ARTICLE IN PRESS

Solar Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Solar Energy

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

Performance analysis of a solar-driven liquid desiccant cooling system with solution storage under adjustable recirculation ratio

Fan Zhang[a], Yonggao Yin[a,b,*], Xiaosong Zhang[a,b]

[a] School of Energy and Environment, Southeast University, Nanjing 210096, China

[b] Jiangsu Provincial Key Laboratory of Solar Energy Science and Technology, Southeast University, Nanjing 210096, China

ARTICLE INFO

Keywords:
Dehumidification
Evaporative cooling
Liquid desiccant
Solar cooling
Energy storage

ABSTRACT

Solar cooling is one of the most promising solutions to the worsening energy and climate issues. A solar-driven liquid desiccant evaporative cooling air-conditioning system with solution storage tanks was proposed. The daily performance of the proposed system under the variable solution recirculation ratio (R_s) adjusting method in a typical hot-humid summer day of Nanjing was investigated using a quasi-dynamic mathematical model. The solution storage effect and the coupled characteristics of the solar collecting subsystem and the liquid desiccant cycle were taken into account. The effects of water tank volume (V_{wt}), the initial solution mass in the solution storage tank ($M_{s,storage,tank}$) and the area of solar collector (A_{sc}) on the overall system performance were also evaluated. The results show that with the help of the stored solution, the proposed system can effectively handle the space cooling load during the whole period of operation. The average values of thermal coefficient of performance (TCOP) and solar coefficient of performance (SCOP) are 0.66 and 0.31, respectively. The variable R_s adjusting method can guarantee the required solution concentration and adapt well to the varying solar radiation. When A_{sc} is limited, a smaller V_{wt} and a larger $M_{s,storage,tank}$ are recommended to achieve a higher SCOP when covering the required space cooling load.

1. Introduction

Heating, ventilation and air conditioning systems play a significant role in ensuring human thermal comfort and are among the largest energy consumers of the building sector (Vakiloroaya et al., 2014) which consumed 20–40% of total energy use in developed countries (Pérez-Lombard et al., 2008). Increased emphasis is put on the design of energy-efficient air-conditioning systems due to the continuing increase in energy demand, costs and the associated environmental problems (Ghaddar et al., 2003). Thermal-driven cooling and air-conditioning system can be an alternative to the conventional vapor-compression system driven by electricity. Among all kinds of the thermal-driven cooling systems, the solar-powered cooling system shows prominent advantages. It is environmentally friendly due to no use of refrigerant with high ODP (Ozone Depression Potential) and GWP (Global Warming Potential). Besides, the solar energy supply and cooling demand match very well. Therefore, solar cooling/air conditioning is one of the most promising solutions to the deteriorating energy and climate issues.

Solar-powered cooling systems mainly include absorption cooling system, solid desiccant cooling system and liquid desiccant cooling system. Extensive researches on solar-powered absorption cooling system have been conducted in the past few years (Bellos et al., 2016; Fong and Lee, 2014; Shirazi et al., 2016; Zhang et al., 2015). Compared with the closed-cycle absorption chiller, the desiccant cooling system can be driven by lower-temperature heat source, and therefore has the higher potential to make full use of solar energy (Gee and Wood, 1995; Grossmann, 2002). Ge et al. (2012) proposed a novel solar driven desiccant coated heat exchanger cooling system and conducted a performance analysis of the proposed system under Shanghai summer condition. The simulation results validated its feasibility when applied under hot and humid climate condition.

Since the liquid desiccant can be regenerated at a lower temperature in comparison with the solid desiccant, many researchers focus on the investigation of the solar-powered liquid desiccant cooling system (Chen et al., 2018; Gommed and Grossman, 2007; Katejanekarn et al., 2009). Gommed and Grossman (2007) constructed a solar-driven liquid desiccant system for air-conditioning and monitored its performance under varying operating conditions. The calculated thermal COP based on the realistic data is about 0.8, which is a satisfactory result. Katejanekarn et al. (2009) carried out experiments on a solar-regenerated liquid desiccant ventilation pre-conditioning system under

* Corresponding author at: School of Energy and Environment, Southeast University, Nanjing 210096, China.
E-mail address: y.yin@seu.edu.cn (Y. Yin).

https://doi.org/10.1016/j.solener.2018.03.061
Received 30 October 2017; Received in revised form 13 March 2018; Accepted 22 March 2018

Please cite this article as: Zhang, F., Solar Energy (2018), https://doi.org/10.1016/j.solener.2018.03.061

