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Advancement of solar desiccant cooling system for building use in subtropical Hong Kong

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ABSTRACT

The solar desiccant cooling system (SDCS) had a saving potential of the year-round primary energy consumption as compared to the conventional air-conditioning system for full fresh air application in the subtropical Hong Kong. In order to further enhance its energy efficiency, advancement of the basic SDCS was carried out through a strategy of hybrid design. Six hybrid system alternatives of SDCS were therefore proposed, three for full fresh air design while another three for return air design for the building zone. Year-round performance evaluation of each solar hybrid desiccant cooling system was conducted for typical office application under different climatic and loading conditions. All the six hybrid system alternatives were found technically feasible, with up to 35.2% saving of year-round primary energy consumption against the conventional air-conditioning systems. Among the hybrid alternatives, recommendations were made on the SDCS hybridized with vapour compression refrigeration for full fresh air design; and the SDCS hybridized with vapour absorption refrigeration for return air design, since they had the saving potentials of both primary energy and initial cost. These two hybrid system alternatives used evacuated tubes, a more economical type of solar collectors compared to the PV or PVT panels.

1. Introduction

Facing the catastrophic disasters around the globe due to climate change in recent years, it is urgent to minimize the use of fossil fuels for electricity generation, and make use of alternative energy as far as possible. It is essential to have effective cut of carbon emission in daily life, and air-conditioning and refrigeration belongs to one of the significant energy-consuming items in buildings. Solar desiccant cooling system (SDCS), which is a type of solar air-conditioning, is featured with direct provision of supply air for building use [1,2]. A number of demonstration projects have been built to serve air-conditioning in different climates [3–5]. Fig. 1 shows the schematic diagram of a basic SDCS, its components mainly include the desiccant wheel, rotary heat exchanger, evaporative coolers, solar collectors, hot water storage tank, hot water pump (HWP), desiccant water pump (DWP), fresh air fan (FAF) and exhaust air fan (EAF). Auxiliary gas heater is commonly adopted to supplement the heat demand. A heating coil is used to provide regenerative heat for the desiccant wheel, the amount of hot water is modulated by a heating coil valve (HCV).

The basic SDCS has the advantages of possible use of solar thermal energy and enhancement of indoor air quality due to full fresh air provision. However, the primary energy consumption has been found larger than the other solar air-conditioning systems, such as solar absorption or adsorption refrigeration system, as well as the conventional vapour compression refrigeration system, in which the return air design can be used in the air side system [6]. In SDCS, however, the return air design is not feasible due to high zone cooling load intensity in the hot and humid region [7]. As a result, the idea of solar hybrid desiccant cooling system is adopted, and the design strategy is to integrate the desiccant cooling with a separate refrigeration cycle, so that the latent and sensible cooling loads of a building zone can be effectively shared and handled.

This paper is structured in the following way. In Section 2, development of the six design alternatives of solar hybrid desiccant cooling system is discussed. Section 3 describes the dynamic simulation models of the major components of the hybrid alternatives. In Section 4, the simulation parameters and related details of the alternatives are presented. Section 5 discusses the results of year-round evaluation based on various performance indicators for the six hybrid system alternatives, as well as the conventional air-conditioning systems. Section 6 is the conclusion.

2. Design of solar hybrid desiccant cooling systems

Through the hybrid design approach, different system alternatives were proposed, either for full fresh air design or return air design for the building zone. Generally, a separate chiller was

