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Investigation on solar hybrid desiccant cooling system for commercial premises with high latent cooling load in subtropical Hong Kong

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A B S T R A C T

This study found that the solar hybrid desiccant cooling system (SHDCS) was more effective to handle the premises with high latent cooling load in the hot and humid climate compared to the conventional air-conditioning system. The SHDCS was designed to use the solar-thermal desiccant cooling to tackle the latent load; and the electrical vapour compression refrigeration to cater the sensible load. In this study, the typical commercial premises with high latent load were the Chinese restaurant and the wet market. The effectiveness of SHDCS included both better indoor cooling performance and higher year-round energy-saving potential. The annual primary energy consumption of SHDCS could be lower than that of the conventional system by 49.5% in the Chinese restaurant and 13.3% in the wet market. For the premises with more stringent temperature and humidity requirements, like the Chinese restaurant, the contribution of SHDCS in energy saving would be significant. Utilization of solar energy could ensure the energy-saving potential of SHDCS for the premises with high latent load. As a whole, the study assures the wider application of solar air-conditioning in the subtropical Hong Kong.

1. Introduction

A general air-conditioning (AC) design is to make use of a cooling coil to handle both the cooling and dehumidification processes. This is suitable for the typical offices and residential units, where the sensible-to-heat ratio (SHR) of the zone cooling load is high. The SHR is defined to be the ratio of zone sensible cooling load to zone total cooling load, which is the sum of sensible and latent loads. Similarly, the latent-to-heat ratio (LHR) is defined as the ratio of zone latent load to total load. In this regard, those places with high SHR would have low LHR. However, the commercial premises with high LHR exist, and a general air-conditioning design cannot effectively cope with the high latent cooling load. Such kind of commercial premises are common, like the restaurants, canteens, indoor markets, entrance lobbies and shopping arcades. The latent heat gain of these commercial premises would come from the humid fresh air, the occupants, and the indoor provisions, such as the hot foods, spas and water ponds. Additional latent heat gain may be due to the excessive infiltration subject to negative pressure or frequent outdoor contact.

Because of the high LHR, substantial sub-cooling followed by reheating of the supply air is needed, causing high energy requirement for these premises. In addition, it is common for the conventional AC system to have over-cooling problem in the commercial premises with high latent load. As the AC equipment would be designed to suit the latent load, so its sensible cooling capacity would be naturally over-provided. If there is no reheat provision, nor simultaneous temperature and humidity control, this would apparently cause thermal comfort problems. Due to the over-cooling potential in these premises, it is common for people to wear jackets or additional clothes. It certainly violates the primary objective of air-conditioning. Furthermore, the risk of condensation at the supply air grilles would be high due to a low supply air temperature. To alleviate the high energy demand and thermal discomfort potential of the conventional AC system design, a solar hybrid desiccant cooling system (SHDCS) is therefore proposed. The SHDCS would separately treat the sensible and latent loads, in order to provide a satisfactory cooling and energy performances for the premises with high LHR. Solar-thermal energy is primarily used to energize the desiccant cooling, supplemented by auxiliary heating.

A number of demonstration projects of solar desiccant cooling have been built for space conditioning in different climates [1–3]. The common solid desiccant materials include silica gel, activated carbon, activated alumina, molecular sieve, lithium chloride and

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Nomenclature

COP_{ch}	coefficient of performance of vapour compression chiller
COP_{dc}	coefficient of performance of desiccant cooling
$H_{fa,sac}$	enthalpy of fresh air entering supply air coil (kJ)
$H_{fa,i}$	enthalpy of fresh air intake (kJ)
PE	primary energy consumption (kWh)
Q_e	refrigeration effect of vapour compression chiller (kJ)
Q_{aux}	energy input of auxiliary heating (kJ)
Q_{regen}	heat input for regeneration (kJ)
Q_{solar}	solar thermal gain from solar collectors (kJ)
RH	relative humidity
RH_z	zone relative humidity
SF	solar fraction
T_z	zone temperature (°C)
W_{in}	energy input to vapour compression chiller (kJ)

