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Simulation–optimization of solar-assisted desiccant cooling system for subtropical Hong Kong

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ABSTRACT

Solar cooling is a novel approach, which primarily makes use of solar energy, instead of electricity, to drive the air-conditioning systems. In this study, solar-assisted desiccant cooling system (SADCS) was designed to handle the cooling load of typical office in the subtropical Hong Kong, in which half of the building energy is consumed by the air-conditioning systems. The SADCS mainly consisted of desiccant wheel, thermal wheel, evaporative coolers, solar air collectors and gas-fired auxiliary heater, it could directly tackle both the space load and ventilation load. Since the supply air flow is same as the outdoor air flow, the SADCS has a feature of sufficient ventilation that enhances the indoor air quality. Although it is inevitable to involve the auxiliary heater for regeneration of desiccant wheel, it is possible to minimize its usage by the optimal design and control scheme of the SADCS. Through simulation–optimization approach, the SADCS can provide a satisfactory performance in the subtropical Hong Kong.

1. Solar cooling in context

Because of the environmental and economic impact of the fossil fuels, renewable energy is being explored in different areas of applications for our modern living. An international scheme, Solar Heating and Cooling Program has been advocated by the International Energy Agency since 1976. And a variety of publications for design, installations, operation and maintenance of the solar energy systems to heat, cool, power and light buildings are currently available to the building practitioners [1]. Solar cooling is still a growing technology in many countries, especially in Europe, USA, Japan and Mainland China [2–5]. Conventional vapour compression refrigeration systems driven by electricity have been applied for a century, commonly found in the commercial, residential, industrial and transportation sectors. In the recent years, feasible technology to utilize solar energy for air-conditioning and refrigeration is available, and different system designs and configurations are being developed.

From the current studies [6–9], solar cooling can be broadly categorized into passive solar cooling and active solar cooling. Passive solar cooling is to apply the principles of protection from sun, thermal mass control and natural ventilation to minimize the solar gain to the indoor spaces. It is common to design and construct the external/internal shading devices, low emittance glazing, double façade and high thermal inertia for this purpose. Active solar cooling, on the other hand, is to make use of the energy acquired from the solar collectors for the electricity- or heat-driven air-conditioning system. Active solar cooling includes solar-electric refrigeration, solar-thermal refrigeration and solar-thermal air-conditioning. The focus of solar-electric refrigeration and solar-thermal refrigeration is to develop new types of chillers for refrigeration purpose, while that of solar-thermal air-conditioning is to directly provide the conditioned air to the indoor space. So the solar-electric or solar-thermal refrigeration is classified to be a closed-cycle system, and solar-thermal air-conditioning to be an open-cycle system.

2. Solar-assisted desiccant cooling system

The solar-assisted desiccant cooling system (SADCS) is a typical type of solar-thermal air-conditioning. The essential component of this system is the sorbent section. Both solid and liquid sorbents can be applied in this desiccant component, such as silica gel and lithium chloride respectively. Although desiccant cooling using liquid sorbent has the merit of thermal storage, it is slightly acidic. Since the supply air would be directly in contact with the liquid sorbent, there is a carry-over potential to the conditioned space. This would have both health and safety problem to the occupants. Desiccant cooling using solid sorbent, however, is stable in the processes of adsorption and desorption, so it is more suitable to be directly applied in the supply air stream. Desiccant wheel which commonly contains the solid sorbent is the major component equipment of the SADCS. The other component equipment includes the thermal wheel, direct evaporative coolers, solar air

