Building and Environment 117 (2017) 218–229

Contents lists available at ScienceDirect

Building and Environment

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

Performance analysis of a novel liquid desiccant evaporative cooling fresh air conditioning system with solution recirculation

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

Article history:
Received 2 November 2016
Received in revised form
17 February 2017
Accepted 9 March 2017
Available online 14 March 2017

Keywords:
Dehumidification
Evaporative cooling
Liquid desiccant
Recirculation
Air conditioning

ABSTRACT

Liquid desiccant evaporative cooling air-conditioning (LDECAC) system, which combines both advantages of liquid desiccant and evaporative cooling technology, has a great potential to utilize low-grade heat for refrigeration and air conditioning. A novel LDECAC system is proposed to obtain lower supply air temperature and humidity ratio at the expense of less thermal energy consumption when used as a dedicated fresh air system. It consists of a liquid desiccant system with self-cycle solution at dehumidification and regeneration sides, a regenerative indirect evaporative cooler (RIDEC) and a direct evaporative cooler with adjustable by-pass flow. A parametric study on steady-state thermal performance of LDECAC system was performed based on the developed mathematical model. The performance was investigated by varying five key parameters: solution self-cycle ratio (R_s), working to intake air flow ratio (R_a), regeneration temperature, ambient air temperature and humidity ratio. The results show that the system can handle the process air to 17.9 °C and 9.2 g/kg with the thermal coefficient of performance of 0.56 under the design condition. The recommended value for R_s lies between 0.6 and 0.7 and that for R_a is 0.2 under the typical operating condition. The variable R_s control method is effective in response to the change of ambient air conditions. Performance comparison with the conventional LDECAC system shows that the novel system can utilize lower temperature heat source and achieve a higher thermal coefficient of performance.

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 [1] which consumed 20–40% of total energy use in developed countries [2]. 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 [3].

Liquid desiccant evaporative cooling air-conditioning (LDECAC) system is a very promising alternative to the conventional vapor-compression air-conditioning system [4]. It has advantages in removing latent load and pollutants from the process air as well as reducing electrical energy consumption [5,6]. The LDECAC system can be driven by low-grade heat sources, such as solar energy and waste heat, and is environmentally friendly due to no use of ozone-depleting refrigerant. In LDECAC system, the liquid desiccant subsystem uses liquid desiccant to extract moisture from process air to handle the total latent load, while the evaporative cooling subsystem copes with the sensible heat load by water evaporation process. The combination of dew-point evaporative cooler (DPEC) with liquid desiccant system has the greatest development potential among the LDECAC systems [7].

The DPEC, which is also called as regenerative indirect evaporative cooler (RIDEC), utilizes a relatively small fraction of the product air leaving RIDEC as its working air, thus can approach the dew point temperature of the inlet process air theoretically. It can be classified into two basic types: the internal cooling type in which the sensible cooling process and the water evaporation process are combined into one unit, and the external cooling type where these two processes occur in separate units [8]. The internal cooling type RIDEC is widely used in LDECAC system [9–12].

Compared with the internal cooling type RIDEC, the external cooling type received less attention when used in LDECAC system [13]. However, it is a simple configuration as it consists of a sensible

---

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

http://dx.doi.org/10.1016/j.buildenv.2017.03.015

Nomenclature

C	Mass concentration (%)
c_p	Specific heat capacity (kJ/kg K)
F	Envelope area of a building (m^2)
H	Height (m)
h	Specific enthalpy (kJ/kg)
h_C	Heat transfer coefficient (W/m^2 K)
h_D	Mass transfer coefficient (kg/m^2 s)
K	Heat conduction coefficient of envelope (W/m^2 K)
L	Length (m)
Le_f	Lewis factor
amb	Ambient
m	Mass flow rate (kg/s)
NTU	Number of mass transfer units
Nu	Nusselt number
Pr	Prandtl number
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)
Re	Reynolds number
R_a	Working to intake air ratio
R_s	Solution recirculation ratio
Sc	Schmidt number
Sh	Sherwood number
T	Temperature (°C)
TCOP	Thermal coefficient of performance
W	Width (m)
u	Velocity (m/s)

