of the tap water in the cooling coil provides comfortable and uniform cooling, and the desiccant-packed bed in the total heat exchanger recovers the indoor energy to handle the fresh air. The performance of each component is discussed, and the actual performance of the whole system is investigated in an office at the Taipei Water Department. The results indicate that using a radiant ceiling-cooling coil to precool the indoor environment enables the traditional window-type air conditioner to reduce two-thirds of the original operating time. In addition, the test of the whole system was conducted in the same office, and it was observed that using this system to handle the incoming air could save 13%–19% of the energy consumption per month during a year-round operation compared to directly introducing untreated fresh air.

1. Introduction

In Taiwan, the annual average humidity ratio is up to 80% RH. Living in such a high humidity environment not only makes people uncomfortable, as the skin moisture is difficult to evaporate, but also causes some severe skin and respiratory diseases. The most common method of removing moisture from the air is using cold water produced by a chiller to cool the air below its dew point, and then re-heating the air to achieve the applicable temperature level. This approach, however, is very energy expensive, because it involves both cooling and heating. In addition, according to the statistics published by the Bureau of Energy, Ministry of Economic Affairs, Taiwan, the energy consumption of an air conditioning system in the summer accounts for approximately 41% of total residential energy consumption [1]. Thus, it is imperative to find an alternative way to dehumidify indoor air.

Using desiccant material to adsorb the moisture in the air seems to be a good method of air conditioning. Desiccant dehumidifiers are divided into two types—liquid desiccant and solid desiccant. Liquid desiccant cooling is popular in the air conditioning industry due to its appealing characteristics, such as operational flexibility, ability to absorb pollutants and bacteria, and relatively lower-temperature regeneration conditions compared to solid desiccant cooling [2]. Thus, there have been many studies in this field [3–7], and the dehumidification technique has even been adopted widely for humidity control in industry and agriculture. Bassuoni [6] presented an experimental investigation on the performance of the structured packing cross flow desiccant dehumidification system using Calcium Chloride solution, and the payback period of this system was 11 months with running cost savings of approximately 31.24% compared with vapor compression system. Lychnos and Davies [7] investigated the feasibility of a $MgCl_2$ liquid desiccant system for greenhouse cooling. Compared with conventional evaporative cooling, this system lowered daily maximum temperatures in hot season by 5.5–7.5 °C, and therefore the growing seasons of some crops such as lettuce, soya bean, tomato, and cucumber could be prolonged. On the other hand, solid desiccant cooling is also widely used [8–12], due to its simple handling of desiccant material [8]. Ge et al. [12] proposed a novel one-rotor two-stage rotary desiccant cooling system of which the size was reduced without decreasing performance.

The total heat exchanger in this paper adopts solid desiccant beds to substitute for the traditional parallel-plate heat exchanger, and the total heat exchanger uses periodic flow to the fixed desiccant bed for periodic adsorption and regeneration. This periodic operation maintains the good adsorptive capacity of the

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desiccant-packed bed. In 2009, Hsu [13] first applied periodic flow to the recuperator, and he put in heat and moisture storage materials in the inlets and outlets of the recuperator to improve the performance with periodic flow. Yang [14] then obtained the US patent for a double flow circuit heat exchanger device for periodic positive and reverse directional pumping in 2010. In the same year, Chen [15] applied periodic flow to a fixed commercial honeycomb silica gel wheel and discussed the influence of the operating period on the performance of the total heat exchanger. Because the price of the commercial honeycomb silica gel wheel is too expensive, Hsieh [16] tested the adsorption and desorption capacities of some adsorbent materials packed in the bed, such as silica gel, activated alumina, and molecular sieve, and tried to find a substitute for the commercial honeycomb silica gel.

Radiant ceiling cooling, which is applied in our system to deal with the sensible load part, has been popular for many years due to its appealing characteristics of low energy consumption and nice thermal comfort, and it was first investigated in laboratory studies in European countries around the early 1990s [17]. Niu et al. [18] compared the annual energy consumption characteristics of the water-panel-type cooled-ceiling system with conventional all-air systems. The results indicated that a cooled-ceiling system could save much of the fan energy required in all-air systems, and the system had a compatible energy performance with a variable air volume (VAV) system for office building cooling purposes in the temperate Dutch climate. In addition, some studies have discussed thermal comfort in the radiant cooling system. Zhang and Niu [19] stressed that the radiant cooling with independent dehumidification and ventilation had high potential to provide better thermal comfort and air quality than conventional all-air systems. Vangtook and Chirarattananon [20] reported that thermal comfort could be obtained with application of radiant cooling using comfort criterion adopted by ASHRAE and International Standards Organization. Niu et al. [11] summarized the advantages of the radiant cooling system. First, the energy consumption of the pump required to move heat in a water-based system was much lower than that of fans in an air-based system. Second, the radiant cooling system improved thermal comfort due to its uniform cooling. Third, the zone control of the system is simpler and more effective.

