Energy & Buildings 178 (2018) 26–37

Contents lists available at ScienceDirect

Energy & Buildings

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

An experimental study on time-based start defrosting control strategy optimization for an air source heat pump unit with frost evenly distributed and melted frost locally drained

Mengjie Song[a,b], Cheng Fan[c], Ning Mao[d,*], Yingjie Xu[e]

[a] Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, Japan
[b] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education of China, Tianjin 300072, China
[c] Department of Construction Management and Real Estate, Shenzhen University, Shenzhen, China
[d] Department of Gas Engineering, College of Pipeline and Civil Engineering, China University of Petroleum (East China), Qingdao, China
[e] Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou 310014, China

ARTICLE INFO

Article history:
Received 21 May 2018
Revised 22 July 2018
Accepted 15 August 2018
Available online 1 September 2018

Keywords:
Air source heat pump
Defrosting control strategy
Frost distribution
Melted frost
Defrosting efficiency

ABSTRACT

Defrosting operation of an air source heat pump unit is always started with a pre-set time, corresponding to a fixed mass of frost accumulation. The exact defrosting initiation time is hard to be quantitatively given due to dynamic and uneven frosting conditions, and thus resulting in series of mal-defrosting phenomena. For an air source heat pump unit with a multi-circuit outdoor coil, when the melted frost locally drained during defrosting was considered, the optimization of start defrosting control strategy becomes more complicated. Here, this fundamental problem was experimentally investigated, with frost nearly evenly distributed on the surface of the outdoor coil at the start of defrosting. Defrosting performance of the experimental air source heat pump unit at different frost accumulations with the melted frost local drainage were then comparatively analyzed. These measured and calculated physical parameters include the temperature of tube surface and melted frost, compressor suction and discharge pressures and their difference, thermal energy taken from indoor air and electricity inputs on compressor and fans during defrosting, etc. Results showed that, the defrosting efficiency reached its peak at 51.80% when frost accumulation was at 933 g. Thus, the time-based start defrosting control strategy was demonstrated to be optimized with this method. Contributions of this study could be used for adjusting the control strategy of air source heat pump units, which are also benefit for energy saving in their industry and residential applications.

1. Introduction

Energy consumed in heating living environment and producing hot water in cold and severe cold regions accounted for as much as 46.4% of the total building energy consumption collectively [1], which has promoted the development of air source heat pump (ASHP) units [2]. An ASHP unit is a high efficiency and low environmental pollution equipment, but it always becomes problematic when working at heating mode at the ambient air temperature of −7 to 5 °C and relative humidity higher than 65% [3]. The frost formed and accumulated on the tube and fin surface of its outdoor coil increases both heat transfer resistance and air flow passage resistance during heating operation, and thus adversely degrades the system performance, or even results in an undesired and unsafe shutdown [2,4].

Frosting duration accounts more than 80% of operation time in a frosting-defrosting cycle, and thus frost retarding measure exploration plays important roles in optimization of ASHP units [3]. These measures include (1) changing ambient air parameters at outdoor coil inlet, such as reducing humidity [5], pre-heating air [6], and increasing airflow rate [7]; (2) frost destroy using additional techniques, such as ultrasonic vibration [8] and air jet [9]; (3) optimizing the structure of the outdoor coil, such as type adjustment of fin and tube [10], fin surface treatment [11]; and (4) system adjustment and optimization, such as vapor-injection [12], two-stage technique [13], adding outside heating source and adjusting refrigerant distribution [14,15]. The use of frost retarding measures is always expensive or consuming additional energy, and frost that is presented after delaying would have to be removed. Periodic defrosting becomes necessary for guaranteeing the satis-

---

[*] Corresponding author.
E-mail address: maoningcas@hotmail.com (N. Mao).

https://doi.org/10.1016/j.enbuild.2018.08.027

factory operation of ASHP units [3]. Reverse cycle defrosting has the distinguish advantages of easy adjustment, no more energy consumed and floor space added, and safe and stable system [3], and thus it becomes widely used. When an ASHP unit is controlled to operate from frosting to a reverse cycle defrosting mode, the indoor air fan in an ASHP unit is normally switched off to avoid blowing cold air directly to a heated indoor space, affecting thermal comfort of occupants. Hence, the energy performance should be improved, and defrosting duration shortened [16].