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Nomenclature

a	half height of air channel inside desiccant wheel (m)
A	area of air channel inside desiccant wheel (m^2)
b	half width of air channel inside desiccant wheel (m)
c	specific heat capacity ($kJ\,kg^{-1}\,K^{-1}$)
C_v	volume coefficient of compressor
COP	coefficient of performance
COP_{ch}	coefficient of performance of chiller
$COP_{ch,a}$	coefficient of performance of vapour absorption chiller
$COP_{ch,c}$	coefficient of performance of vapour compression chiller
COP_{dec}	coefficient of performance of desiccant cooling
D	diffusion coefficient of water vapour in air ($m^2\,s^{-1}$)
E_e	electrical energy consumption (kWh)
E_g	gas energy consumption (kWh)
E_p	primary energy consumption (kWh)
$E_{p,aux}$	primary energy consumption of auxiliary provision (kWh)
$E_{p,cent}$	primary energy consumption of central plant including chiller and desiccant cooling, or that of chiller alone for conventional system (kWh)
$E_{p,para}$	primary energy consumption of all the parasitic equipment (kWh)
$E_{p,solar}$	primary solar energy gain(s) (kWh)
$E_{p,total}$	primary energy consumption of entire air-conditioning system (kWh)
EMF	back emf of motor (V)
f	mass per unit length ($kg\,m^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$) or specific enthalpy ($kJ\,kg^{-1}$)
I	motor current (A)
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 flow rate ($kg\,s^{-1}$)
n	polytropic compression index of compressor
Nu	Nusselt number
P	pressure (kPa)
P_{sat}	saturated vapour pressure of LiBr solution (kPa)
q	relative amount of water in silica gel ($kg\,kg^{-1}$)
Q	heat transfer rate (kW)
Q_{aux}	input of auxiliary energy provision (kW)
Q_{regen}	heat input for regeneration (kW)
Q_{solar}	solar gain from solar collectors (kW)
R	motor resistance (Ω)
RH	relative humidity of air
SF	solar fraction
SF_{ch}	solar fraction of solar-driven chiller
SF_{dec}	solar fraction of desiccant dehumidification
SF_{hyb}	solar fraction of solar hybrid desiccant cooling system
Sh	Sherwood number
t	time (s)
T	temperature (°C)
T_m	log mean temperature difference (°C)
u	air velocity ($m\,s^{-1}$)
UA	overall heat transfer value ($kW\,K^{-1}$)
V	motor voltage (V)
V_c	swept volume of compressor (m^3)
W_{in}	power input to motor (kW)
Y	humidity ratio of air ($kg\,kg^{-1}$)
z	distance in axial direction (m)

Greek letters

$\alpha_1 \ldots \alpha_7$	coefficients in Eqs. (3) to (13) (–, s^{-1}, –, $K\,s^{-1}$, s^{-1}, $K\,s^{-1}$, $K\,s^{-1}$)
β	motor torque constant ($N\,m\,A^{-1}$)
Δh	specific enthalpy change across compressor ($kJ\,kg^{-1}$)
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
ξ	LiBr solution concentration
ρ	density ($kg\,m^{-3}$)
τ	torque (N m)
ω	rotational speed ($rad\,s^{-1}$)

Subscripts

a	air
ab	absorber
abw	absorber water
ai	absorber inlet
ao	absorber outlet
$cond$	condenser
cw	cooling or condenser water
dis	condenser inlet
eq	condition of air in equilibrium with desiccant wall
$evap$	evaporator
ew	chilled water
fa	fresh air
gen	generator
gi	generator inlet
go	generator outlet
hw	regenerative water
i	inlet
mat	matrix material in desiccant wheel
o	outlet
pa	processed air after rotary heat exchanger
r	refrigerant
s	LiBr solution
sa	supply air
sg	silica gel
$sshxr$	solution-to-solution heat exchanger
suc	evaporator outlet
sv	saturated vapour
v	water vapour
w	liquid water

involved to share off the sensible cooling load of the building zone, so that the desiccant cooling would concentrate on handling the latent load. In addition, different types of solar collectors, hence different corresponding system configurations and auxiliary energy provisions, were considered in the study. The first three alternatives adopted full fresh air design, with a similar approach of the basic SDCS. In order to evaluate the possibility of further advancement of the SDCS, three more alternatives were evolved for return air design. As a result, altogether six system alternatives of solar hybrid desiccant cooling were generated, they are:

a. SDCS for full fresh air design, hybridized with conventional vapour compression refrigeration ($SDCS_{FA}$-VCR);
b. SDCS for full fresh air design, hybridized with direct-current (DC)-driven vapour compression refrigeration using photovoltaic (PV) panels ($SDCS_{FA}$-$DVCR_{PV}$);