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Solar hybrid air-conditioning system for high temperature cooling in subtropical city

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A B S T R A C T

Although solar energy is able to power the heat-driven refrigeration, its contribution is quite limited due to the conventional cooling requirement. In building air-conditioning, it is common to supply low temperature chilled water, usually in 5–7 °C. If this temperature can be elevated, it would enhance the effectiveness to harness solar energy and minimize auxiliary heating. Solar refrigeration would then be more effective through high temperature cooling, by providing 15–18 °C chilled water instead. In such provision, radiant ceiling cooling can be coupled to handle the space cooling load, particularly space sensible load. And the space latent load and ventilation load are handled by a separate dehumidification provision, like the heat-driven desiccant dehumidification. Therefore, a solar hybrid air-conditioning system is formulated, using adsorption refrigeration, chilled ceilings and desiccant dehumidification. In this study, the year-round performances of the proposed solar hybrid air-conditioning systems were evaluated for two typical office types. The performance metrics include the solar fraction, coefficient of performance, solar thermal gain, primary energy consumption and indoor conditions. Comparative study was conducted for the hybrid air-conditioning system worked with the three common types of chilled ceilings, namely the chilled panels, passive chilled beams and active chilled beams. The solar hybrid air-conditioning system was also benchmarked with the conventional vapour compression refrigeration for office use. It is found that the proposed solar hybrid air-conditioning system is technically feasible through high temperature cooling. Among the three types of chilled ceilings, the passive chilled beams is the most energy-efficient option to work with the solar adsorption refrigeration for space conditioning in the subtropical city.

1. Introduction

The demand of air-conditioning is increasing due to the effect of climate change and global warming. If we still rely on the conventional electric air-conditioning but electricity is generated from fossil fuels, the greenhouse gas emission would continuously worsen global warming, in turn the demand of air-conditioning would be further increasing. In the subtropical cities, air-conditioning is a standard provision for buildings. However, air-conditioning would commonly take up half of building electricity consumption. More and more evidents show that the climate change is getting worse. The changes of global surface temperature, global average sea level, snow and ice over 1850 to 2000 are reported [1]. The increasing trend of the environmental temperatures would affect the future air-conditioning requirements [2]. Therefore it is urgent to minimize the consumption of fossil fuels and promote wider use of alternative energy, particularly in refrigeration and air-conditioning.

Application of solar cooling is a feasible way to replace the electric refrigeration machines for building air-conditioning. In the recent years, more reviews have been made about the feasibility of wider application of solar cooling technologies [3–5]. Especially the solar thermal technologies, they are getting mature for refrigeration and air-conditioning purposes. A number of demonstration projects have been launched to study the design and operation of the solar refrigeration and air-conditioning [6–8]. It is fit to apply solar energy in air-conditioning for office and commercial buildings, since the major cooling demand is coincident to the time of solar energy supply.

In a centralized air-conditioning, it is common to supply 5–7 °C chilled water for cooling and dehumidification purpose. If this temperature can be elevated, it would enhance the effectiveness to harness solar energy. Solar refrigeration is more effective to provide 15–18 °C chilled water for high temperature cooling,

