Applied Thermal Engineering 111 (2017) 122–133

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Dynamic character investigation and optimization of a novel air-source heat pump system

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HIGHLIGHTS

- A mathematical model of the novel air-source heat pump system is constructed.
- The model results show good agreement with the corresponding experimental data.
- An optimization control strategy for the novel system is developed.
- A correlation of COP with ambient temperature and relative humidity is proposed.

ARTICLE INFO

Article history:
Received 7 August 2016
Revised 13 September 2016
Accepted 14 September 2016
Available online 15 September 2016

Keywords:
Air-source heat pump
Frost
Solid desiccant
Thermal energy storage
Mathematical model
System optimization

ABSTRACT

Heating capacity of an air-source heat pump (ASHP) system often decreases when it is operated in winter. This is because of frosting significantly affects the heat transfer efficiency of evaporator, and thus the airflow passage blocked. In order to solve this problem, a novel frost-free ASHP system, integrated with dehumidification and thermal energy storage, has been developed. In this paper, to further investigate the dynamic characteristics of the system working at low temperature, a mathematical model of the novel frost-free ASHP system was constructed. The mathematical model was verified by comparison with experimental data that showed that the measured results were in good accordance with the numerical ones. According to the mathematical model, the research results indicated that, at relatively humidity (RH) of 80%, the system average COP increased by 56.2% when ambient temperature increased from −10 °C to 0 °C. However, it decreased by 6.7% when RH increased from 75% to 85% at temperature of 0 °C. In addition, the system average COP at the air velocity of 3.0 m s^{-1} was higher 0.22 and 0.16 than that of 2.5 m s^{-1} and 3.5 m s^{-1}. Finally, the correlations of the system frost-free working time and the system COP with ambient temperature and relative humidity were obtained, respectively, by multivariate linear regression. These results provided a basis in improving and optimizing the thermal system COP and other main performance parameters.

1. Introduction

Air-source heat pump (ASHP) has been widely used in domestic and commercial buildings because of their high-efficiency, energy-saving, and practical studies have shown the potential of ASHP to drastically reduce CO_2 emissions [1] and haze to improve air quality. However, frost layer may accumulate on the fin surfaces of the outdoor heat exchanger of ASHP when it is operated in heating mode in winter. Frosting has significantly affected the heat transfer efficiency of heat exchangers and blocks the airflow passage, leading to increase of energy consumption and deterioration of performance of the ASHP. As reported by Kondepudi et al. [2,3], at least 15% degrade in the coil thermal performance was caused by frost formation. Kwak and Bai [4] carried out experiments to demonstrate that the heating capacity and COP reduced by 20.0% and 33.3%, respectively, after the ASHP working for 100 min under the condition of frost formation on a heat exchanger. And hence, it is necessary to implement periodic defrosting to maintain its normal operation.

Over the years, some researchers have studied to improve defrosting efficiency and delay frosting. At present, the most

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http://dx.doi.org/10.1016/j.applthermaleng.2016.09.076
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Nomenclature

A	area, m^2
C_d	the degree of the opening of the valve
D	the pipe diameter, m
G_w	the mass velocity of the water, $kg\,(m^2\,s)^{-1}$
H_m	the PCM heat of fusion, $kJ\,m^{-3}$
L	the length of tube, m
P	pressure, Pa
Q	heating capacity, kW
R	thermal resistance, $m^2\,K\,W^{-1}$
T	temperature, °C
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Le	Lewis
V	latent heat of condensation (water vapor), $kJ\,kg^{-1}$
$c_{p,w}$	the specific heat capacity of water, $J\,(kg\,K)^{-1}$
$c_{p,a}$	the specific heat capacity of air, $J\,(kg\,K)^{-1}$
d_{air}	the humidity ratios of ambient air, $g\,kg^{-1}$
h	the specific enthalpies of the refrigerant, $kJ\,kg^{-1}$
m	the mass flow rate, $kg\,s^{-1}$
q_{st}	the adsorption heat of solid desiccant, $kJ\,kg^{-1}$
v	velocity, $m\,s^{-1}$
υ_0	the specific volume of the refrigerant, $m^3\,kg^{-1}$
x	the dryness in two - phase region