It is easy to understand that system energy efficiency is always affected by the start defrosting control strategy, as well as its reliability and durability [17]. As previously reviewed by authors, control strategies to start a defrosting operation can be simply divided into two types: time-based start defrosting and demand-based start defrosting [3]. For the former, start defrosting is simply controlled by a pre-set timer, at 60–90 min of frosting time. This technique is commonly used in commercial products due to its low cost [18]. It is hard to give an exact and fixed frosting duration or defrosting starting point, due to the complicated and changeable ASHP operating conditions [17]. This results in time-temperature control, which measures not only the operating time of the compressor but also the evaporation temperature or degree of superheating to determine the defrosting time [19,20]. Therefore, it is commonly applied to commercially available products. Typically, Kim and Lee proposed a novel determination method of defrosting start-time based on temperature measurements, using effective mass-flow fraction (EMF) to provide accurate defrosting start-times under varied frosting conditions [21]. Steiner and Rieberer numerically investigated the ideal defrost start time for a heat pump system. As concluded, at chosen operating conditions there is an optimum defrost start time regarding average COP [22]. Demand-based start defrosting control strategy could start a defrosting operation only when sufficient frost is formed to adversely affect the operating performance of ASHP units. It relies on accurately detecting the presence and growth of frost by using direct and indirect frost accumulation sensing technologies, such as measuring the ice thickness using holographic interferometry technique [23], measuring the frost surface temperature by infrared thermometer [24], and sensing refrigerant flow instability [25], etc. In conclusion, the frost accumulation directly influence the system defrosting performance, which should be quantitatively investigated. The frost accumulation on surface of fan-supplied tube-fin evaporators was investigated by many scholars, such as Diogo L.da Silva et al. [26,27] and Huee-Youl Ye et al. [28] with both of experimental and modelling approaches. However, it is still a problem to accurately detect the frost accumulation on the surface of a multi-circuit outdoor coil in an ASHP unit. Moreover, in open literature, investigation on start defrosting control strategy with frost distribution status considered is not found. Clearly, for a time-based start defrosting control strategy, the uneven frosting start directly leads to two types of mal-defrosting phenomena. One is unnecessary defrosting cycles when no or few frost accumulated on surface of outdoor coil, and the other is no defrosting in progress when necessary. As reported by Wang et al., the mal-defrost phenomenon was found with more than 60% frosted area of the outdoor coil after the system running 5 days, which decreased the system COP by up to 40.4% and the heating capacity by up to 43.4% [29].

On the other hand, for an ASHP unit having a multi-circuit outdoor coil, the downwards flowing melted frost over the surface of outdoor coil always plays negative effect on system defrosting performance [3]. In addition, frost is always unevenly accumulated on the surface of multi-circuit outdoor coil. However, an experimental study on defrosting performance for an ASHP unit at different frosting evenness values (FEVs) with melted frost local drainage was carried out [30]. After the melted frost was taken away by the water collecting trays during defrosting, defrosting duration was shortened by 11.2%, and defrosting efficiency increased by 5.7%, as the FEV increased from 79.4% to 96.6%. Clearly, it is meaningful to improve the FEV during frosting stage, and locally drain the melted frost during defrosting stage. To further clarify the negative effect of melted frost, a semi-empirical modeling study on the defrosting performance for an ASHP with local drainage of melted frost from its three-circuit outdoor coil was developed [31]. Based on the validated model, three study cases of varying heat supply to outdoor unit were further investigated, demonstrating the optimization of ASHP unit by defrosting energy decreased to 96.4%, and defrosting duration reduced by 7 s [32]. Clearly, when we optimize the time-based start defrosting control strategy, the melted frost effects could not be neglected.

The outline of the proposed problem is shown in Fig. 1. Although it was demonstrated that a higher FEVs would improve both of the frosting and defrosting performances for an ASHP unit [14,15], how to influence the defrosting performance for different frost accumulations at high FEVs with the melted frost locally drained is still unknown. After this fundamental problem was qualitatively and quantitatively solved, the pre-set frosting duration could be given in a time-based start defrosting control strategy. The mal-defrosting problems could also be effectively avoided, and thus potentially large amounts of energy saved. Therefore, in this paper, an experimental study on time-based start defrosting control strategy optimization for an ASHP unit with frost evenly distributed and melted frost locally drained is carried out. Firstly, the experimental setup was introduced. Then, the experimental procedures and five continuous cases were designed. After these observed, measured and calculated results given, system energy and stability performances and start defrosting indexes were comparatively analyzed and discussed. Finally, a conclusion is given. It was expected that this work will be used to optimize the control strategy for intelligent heat pump and the ultimate goal of building energy saving.

2. Experiment

2.1. Experimental chamber and setup

The experimental ASHP unit was established in an environmental chamber having a simulated heated indoor space and a simulated outdoor frosting space, as shown in Fig. 2. The sizes of both spaces were the same at 3.8 m (L) × 3.8 m (W) × 2.8 m (H). In each space, sensible and latent load generating units (LGUs) were installed and used to simulate different thermal loads. The experimental conditions were jointly maintained by using the two LGUs and a separate direct expansion (DX) air conditioning (A/C) system. During experiments, to accurately control the frost accumulation by minor adjusting air relative humidity, four household humidifiers were placed at the two sides of outdoor coil entrance. During normal heating (or frosting) operation, a frosting environment in the outdoor space was maintained by running the experimental ASHP unit, four humidifiers, and two LGUs together, while an indoor heated environment by the experimental ASHP unit and the existing DX A/C system. The experimental ASHP unit was modified from a commercially 6.5 kW heating-capacity variable speed split-type unit, with its swing type compressor and electronic expansion valve (EEV) shown in Fig. 3. In this unit, the refrigerant tubes for liquid and vapor were at external diameters of 6.4 mm and 12.7 mm, respectively. It was the four-way valve that switched the heating/frosting and defrosting modes, with the corresponding refrigerant flow direction marked as red and blue arrows in Fig. 3.

In the experimental ASHP unit, the three-circuit outdoor coil was specially designed, which was vertically installed in the outdoor frosting space. To keep the status of air flow distribution were constant at start of frosting, the three-circuit outdoor coil was con-