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Nomenclature

A	top surface area of solar air collector
a	first coefficient to determine $\bar{T}_a$
$B1$	isopotential line for process air stream
$B2$	isopotential line for regeneration air stream
b	second coefficient to determine $\bar{T}_a$
C_p	specific heat capacity of air
COP	coefficient of performance of solar-assisted desiccant cooling system
COP_{avg}	annual average coefficient of performance of solar-assisted desiccant cooling system
F'	heat transfer effectiveness above the air channel, used to determine $\bar{T}_p$
F_{best}	the best function value among the population in each epoch
F_{mean}	the average function value among the population in each epoch
G'	heat transfer effectiveness below the air channel, used to determine $\bar{T}_3$
G_t	total solar radiation incident upon the collector top surface
h_a	heat transfer coefficient from the air to the inside surface of the flow channel
$h_{c,bk}$	convection heat transfer coefficient from the back surface of collector
$h_{c,top}$	convection heat transfer coefficient from the top surface of collector
h_{oa}	outdoor air enthalpy
$h_{r,bk}$	linearized radiation heat transfer coefficient from the back surface of collector
$h_{r,top}$	linearized radiation heat transfer coefficient from the top surface of collector
$h_r, 1 \rightarrow 2$	linearized radiation heat transfer coefficient from the top surface to the bottom surface of the air channel
h_{sa}	supply air enthalpy
h_1	outdoor air enthalpy
h_4	supply air enthalpy
IAM	incidence angle modifier
M	heat transfer factor other than the effect above air channel
$\dot{m}_a$	mass flow rate of supply air (same as that of exhaust air)
$\dot{m}_{fan}$	rated mass flow rate of supply/exhaust air fan
N_{ex}	number of hours exceeding T_u throughout a year
N_{op}	number of hours of SADCS in operation throughout a year
P	heat transfer factor related to the air channel
Q_{abs}	heat absorbed by the solar air collector
Q_{add}	heat added to the air flow stream by the collector
$Q_{c,bk}$	convection heat loss from the back of collector
$Q_{c,top}$	convection heat loss from the top of collector
$Q_{r,bk}$	radiation heat loss from the back of collector
$Q_{r,top}$	radiation heat loss from the top of collector
$\dot{Q}_{ah}$	heat flow rate generated from auxiliary heater
$\dot{Q}_{in}$	total heat flow rate input to the solar-assisted desiccant cooling system
$\dot{Q}_{sac}$	thermal gain from solar air collectors
R_{bk}	conductive resistance of the back insulation layer
R_{top}	conductive resistance of the absorber plate and structural layer
S	absorbed solar radiation
SF_{avg}	annual average solar fraction
T	air temperature
$\bar{T}_a$	mean air temperature in the collector
$T_{a,in}$	entering air temperature of solar air collector
$T_{c,bk}$	environment temperature for convection heat loss from the back of collector
T_{co}	outlet air temperature of solar air collector
T_o	ambient temperature
T_{os}	offset temperature differential for calling in desiccant cooling mode
$\bar{T}_p$	mean temperature of absorber plate
$T_{r,bk}$	environment temperature for radiation heat loss from the back of collector
T_{ra}	room air temperature
$T_{ra,sp}$	set point of room air temperature
T_{reg}	regeneration air temperature
T_s	sky temperature
T_{sa}	supply air temperature
$T_{sa,sp}$	set point of supply air temperature
T_u	upper limit of comfort temperature
$\bar{T}_1$	mean inside surface temperature of the structural layer under the absorber plate
$\bar{T}_2$	mean inside surface temperature of collector back insulation
$\bar{T}_3$	mean collector back surface temperature
X	heat transfer factor other than the effect below air channel

Greek symbols

α_1	effectiveness for isopotential line $B1$
α_2	effectiveness for isopotential line $B2$
ε_{bk}	emissivity of the back surface of the collector
ε_{top}	emissivity of the top surface of the collector
ε_1	emissivity of the bottom side of the upper surface of the air channel
ε_2	emissivity of the top side of the lower surface of the air channel
σ	Stefan–Boltzmann constant
$(\tau\alpha)_n$	transmittance-absorptance product at normal incidence of solar air collector
ω	humidity ratio
$\omega_{dd,sp}$	set point of humidity ratio of desiccant dehumidification
ω_o	leaving humidity ratio of desiccant wheel at the process air stream

Subscripts

Pi	the air conditions of entering process air
Po	the air conditions of leaving process air
Ri	the air conditions of entering regeneration air

collectors and gas-fired auxiliary heater, as shown in Fig. 1. Solar air collector can be adopted when the air-conditioning period of the conditioned space is coincident to the availability of solar irradiation in day time. The thermal wheel is used to remove the sensible heat of the process air after passing the desiccant wheel. The evaporative cooler at the supply air stream is used to cool down the process air to become supply air, which still has low humidity ratio fit for handling the space latent load. The evaporative cooler at the exhaust air stream is used to cool down the room air for better sensible heat recovery at the thermal wheel.

The SADCS can be designed according to the outdoor air (OA) scheme or mixed air (MA) scheme. In the former, desiccant cooling would fully make use of the OA to fulfill the required cooling load. In the latter, the pretreated outdoor air and the return air would form the MA for cooling purpose. As compared to the MA scheme, the OA scheme would generally have larger size and higher capital