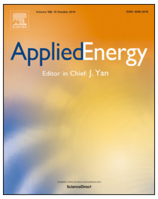
Applied Energy 219 (2018) 325–337

Contents lists available at ScienceDirect

Applied Energy

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



Study on performance of a novel energy-efficient heat pump system using liquid desiccant

Nannan Shan[a], Yonggao Yin[a,b,*], Xiaosong Zhang[a,b]

[a] School of Energy and Environment, Southeast University, Nanjing 210096, China
[b] MOE Key Laboratory of Energy Thermal Conversion and Control, Southeast University, Nanjing 210096, China

HIGHLIGHTS

- A novel energy-efficient heat pump system using liquid desiccant was proposed.
- A detailed mathematical model was developed and validated by experiments.
- The COP of the system is 13.4% higher than that of conventional chillers.
- Effects of key factors on system performance were analyzed.
- Optimal area design of the solution-cooled condenser was investigated.

ARTICLE INFO

Keywords:
Energy-efficient heat pump
Liquid desiccant dehumidification
Evaporative cooling
Condensation heat recovery
Sub-cooling

ABSTRACT

In this paper, a novel heat pump system is proposed, which operates as a heat-source-tower heat pump with no frosting in winter, and as a hybrid refrigerant system consisting of a conventional chiller combined with a liquid desiccant dehumidification and evaporative cooling subsystem in summer. A validated mathematical model of the proposed system operating in summer is established to investigate the effects of key parameters, including solution to refrigerant flow ratio (*FR*), condensation heat recovery ratio (R_{cond}) and ambient parameters, on the cooling performance. Besides, this paper analyzes key factors that should be considered in designing the heat exchange area of the solution-cooled condenser (SCC). The results show that the maximum COP and ECOP of the heat pump system are 13.4% and 10.3% higher than those of conventional vapor compression refrigerant systems under the typical summer condition of Nanjing, respectively. The recommended range of *FR* is from 1.2 to 6 and that for R_{cond} is from 16% to 40%. Moreover, the proposed system is more superior to conventional ones when applied in hot and humid regions.

1. Introduction

In some subtropical monsoon climate regions, such as most cities in south-central of China and some areas in southeast of America, characterized by hot summer and raw winter, provides harsh thermal environment for the residents and makes it considerably energy-intensive to improve the indoor thermal comforts. The conventional cooling and heating source of air-conditioning systems have shown their own disadvantages or limitations when used in this area [1], including the frosting problem or low cooling efficiency in air source heat pumps (ASHP) [2], the low heating efficiency in chiller with boiler systems and the topographical limitations or high initial investment in ground source heat pump systems [3].

The heating tower heat pump (HTHP) became popular in recent studies as it takes advantage of the high cooling efficiency of water-cooled chillers in summer, and provides heating continuously with non-frosting surface by reversibly using cooling tower that replaces its working fluid with the solution. It is theoretically proved by Li et al. [4] that HTHP could operate continuously with higher efficiency compared to the widely used ASHP in winter. Experimental results provided by Li et al. [5] showed that the COP and SEER (seasonal energy efficiency ratio) of HTHP ranged from 2.358 to 4.34 and 2.45 to 3.45 when the outdoor temperature varied from -1 °C to 5 °C and the relative humidity changed from 71–95%, respectively. Wen et al. [6,7] pointed out that the heat transfer rate of the packing towers in summer was about 3 times higher than that in winter, resulting in that HTHP required more packing towers than conventional water chiller with boiler systems. Although HTHP is a perfect substitute for ASHP or chiller with boiler

---

[*] 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.apenergy.2018.03.006
Received 9 September 2017; Received in revised form 16 February 2018; Accepted 9 March 2018
0306-2619/

Nomenclature

A	area (m^2)
C_p	specific heat capacity (kJ/kg K)
COP	coefficient of performance
ECOP	electric coefficient of performance
FR	solution to refrigerant mass flow ratio
H	hight (m)
h	specific enthalpy (kJ/kg)
IEC	indirective evaporative cooler
L	length (m)
Le_f	Lewis factor
M	mass flow rate (kg/s)
m	moisture removal rate (g/s)
N	electric power
Nu	Nusselt number (kW)
P	pressure (P)
Pr	Prandtl number
Q	heat (kW)
q_e	specific cooling capacity (kW/kg)
R_{cond}	condensation heat recovery ratio
Re	Reynolds number
SCC	solution-cooled condenser
T	temperature (°C)
V	volume flow rate (m^3/h)
W	width (m)
WCC	water-cooled condenser
X	mass concentration (%)