Greek letter

α	transfer coefficient, $W\,(m^2\,K)^{-1}$
γ	the heat coefficient of the evaporator, $W\,(m^2\,K)^{-1}$
ε	the latent heating mass transfer coefficient, $W\,(m^2\,K)^{-1}$
θ	the eccentric shaft rotation, rad
λ	the heat conductivity coefficient, $W{\cdot}(m{\cdot}K)^{-1}$
η	efficiency, %
μ_w	the dynamic viscosity, Pa s
ρ	the density of the refrigerant, $kg\,m^{-3}$
τ	time, min

Subscripts

HM	heating mode
RM	regeneration mode
a	air
de	dehumidifying efficiency
m	mean
f	fluid
$_i$	inner
o	outer
r	refrigerant
re	regeneration efficiency
w	water
in	inlet
out	outlet
rm	refrigerant side mean value
$_{tp}$	two-phase region
wm	water side mean value
cond	condenser

Abbreviations

ASHP	air-source heat pump
COP	coefficient of performance
EHECSD	extra heat exchanger coated with a solid desiccant
ESD	energy storage device
EEV	electronic expansion valve
HGBD	hot-gas bypass defrosting
PCM	phase change material
RCD	reverse-cycle defrosting
RH	relatively humidity

widely used method of frost removal for ASHP is reverse-cycle defrosting (RCD). Song et al. [5,6] studied the uneven refrigerant distribution over a vertically installed multi-circuit outdoor coil in an ASHP unit during RCD. Liang et al. [7] proposed a new defrosting method, the sensible heat defrosting method, which greatly improved the thermal comfort and avoided the adverse shock from conventional RCD defrosting as well as eliminated the problem of "oil rush". However, the indoor thermal comfort is reduced in the RCD operation.

Hu et al. [8] developed a thermal energy storage defrosting method for ASHP which took PCM as a low temperature resource during defrosting to improved the stability of the system and reduce the defrosting time. Based on RCD method, Zhang et al. [9] proposed a new method which using thermal energy storage of the heat dissipated by the compressor. Experimental results showed that compared to conventional RCD method, the total heating capacity and the system COP were increased by 14.2% and 1.4 %, respectively.

Some scholars [10] used hot-gas bypass defrosting (HGBD) method, a portion of the high temperature refrigerant running through the compressor exhaust into the evaporator to retard frost formation, was developed. Byun et al. [11] reported that the average system COP and heating capacity were higher 8.5% and 5.7% respectively than that of a conventional heat pump. A novel dual HGBD method was proposed by Choi et al. [12]. The results showed that this method reduced the defrosting time by 36% compared to the HGBD method. Compared to the RCD method, the defrosting time was slightly longer (126%), however, the thermal comfort of the novel method is superior than that of the RCD method.

In addition, anti-frosting paint was used to spray on the heat exchanger fins to retard the frost formation. The use of hydrophilic coating on outdoor heat exchanger will reduce the wet pressure drop and extend the defrost cycle time [13]. Huang et al. [14] showed that the heat exchanger was coated anti-frosting paint can keep pressure drop below 30 mmAq for 137 min while the uncoated heat exchanger lasted only 80 min during the first frost at the air temperature of (T_{in} = 2.2 °C, T_{out} = 0.5 °C) and the relative humidity of 90%.

These methods above mentioned have greatly improved the ASHP performance at low temperature operation. However, the issue of frosting occurs at the evaporator has not been resolved fundamentally, because all of them have a common disadvantage of defrosting after frost formation accumulated on the surface of the evaporator, which reduces the thermal comfortable and the heating capacity as well as the system COP. In addition, for the method of RCD, the compressor suction and discharge pressure is changed suddenly when the system switches to defrost mode. It creates a compressor reliability problem during long term operation.

Recently, to solve these deficiencies, some frost-free ASHP systems have been developed. Researchers used liquid desiccant or solid adsorbent to dehumidify the outdoor air before it entered the evaporator to prevent ASHP system from frosting [15,16]. Jiang et al. [17] had been added a solution spray subsystem to the outdoor coil to prevent frosting in winter. The results indicated that the system took on the better stability and thermal comfort of occupants during defrosting process. Zhang and Saikawa [18] found that the COP of the frost-free ASHP system combined with