Applied Energy 169 (2016) 696–708

Contents lists available at ScienceDirect

Applied Energy

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

Performance evaluation of a novel method of frost prevention and retardation for air source heat pumps using the orthogonal experiment design method

Jinchen Tang [a,b], Guangcai Gong [a,*], Huan Su [a], Fanhao Wu [a], Cila Herman [b]

[a] Civil Engineering College, Hunan University, Changsha, Hunan Province 410082, China
[b] Department of Mechanical Engineering, The Johns Hopkins University, Baltimore, MD 21218-2868, USA

HIGHLIGHTS

- A novel design ASHP equipped with heaters installed before (B-AEH) the evaporator for frost prevention is proposed first.
- The orthogonal experiment design was deployed to aid the selection of design parameters and the analysis of the results.
- The performance of the novel design increased COP up to 17.94% and decreased input power 25.63% under frosting conditions.
- It was demonstrated that the novel system can prevent the evaporator from frosting formation under frosting conditions.

ARTICLE INFO

Article history:
Received 24 August 2015
Received in revised form 12 November 2015
Accepted 5 February 2016
Available online 27 February 2016

Keywords:
Frost prevention
Frost retardation
Orthogonal experiment design (OED)
Auxiliary electric heater (AEH)

ABSTRACT

In this study, a novel technology of frost prevention and retardation for air source heat pump (ASHP), which reduces thermal discomfort, is introduced. It utilizes auxiliary electric heaters (AEH) on tubes before (B-AEH) and (or) after (A-AEH) the outdoor evaporator to retard frost formation or prevent frost from accumulating on the outdoor heat exchanger. This enables the supply of hot air into the interior space without interruption. This new method differs from the common high pressure hot gas bypass defrosting (HGBD) methods and the reverse cycle defrosting (RCD), both of which could result in significant temperature fluctuations and thermal discomfort. The orthogonal experiment design (OED) was applied in this study to evaluate the performance of the air source heat pump (ASHP) with different magnitudes of AEH power under a range of ambient frosting conditions. The $L_{25}(5^6)$ orthogonal array was selected for the experiment and data were analyzed by means of the analysis of range (ANORA) and the analysis of variance (ANOVA). The optimum parameter combination affecting the performance of the ASHP was determined and the most significant parameters were identified. It was demonstrated that the proposed ASHP design is effective for frost prevention and retardation in real applications.

1. Introduction

Currently, the most widely used standard defrosting method for air source heat pumps (ASHPs) is the reverse cycle defrosting (RCD) method [1,2]. The RCD method is a procedure that switches the heating mode of heat pumps to the cooling mode to defrost the coil. When using the cooling mode for defrosting, the hot refrigerant normally pumped into the indoor condenser (to heat the room air in the heating mode), is instead pumped into the outdoor evaporator to melt the frost on it. When the frost is melted, the heat pump is switched back to heating mode and resumes its normal operation. Many studies have examined the thermal characteristics of the system during the RCD defrosting process for ASHPs [3–7]. O'Neal et al. [4] studied the thermal properties of the RCD process for a residential ASHP in 1989. Anand et al. [5] investigated the discharge and suction pressure changes in the compressor in an RCD system to increase energy savings and decrease the defrosting time. They found sudden pressure fluctuations from the discharge and suction lines of the compressors when switching the four-way reversing valve during the RCD process. This would also cause mechanical damage to the compressors and refrigerant lines. In addition, the diameter of the orifice used as the throttle valve was also increased in order to reduce defrosting time during the RCD cycle [6]. Nutter et al. [7] studied the thermodynamics of a

* Corresponding author. Tel.: +86 139 73123865; fax: +86 731 88823082.
E-mail addresses: jinchentang@hnu.edu.cn (J. Tang), gcgong@hnu.edu.cn (G. Gong), cherman.jhu@gmail.com (C. Herman).

http://dx.doi.org/10.1016/j.apenergy.2016.02.042
0306-2619/

Nomenclature

A_{tot} total heat exchanger surface area (m^2)
c_{ice} specific heat of ice (J/kg °C)
d_a moisture content of air (kg/kg_{air})
d_{eq} equivalent diameter of cross-section tube-fin (m)
d_s moisture content of air at the surface tube wall (kg/kg_{air})
h_a specific enthalpy of air (kJ/kg)
h_s specific enthalpy of air on the surface of tube wall (kJ/kg)
M_{fr} amount of frost accumulation on the evaporator surface per unit length (kg/m)
M_δ amount of water vapor increasing frost layer thickness per unit length (kg/m)
M_ρ amount of water vapor increasing frost layer density per unit length (kg/m)
q_a mass flow rate of air (kg)
Q total amount of heat during frosting formation (W)
Q_c heating capacity of the air source heat pump of interest (W)
Q_l least energy needed to defrost (W)
r_{ice} latent heat of ice (kJ/kg)
T_d dew-point temperature of ambient air (°C)
T_s temperature of air at the surface tube wall (°C)