Nomenclature

A	area (m^2)
c_p	specific heat capacity (kJ/kg K)
h	specific enthalpy (kJ/kg)
I_t	total solar radiation incident onto the solar collector (W/m^2)
Le_f	Lewis factor
M	mass (kg)
m	mass flow rate (kg/s)
NTU	number of mass transfer units
Q	heat transfer rate (kW)
Q_{cond}	sensible load due to the heat conducting through protection structure (kW)
$Q_{removed,cl}$	removed cooling load from the conditioned space (kW)
Q_{sys}	system cooling capacity (kW)
R_a	working to intake air ratio
R_s	solution recirculation ratio
r	latent heat of vaporization (kJ/kg)
SCOP	solar coefficient of performance
T	temperature (°C)
t	time
TCOP	thermal coefficient of performance
V	volume (m^3)
X	mass concentration (%)

Greek symbol

ΔQ_{stored}	variation of the stored chemical potential energy of solution (kW)
Δm_w	accumulation rate of water (kg/s)
$\Delta\tau$	time interval between t^{i-1} and t^i
ε	effectiveness
η	efficiency
ω	humidity ratio (g/kg)

Subscript

a	air
amb	ambient
cal	calculated value
cl	cooling load
cold	cold fluid
conc	concentrated
deh	dehumidifier
dil	diluted
exh	exhaust air
hot	hot fluid
in	inlet
out	outlet
reg	regenerator
req	required
s	solution
sc	solar collector
stor	storage
sup	supply air
sys	system
w	water
wt	water tank

Superscript

i	current time
i − 1	last time

different weather conditions and concluded that it can work under hot and humid climate conditions.

The dehumidifier/regenerator used in the above two researches are of packed-bed type, which may lead to the carryover of liquid desiccant droplets in the air stream. To reduce the entrainment of droplets, low-flow falling-film type with internally cooled/heated configuration is adopted in solar-driven LDAC system by some researchers (Bouzenada et al., 2016; Lowenstein et al., 2006; Qi and Lu, 2014). In addition, liquid-to-air membrane energy exchanger (LAMEE), where the air and liquid desiccant is separated using the semi-permeable membrane, can also avoid the entrainment of droplets (Abdel-Salam et al., 2013; Ge et al., 2017). Abdel-Salam et al. (2014) used the TRNSYS software to investigate the performance of a solar-driven membrane liquid desiccant air-conditioning system under hot and humid climate conditions from thermal, economic and environmental perspective. It was found that both the economic and environmental performances of the LDAC system can be significantly improved if the solar thermal system with natural gas boiler backup is selected as its heating system. Das and Jain (2017) experimentally investigated the overall performance of a solar-driven liquid desiccant evaporative cooling system under tropical climatic conditions. Results showed that the effectiveness of the adopted membrane dehumidifier was a little lower due to the additional mass transfer resistance. Thermal COP of the system varied between 0.25 and 0.8 under different operating conditions.

Although the low-flow falling-film dehumidifier/regenerator and LAMEE can overcome the droplets carryover problem, traditional packed-bed dehumidifier/regenerator are still adopted in this study due to their compactness, simple configuration, low cost and relatively high mass transfer performance. By controlling solution/air flow rates and using the proper mist eliminator, the carryover content of liquid desiccant droplets in the dehumidified air can be decreased effectively and lower than a safety threshold (Fu and Liu, 2017). Since the entrainment content will increase with the increase of mass flow rates of the solution and air, both the liquid desiccant flow rate and the dehumidified air flow rate will not be adopted as the adjusting parameters; instead, the concentration of liquid desiccant entering the dehumidifier ($X_{s,deh,in}$) will be regulated in response to the varying ambient conditions and cooling load in this study. The $X_{s,deh,in}$ can be adjusted by changing the recirculation ratio at the dehumidification/regeneration side.

In most liquid desiccant cooling systems, to decrease the circulation loss, a relatively large part of the solution leaving the dehumidifier/regenerator is sent back to the dehumidifier/regenerator together with the concentrated/diluted solution from the regenerator/dehumidifier (Bergero and Chiari, 2010; Chen et al., 2016; Gommed and Grossman, 2004). The solution recirculation ratio (R_s) at the dehumidification/regeneration side ($R_{s,deh}$/$R_{s,reg}$) is defined as the mass flow rate ratio of the solution recirculated towards dehumidifier/regenerator to the total solution leaving the dehumidifier/regenerator sump. Zhang et al. (2017) investigated the effect of R_s on the performance of a liquid desiccant evaporative cooling air-conditioning (LDECAC) system and concluded that the variable R_s adjusting method is effective in response to the change of ambient conditions. Under part load conditions, the R_s should be increased; while under some extreme hot and humid conditions, it should be set to zero and the regeneration temperature is to be increased. However, in this research, solution storage effect is not considered and the temperature of the heat source is assumed to be constant, which are invalid for solar-driven air-conditioning system. Therefore, it is necessary to further verify the feasibility of this adjusting method when the system is integrated with solution storage and driven by time-dependent solar energy.

To overcome the instability and intermittency of solar energy,