Indoor air quality is an increasingly important issue these days, and introducing outdoor fresh air is essential. However, this ventilating process burdens the traditional air conditioner. Zhang [21] analyzed four independent air dehumidification systems with energy recovery measures like a heat pump, membrane enthalpy recovery, sensible heat exchanger and desiccant wheel, and the simulation results indicated that the systems with energy recovery could save 29–42% of primary energy. In the present study, a novel energy-efficient air conditioning system, composed of a periodic total heat exchanger, radiant ceiling-cooling coil, and a traditional window-type air conditioner, is proposed in order to reduce energy consumption due to ventilation. The desiccant-packed bed is the basis of the total heat exchanger system. In contrast to traditional rotary desiccant dehumidifiers, the dehumidifiers in this system are stationary, and this system uses four centrifugal fans for periodic adsorption and regeneration. Such a design not only reduces some energy consumption of desiccant rotation, but also maintains the good adsorptive capacity of the desiccant bed. In addition, the traditional desiccant dehumidifier uses high-temperature and low-humidity gas to regenerate the desiccant wheel to maintain solid adsorptive effect. The demands for environmental humidity control of general residential space, however, are not as rigorous. As a result, if the lower regeneration condition could fill the requirement for a comfortable environment, the system would save substantial energy, because the additional regeneration heat source would not be needed. Moreover, the radiant ceiling-cooling coil in the cooling system uses natural cold energy from tap water and provides comfortable and uniform cooling. Finally, this research aims at investigating the practical performance and energy conservation of the novel air conditioning system.

2. Description of the energy-efficient air conditioning system

Fig. 1 shows a schematic of the novel energy-efficient air conditioning system, which consists of a periodic total heat exchanger, radiant ceiling-cooling coil, and a traditional window-type air conditioner. In this system, the incoming outdoor air is first cooled down and dehumidified by the periodic total heat exchanger, and then conditioned to the desired indoor air condition by the radiant ceiling-cooling coil and the traditional window-type air

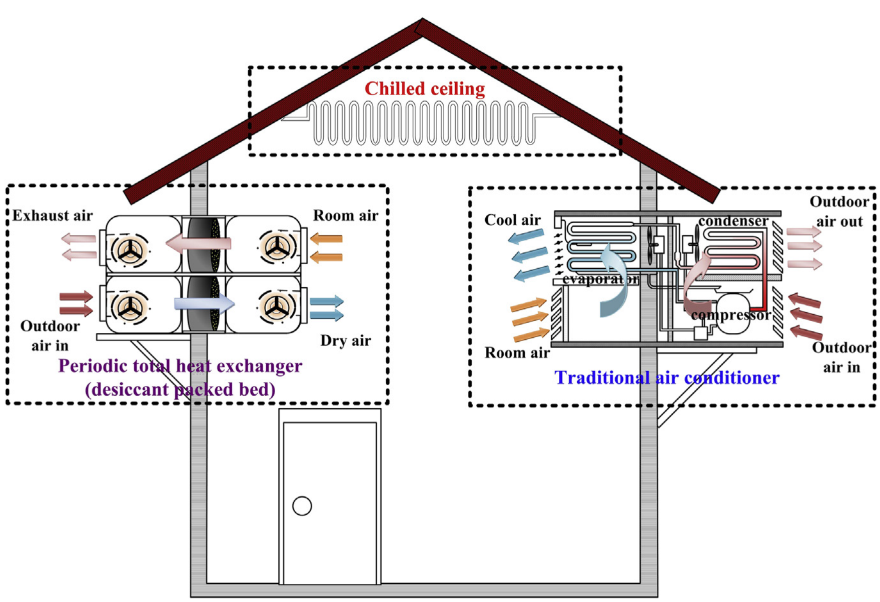

Fig. 1. Schematic view of the energy-efficient air conditioning system.