Energy and Buildings 43 (2011) 2068–2076

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Application potential of solar air-conditioning systems for displacement ventilation

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ARTICLE INFO

Article history:
Received 24 December 2010
Received in revised form 7 March 2011
Accepted 19 April 2011

Keywords:
Solar air-conditioning
Displacement ventilation
Desiccant cooling
Absorption refrigeration
Adsorption refrigeration

ABSTRACT

Solar air-conditioning can have higher application potential for buildings through the strategy of high temperature cooling. In recent years, displacement ventilation (DV), which makes use of the indoor rising plumes from the internal heat gains, provides a more effective supply air option than the traditional mixing ventilation (MV) in terms of both thermal comfort and indoor air quality. As it is possible to raise the supply air temperature to 19 °C for DV, it would enhance the competitive edge of the solar air-conditioning against the conventional vapour compression refrigeration. Through dynamic simulation, a solar-desiccant-cooling displacement ventilation system (SDC_DV) was developed for full-fresh-air provision, while a solar-hybrid-desiccant-cooling displacement ventilation system (SHDC_DV) for return air arrangement. The latter was further hybridized with absorption chiller (AB) to become $SHDC_{AB}$_DV, or adsorption chiller (AD) to be $SHDC_{AD}$_DV, in order to be wholly energized by the solar thermal gain. Benchmarked with the conventional system using MV, the SDC_DV had 43.3% saving in year-round primary energy consumption for a typical office in the subtropical climate; the $SHDC_{AB}$_DV had 49.5% saving, and the $SHDC_{AD}$_DV had 18.3% saving. Compared with their MV counterparts, the SDC_DV, the $SHDC_{AB}$_DV and the $SHDC_{AD}$_DV could have 42.4%, 21.9% and 30.3% saving respectively.

1. Introduction

Solar air-conditioning can be broadly classified as the solar-thermally driven type and the solar-electrically driven type. With the technical and economic advancement of different solar thermal collectors, particularly the evacuated tubes and the flat-plate collectors [1], it is getting more and more feasible to apply solar-thermally driven air-conditioning systems for building use. Technical information and guidelines have been published to describe the principles of different solar air-conditioning systems using desiccant cooling, absorption refrigeration and adsorption refrigeration for space conditioning [2–4]. In order to make the solar air-conditioning more competitive against the conventional compression refrigeration, it is necessary to have enhancement on its performance. Due to the intermittent nature, solar energy may provide low grade heat in certain occasions, which would affect the heat-driven desiccant cycle or refrigeration effect. Although auxiliary heating is commonly involved, more frequent operation would impede the merit of renewable energy source of the solar air-conditioning.

For space conditioning, if the supply air temperature can be raised without sacrificing thermal comfort, it would be helpful to enhance the overall performance of the solar air-conditioning systems. In the conventional design of indoor air distribution for air-conditioning, mixing ventilation (MV) is used in order to have a homogenous air conditions within the occupied zone. The supply air temperature of MV is generally around 15 °C. Displacement ventilation (DV), however, allows the supply air temperature of 19 °C for office use [5], this would be a useful strategy of high temperature cooling for solar air-conditioning. In this sense, the supply air flow rate of DV can be maintained or reduced compared with that of MV, but a higher return/exhaust air temperature would be yielded. This can particularly lower the ventilation load, hence the system cooling capacity due to the fresh air.

In fact, the approach of high temperature cooling has been used for desiccant cooling in the previous studies. A radiant floor cooling system combined with dehumidified ventilation was applied for the hot and humid Seoul in Korea [6], in which the radiant floor cooling was mainly used to tackle the sensible cooling load, while separate desiccant dehumidification for the latent cooling load. Energy saving potential was also found for chilled ceiling integrated with desiccant cooling in the hot and humid climate [7]. In these studies, the approach of high temperature cooling was based on radiant cooling, which makes use of a higher chilled water supply

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doi:10.1016/j.enbuild.2011.04.010

Nomenclature

COP	coefficient of performance
COP_{ab}	coefficient of performance of absorption chiller
COP_{ad}	coefficient of performance of adsorption chiller
COP_{dc}	coefficient of performance of desiccant cycle
COP_{vcc}	coefficient of performance of vapour compression chiller
$H_{fa,i}$	enthalpy of fresh air intake (kW h)
$H_{fa,sac}$	enthalpy of fresh air entering supply air coil (kW h)
PE	primary energy consumption (kW h)
Q_{aux}	energy input of auxiliary heating (kW h)
Q_e	refrigeration effect of chiller (kW h)
Q_{reg}	heat input for regeneration (kW h)
Q_{sol}	solar thermal gain from solar collectors (kW h)
RH_{zone}	zone relative humidity
SF	solar fraction
T_{zone}	zone temperature (°C)
W_{in}	energy input to vapour compression chiller (kW h)