calcium chloride. In recent years, different hybrid designs for the solid desiccant cooling have been studied. Jia et al. [4] integrated a rotary solid desiccant dehumidification and vapour compression refrigeration, which used evaporator for sensible cooling and condenser for assisting regeneration of desiccant wheel. This system configuration could have power saving of 37.5% against the conventional compression AC unit. Geoghegan et al. [5] developed a simulation model of an integrated vapour compression refrigeration and desiccant rooftop unit, in order to evaluate the effect of frost growth. Ghali [6] used numerical simulation to evaluate the energy saving cost of a hybrid desiccant dehumidification and vapour compression refrigeration system, it was found that the payback period of the hybrid system could be less than five years in Beirut. Khalid et al. [7] carried out the empirical and simulation studies of a solar hybrid desiccant cooling used for precooling of an air-conditioning system, it was found that the payback period of the solar hybrid system could be 14 years in Pakistan. In that system design, solar air collector was used to directly heat up the air stream for regeneration of desiccant wheel. Fatouh et al. [8] put forward the solid desiccant hybrid air-conditioning system by using a R407C vapour compression refrigeration, in which the coefficient of performance (COP) could be enhanced through the increase of desiccant mass, air flow rate and regeneration temperature. Enteria et al. [9] investigated a solid desiccant heat pump system, which had direct impregnation of the desiccant material in the evaporator and the condenser of the heat pump. This system configuration could have the COP up to 5.7, which was higher than the conventional vapour compression type. The hybrid systems proposed in Refs. [4–9] generally needed the integration between the vapour compression refrigeration and the desiccant part at the component level, therefore such new packaged equipment should be manufactured first for real applications. Apart from the solid desiccant cooling, liquid desiccant cooling is another heat-driven cooling strategy for space conditioning. However, direct use of the process air as the supply air in liquid desiccant cooling would have a risk of carry-over of the corrosive desiccant solution, additional treatment is needed in order to safely apply for the space conditioning.

In this study, a more straightforward system configuration of SHDCS was proposed in order to facilitate wider application of solar air-conditioning and sustainable design. The effectiveness of the proposed SHDCS was evaluated through the provision of high LHR space conditioning in the subtropical Hong Kong (22.32°N and 114.17°E). Necessary control strategies would be included, particularly with individual control for the zone temperature and the zone humidity. The use of solar energy would be maximized, through separate handling of latent cooling and incorporating the vapour compression refrigeration. The cooling and energy performances of the SHDCS were evaluated not just for certain design days, but for dynamic loading and climatic conditions of the high LHR premises throughout a year. The performance results would be compared with those of the conventional centralized AC system. As the system design and application of the SHDCS was different from those hybrid systems in Refs. [4–9], a thorough performance evaluation was required for the premises with high latent load in the hot and humid climate.

In this paper, Section 2 presents the design of the SHDCS for handling high latent load, as well as the conventional centralized AC system. Section 3 introduces two typical functional areas with high LHR, and discusses the design parameters, the major component models and the simulation details for the year-round dynamic simulation. Section 4 discusses and verifies the results of cooling and energy performances of the SHDCS against the conventional centralized AC system. Section 5 is the conclusion of this study.

2. System design for handling high latent load

2.1. Conventional centralized air-conditioning system

In a conventional centralized air-conditioning (AC) design for high latent cooling load, the air handling unit (AHU) would include both the cooling coil and reheater [10], with separate temperature control and humidity control, as shown in Fig. 1. A vapour compression refrigeration system is used to provide the chilled water to the AHU. The capacity of the cooling coil is designed to cover the total cooling load and the additional load due to reheating. The supply air valve is proportionally controlled to maintain the air temperature leaving the supply air coil. This ensures sufficient dehumidification provided by the supply air coil. A humidistat and a thermostat are used to monitor the zone humidity ratio and temperature respectively. The supply air valve operates when any of the zone humidistat and thermostat is “ON”. The reheater functions when the supply air valve opens, and the set point of supply air temperature of the reheater depends on the status of the zone thermostat. When the zone thermostat is “ON”, the set point would be the design value. Otherwise, the set point would be proportionally increased with the drop of the zone temperature.

2.2. Solar hybrid desiccant cooling system

Fig. 2 presents the design of the SHDCS. The design principle of the hybrid configuration of SHDCS was to make use of the equipment already available in the HVAC market, so that the system installation and promotion of wider application could be more readily. Vapour compression chiller was used to provide chilled water to a supply air cooling coil. Silica-gel solid desiccant wheel was adopted and its regenerating heat primarily came from the solar thermal gain of the evacuated tubes, which are popular type of solar collectors in Hong Kong and South China. The desiccant wheel dehumidified the fresh air to the required level and the supply air coil provided the sensible cooling. Unlike the typical design of desiccant cooling, evaporative coolers were not required in the SHDCS. For the SHDCS, only a room thermostat was used to govern the functioning of the supply air valve. The supply air temperature would be used to proportionally control the supply air valve. For the desiccant cooling cycle, the heating coil valve, which regulated the regenerating temperature of the desiccant wheel, was controlled proportionally from the zone humidity ratio.