Greek letters
α_{sen} sensible heat transfer coefficient of air (W/m^2 K)
r_{sub} latent heat of sublimation (J/kg)
σ mass transfer coefficient determined by Lewis criterion (kg/m^2 s)

Abbreviations
AEH auxiliary electric heater
A-AEH auxiliary electric heater located after the evaporator, between evaporator and compressor
B-AEH auxiliary electric heater located before the evaporator, between capillary and evaporator
ASHP air source heat pump
RCD reverse cycle defrosting
HGBD hot gas bypass defrosting
OED orthogonal experiment design
ANORA analysis of range
ANOVA analysis of variance

heat pump when installing an accumulator in the suction line of a scroll compressor operating during the frosting and defrosting conditions of an ASHP. Results showed that removing the accumulator would produce a 2% reduction in the coefficient of performance (COP) and a 10% reduction in the defrosting time. However, in this operation mode, a temporary phenomenon was observed during which liquid refrigerant floods to the suction line of the compressor and causes a mechanical shock to it. Song et al. [8] reported a modeling study on varying heat supply (via refrigerant) to each refrigerant circuit in a three-circuit outdoor coil in the RCD process. Therefore, long-term RCD operation would definitely lead to deterioration of the performance of the ASHPs and damage the components of the system.

Hot gas from the compressor's discharge can be a good source of heat to melt frost easily. The advantages of hot gas bypass defrosting (HGBD) are lower noise, smaller indoor temperature fluctuations, and no cold air blowing from the indoor condenser, when compared to the RCD method (switching to a cooling mode to defrost). However, because of limitations in the amount of available heat, defrosting time for HGBD is much longer than for RCD [9,10]. Liu et al. [11] simulated the dynamic hot-gas defrosting process, described by the fundamental conservation equations, and used experimental results for validation of the model. A comparative study of the RCD and HGBD methods on a water source heat pump was carried out by Huang et al. [12]. The HGBD enabled continuous heating in a no-switching reverse cycle, but the drawback of the solution was an increase of the defrosting time by a factor of 2.89 over the RCD defrosting time. Wang et al. [9] used a compensator instead of an accumulator to reduce the defrosting time. However, the liquid refrigerant could easily enter into the compressor suction line during defrosting, in the absence of an accumulator in the suction line before a compressor. This is a common situation which can be dangerous and could easily cause mechanical damage to the ASHP when the indoor fan of condenser is turned off. Recently, Kim et al. [13] demonstrated an alternative defrosting method with a multi-evaporator structure for continuous heating, by adopting an on-off cycling operation without a cooling mode. Byun et al. [14] studied frost retardation of an ASHP using the HGBD method. Choi et al. [15] developed a dual hot gas bypass defrosting method to remove frost from the outside evaporator to lower the defrosting time. They compared the dynamic characteristics and defrosting time with the traditional RCD method. However, whenever the HGBD is activated, as for heating originating from the evaporator, the heating capacity cannot be guaranteed with this solution. Not only does the defrosting time remain long, but the overall indoor thermal performance of the amenity is also degraded.

In addition to the numerous studies focusing on these two main defrosting methods, there are also extensive research efforts aiming to find new methods to solve the frosting problem [16–24]. Jiang et al. [16] investigated experimentally glycerol as spray solutions with different concentrations and variable mass flow rates for ASHP, as a new non-frost refrigerant. Mei et al. [17] suggested that the temperature on the evaporator tube can be raised by several degrees by adding a moderate amount of heat to the refrigerant steam in the accumulator. Silva et al. [18] studied the performance of the fan attached to the heat exchanger, with increasing frost layer thickness, for various tube-fin heat exchanger designs. Thybo and Mader [19] proposed a dynamic distribution valve that can feed parallel evaporators with individual passages, and that would be able to regularly shut individual evaporator circuits off, so as to maintain frost-free conditions. Kwak and Bai [20] applied an electric heater in front of the outdoor heat exchanger to heat the outdoor evaporator inlet air, in order to enhance the heating capacity and delay frost formation. Kondepudi et al. [21] utilized a solid desiccant to dehumidify the air at the inlet of the outdoor evaporator. This solution was able to prevent frosting efficiently by lowering the humidity of the ambient air at initial times. However, the moisture absorption capability of desiccant as well as its ability to prevent frost accumulation would fall off over time. The influence of increasing the heat exchange area of the evaporator and fin spacing, as well as changing the structure of fins, was also addressed in this study [22]. Gu et al. [23] found that delaying frosting can be accomplished by increasing the fin spacing. Therefore, the value of fin spacing should be selected depending on the regional humidity levels. Zhang et al. [24] proposed a frost-free