Greek symbol

α	specific area per volume (m^2/m^3)
ε	effectiveness
η	efficiency
ω	humidity ratio (g/kg)
φ	relative humidity (%)

Subscript

a	air
amb	ambient
cal	calculated value
cold	cold fluid
cond	condensation
com	compressor
con	conventional
deh	dehumidifier
e	evaporation
hot	hot fluid
i	directive efficiency
in	inlet
lat	latent
nov	novel
out	outlet
ref	refrigerant
reg	regenerator
s	solution
sat	saturated
sc	sub-cooling
sen	sensible
w	water

systems in winter, the surplus packing towers do not benefit the system in summer. The condensing temperature would not drop significantly as the temperature of the cooling water is limited by the local wet-bulb temperature; in addition, the use of more pumps and fans in the extra towers would increase the power consumption, which is unfavorable for improving the efficiency of the system.

Some researchers used the condensation heat for improving the comprehensive performance of the cooling system. Apart from serving hot water [8,9], condensation heat was also recovered for the desiccant regeneration in temperature and humidity independent control systems [10–14]. However, the processed air in the dehumidification system regenerated by condensation heat could meet requirements for air conditioning only when the condensation heat was upgraded by heat pump [11,12] or combined with higher grade of heat source like solar energy [10]. Besides, heat distribution has great influence on the efficiency of condensation heat utilization in vapor-compression refrigerant systems [14].

Further cooling of the refrigerant leaving condenser is believed to be beneficial for the performance of the refrigerating system by increasing the cooling capacity as well as reducing thermodynamic loss in the throttling process. The sub-cooling capacity obtained through the conventional methods, including suction-line heat exchanger [15], mechanical sub-cooler [16] and sub-coolers based on heat storage [17,18], is basically converted from electricity and is not electric-efficient in essence. Many novel hybrid refrigerant systems, where the low-grade heat-driven cooling system was used for sub-cooling the electricity-driven vapor compression refrigeration system, showed promising energy-saving potential in recent studies. Xu et al. [19] showed that the COP of an absorption-compression cascade refrigeration was 38% higher than that of compression auto-cascade cycle, where the low-grade cooling capacity obtained from the absorption system was used for sub-cooling. Solar energy was often used as the regeneration source for the absorption subsystem in the above hybrid refrigerant systems [20]. Actually, low-grade cooling capacity, which was transformed to sub-cooling capacity in the mentioned hybrid systems, could also be produced by the Dehumidifier-Evaporator-Regenerator system (DER) [21,22] driven by much lower grade heat that ranges from 40 °C to 60 °C. In the DER system, the dry air from the dehumidifier was used to produce chilled water through evaporating cooling process. She et al. [23] investigated the performance of a hybrid refrigerant system combining the DER with the air-cooled vapor-compression refrigeration cycle. The thermodynamic analysis showed that the hybrid cooling system could achieve higher cooling efficiency and the maximum COP increases by 18.8% and 16.3% when using hot air and ambient air for regeneration respectively. However, few researches of this type of energy-efficient hybrid refrigeration system have been done so far.

In this paper, a novel energy-efficient heat pump system using liquid desiccant was developed to solve the idle problem of packing towers of HTHP system and improve its cooling efficiency in summer. The novelty of this study is that it proposed a novel economic substitute for conventional heat sources by reducing initial investments as well as operating power consumption. Firstly, the present study developed a detailed mathematical model of the system, which was validated by experiments and could be utilized to evaluate the energy-saving potential of the proposed system compared to conventional chillers. Secondly, this paper investigated the effects of key parameters, such as solution to refrigerant mass flow ratio, the condensation heat recovery ratio and ambient parameters, on the system performance using the validated model. Based on these results, this paper provided guidance for optimal design of the system for real applications. Finally, the key factors influencing heat exchange area demand of the solution-cooled condenser, which is of great importance to improving the energy-saving