Abbreviations

AB	absorption chiller
AD	adsorption chiller
DV	displacement ventilation
FA	full fresh air
MV	mixing ventilation
RA	return air
SDC	solar-desiccant-cooling system
SHDC	solar-hybrid-desiccant-cooling system
VCC	vapour compression chiller

temperature. This would clearly enhance the coefficient of performance *COP* and energy saving potential of the conventional vapour compression refrigeration. However, the effect of high temperature cooling through the appropriate indoor ventilation strategy of displacement ventilation has not been studied yet. Even the high temperature approach of radiant cooling was adopted, it was related to the performance enhancement of the refrigeration cycle, not found for the desiccant cooling. Despite studies of hybrid design of solar air-conditioning are found in the previous studies [8–11], the desiccant cooling was mainly hybridized with the electrically driven compression refrigeration, not the heat-driven absorption or adsorption refrigeration. There is no study by others about the evaluation of different year-round performances of solar desiccant cooling hybridized with the absorption or adsorption refrigeration.

As a result, this paper is to study different designs of solar air-conditioning systems using the high temperature cooling approach of displacement ventilation, and to evaluate the cooling and energy performances against their MV counterparts, as well as the conventional compression systems. This paper has the following arrangement: Section 2 illustrates the design of the solar air-conditioning system for full-fresh-air or return air provision. Section 3 presents the building zone and component models of different air-conditioning systems for dynamic simulation. Section 4 describes the year-round operation of the solar air-conditioning systems. Section 5 discusses the cooling and energy performances of different solar air-conditioning systems. Section 6 is conclusion.

2. Design of solar air-conditioning systems for displacement ventilation

2.1. Solar air-conditioning system for full-fresh-air provision

Fig. 1 illustrates the design of a solar-desiccant-cooling displacement ventilation system (SDC_DV) for full-fresh-air (FA) provision. From the system point of view, it is a typical design of desiccant cooling. In this study, air was supplied to the building zone at the floor level and exhausted at the ceiling level. A temperature gradient, and subsequently a humidity gradient, was developed along the zone height. The desiccant cooling part contained the desiccant wheel, rotary heat exchanger, evaporative coolers, supply air fan, exhaust air fan and heating coil. Solar collector and hot water pump were used to capture the thermal energy in the hot water storage tank. Desiccant water pump, auxiliary heater (when necessary) and heating coil valve were involved to provide hot water from the storage tank to the heating coil at the design temperature and flow rate.

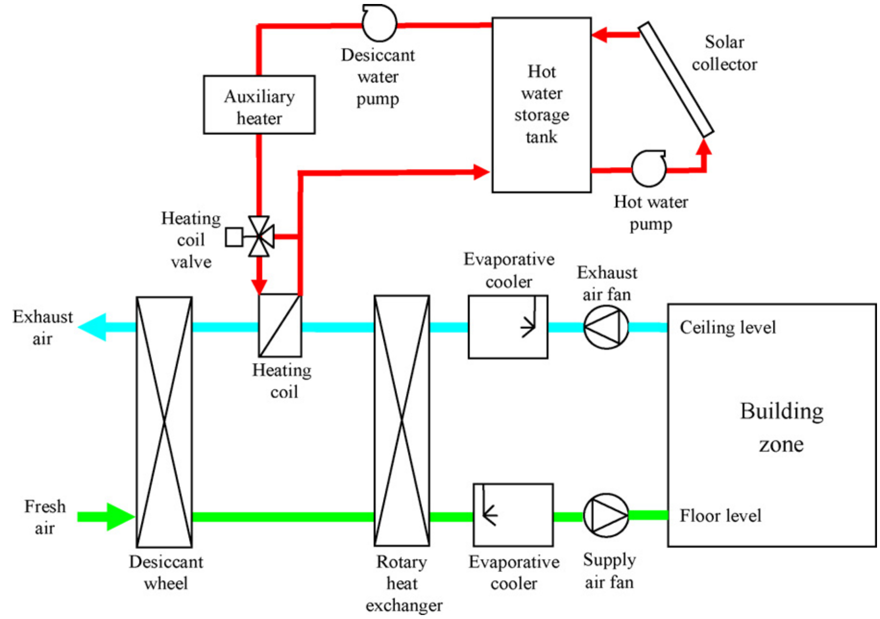

Fig. 1. Schematic diagram of solar-desiccant-cooling displacement ventilation system for full-fresh-air provision.