Greek symbol

α	Specific area of the packing per volume (m^2/m^3)
ε	Efficiency
ω	Humidity ratio (g/kg)

Subscript

a	Air
deh	Dehumidifier
cl	Cooling load
cold	Cold fluid
exh	Exhaust air
hot	Hot fluid
in	Inlet
ind	Indoor
mix	Mixed
out	Outlet
reg	Regenerator
s	Solution
sup	Supply air
sys	System
w	Water

heat exchanger and a direct evaporative cooler [14], and can handle a larger amount of process air. Therefore, the external cooling type RIDEC is used in this paper. In addition, although many researchers [15–17] have determined the optimum working to intake air flow ratio (R_a) in terms of the cooling capacity of standalone RIDEC, few reports exist of optimizing R_a at the system level [18]. Since R_a has great impacts on temperature and flow rate of the supply air, it is necessary to seriously select R_a in terms of the overall performance of LDECAC system.

The overall performance of LDECAC system is also tightly associated with the performance of liquid desiccant subsystem, which can be improved by sending back a relatively large part of the solution leaving the dehumidifier/regenerator to the dehumidifier/regenerator together with the concentrated/diluted solution from the regenerator/dehumidifier. This design concept of the solution recirculation at the dehumidification/regeneration side is called as solution self-cycle [19]. In this paper, the solution self-cycle ratio 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 dehumidifier/regenerator outlet solution.

Chen et al. [19] proposed an improved liquid desiccant system driven by heat pump and experimentally investigated its characteristic. Under typical working conditions, the $R_{s,deh}$ was set to around 0.7. Yamaguchi et al. [20] conducted experiments and simulations to evaluate the performance of a hybrid liquid desiccant air-conditioning system which consists of a liquid desiccant system and a vapor-compression heat pump. The $R_{s,deh}$ used in the experiments was 0.9. Zhang et al. [21] adopted two different methods for removing the superfluous condensation heat from the heat pump driven liquid desiccant system. The adopted $R_{s,deh}$ and $R_{s,reg}$ in the simulation were about 0.87. Although the above studies involve the use of solution self-cycle, it can be seen that the effect of $R_{s,deh}/R_{s,reg}$ on system performance is beyond their scope.

Gommed and Grossman [22] conducted a parametric study on a liquid desiccant cooling system coupled with a heat pump. It was found that the decrease of $R_{s,reg}$ led to improved dehumidification performance together with increased circulation losses. The optimum $R_{s,reg}$ was between 0.85 and 0.9. Bergero and Chiari [23] theoretically analyzed the steady-state performance of a liquid desiccant air-conditioning system integrated with a vapor-compression inverse cycle by varying several key operating parameters. The simulation results showed that the minimum humidity ratio of indoor air could be achieved when $R_{s,deh}$ was 0.98 under typical summer conditions.

However, the research object of the above literature is heat pump driven liquid desiccant air-conditioning (HPLDAC) system, which is different from LDECAC system used in this study. They operate at different temperature and concentration levels. For LDECAC system, the dehumidified air at the dehumidifier outlet has a lower humidity ratio and affects the cooling potential of the downstream sensible cooling units. Therefore, the conclusions deduced from the HPLDAC system cannot be directly extended to LDECAC system without further investigation.

In this paper, a novel LDECAC system is proposed and a parametric study on its steady-state thermal performance is conducted. It consists of a liquid desiccant system with solution self-cycles at dehumidification/regeneration side, an external cooling type RIDEC and a direct evaporative cooler with by-pass flow which can adjust sensible heat ratio over a wide range. The objective of the present study is to select appropriate working air ratio and solution self-cycle ratio for the proposed LDECAC system to further enhance its performance. One of the two contributions of this work is to establish a detailed and realistic mathematical model to investigate the effects of self-cycle ratio on the overall performance of LDECAC system. The other is that the variable self-cycle ratio adjustment