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Nomenclature

A	area of air channel inside desiccant wheel (m^2)
a	half height of air channel inside desiccant wheel (m)
b	half width of air channel inside desiccant wheel (m)
c	specific heat capacity (kJ kg^{-1} K^{-1})
COP	coefficient of performance of adsorption chiller
D	diffusion coefficient of water vapor in air (m^2 s^{-1})
$E_{e,\ air}$	electrical energy consumption of air side equipment (kWh)
$E_{e,\ water}$	electrical energy consumption of water side equipment (kWh)
$E_{g,aux}$	gas energy consumption of auxiliary heating (kWh)
E_p	primary energy consumption (kWh)
$E_{p,air}$	primary energy consumption of air side equipment, including all the fans (kWh)
$E_{p,aux}$	primary energy consumption of auxiliary heating (kWh)
$E_{p,total}$	primary energy consumption of entire solar hybrid air-conditioning system (kWh)
$E_{p,water}$	primary energy consumption of water side equipment, including all pumps and cooling tower (kWh)
F	temperature effectiveness of heat exchanger
f	mass per unit length (kg m^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{OT}	number of air-conditioning hours with room temperature above the upper limit of comfort temperature
k	thermal conductivity (W m^{-1} K^{-1})
K_y	mass transfer coefficient (kg m^{-2} s^{-1})
L_p	perimeter of air channel inside desiccant wheel (m)
M	mass (kg)
m	mass flow rate (kg s^{-1})
n	exponent for Freundlich equation
Nu	Nusselt number
P	pressure (kPa)
Q	heat transfer rate (kW)
q	relative amount of water in silica gel (kg kg^{-1})
q^∞	limiting amount of water in silica gel (kg kg^{-1})
Q_{aux}	heat output of auxiliary heater (kW)
Q_{solar}	solar thermal gain from evacuated tubes (kW)
RH	relative humidity of air
SF	solar fraction
Sh	Sherwood number
T	temperature (°C)
t	time (s)
UA	overall heat transfer value (kW K^{-1})
V	air velocity (m s^{-1})
$\dot{V}$	air flow rate (m^3 s^{-1})
Y	humidity ratio of air (kg kg^{-1})
z	distance in axial direction (m)

Greek symbols

ΔH_a	heat of adsorption (kJ kg^{-1})
ΔH_v	specific latent heat of vaporization of water (kJ kg^{-1})
η_e	energy efficiency for electrical energy converted into primary energy
η_g	energy efficiency for gas energy converted into primary energy
ρ	density (kg m^3)
$\omega_1 \ldots \omega_7$	coefficients in Eqs. (23), (25), (27), (28), (30)–(32) respectively (–, s^{-1}, –, K s^{-1}, s^{-1}, K s^{-1}, K s^{-1})

Subscripts

a	air
ACB	active chilled beams
ad	adsorption chamber
adw	adsorption chamber water
am	metal in adsorption/desorption chamber
c	condenser
cm	metal in condenser
cw	cooling water
de	desorption chamber
e	evaporator
em	metal in evaporator
eq	condition of air in equilibrium with desiccant wall
ew	chilled water
hw	regenerative water
i	inlet
m	total number of time steps in a month for hot water pump in operation
m'	total number of time steps in a month for adsorption chiller in operation
mat	matrix material in desiccant wheel
me	metal
o	outlet
PCB	passive chilled beams
s	silica gel
sa	supply air
sv	saturated vapor
w	liquid water
v	water vapor
y	total number of time steps in a year for hot water pump in operation
y'	total number of time steps in a year for adsorption chiller in operation

which can be implemented by means of radiant ceiling cooling. Among different options of solar cooling, adsorption refrigeration is the most feasible one to be used with the conventional solar collectors, since its driving temperature can be as low as 60 °C. By applying the strategy of high temperature cooling, the heat-driven adsorption refrigeration can make use of the low grade heat as driving source.

In view of the condensation potential of radiant cooling in the subtropical cities with humid climate, the latent load should be handled separately. A radiant floor cooling system integrated with dehumidified ventilation was designed for the hot and humid Seoul in Korea [9], in which the radiant floor cooling was mainly used to handle the sensible load, while separate dehumidification equipment for the latent load. However, such design may cause thermal discomfort due to cold floor and temperature stratification. Energy saving potential was found for chilled ceiling combined with desiccant cooling in hot and humid climate [10].

In this study, a solar hybrid air-conditioning system is therefore proposed for space conditioning in the subtropical cities. The space cooling load (from internal and transmission heat gains, largely sensible) is handled by radiant ceiling cooling with chilled water supplied by the adsorption refrigeration, while the ventilation load (from humid and hot outdoor air) by the desiccant dehumidification. Then the total building cooling load, the sum of space cooling load and ventilation load, can be fully handled by the proposed system. This hybrid system uses solar energy to drive the adsorption refrigeration cycle and desiccant dehumidification. It is novel to unite radiant ceiling cooling, adsorption refrigeration and