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Energy transfer procession in an air source heat pump unit during defrosting with melted frost locally drainage in its multi-circuit outdoor coil

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ABSTRACT

Air source heat pump (ASHP) units are widely used in recent years, and reverse cycle defrosting becomes the most popular method to solve their undesired frosting problem. During defrosting, a transient and nonlinear heat and mass transfer procession, the metal energy stored in the indoor and outdoor coils are varying as their temperature fluctuations. On the other hand, authors have previously confirmed the effects of melted frost and metal energy storage on system defrosting performance. However, detailed energy transfer procession without melted frost influence is still not identified. This fundamental problem directly affects the development and modification of two coils in a novel ASHP unit or an existing one. Consequently, basing on frost evenly accumulated on each circuit's surface, two cases were thereby designed in this study. Experimental results show that, the heating supply of indoor air thermal energy contributed about 80% of the total energy usage for defrosting, nearly 90% of energy consumed on frost melting and ambient air heating, respectively. After the total area of outdoor coil was enlarged by 50%, the metal energy storage effect was changed from −0.44% to −3.67%. Meanwhile, defrosting efficiency was improved by 11.66%, from 47.13% to 58.79%. Contributions of this study can effectively guide the design optimization of an ASHP unit, improve occupant's thermal comfort and promote the energy saving in buildings and industry.

1. Introduction

In recent years, air source heat pump (ASHP) units have found their wide applications as heating source for heating source due to their advantages of high efficiency and low environmental pollution [1,2], and the governmental subsidies [3,4]. Their applications include building heating [5], hot water supply [6], and material drying [7], etc. For an ASHP unit working at heating mode, when its outdoor coil surface temperature is below both the air dew point and the water freezing point, frost will form and accumulate there, and thus play negative effects on the coefficient of performance (COP) of system [8]. Although some frost retarding measures can delay frost formation or growth [9,10], they are always expensive or consume additional high grade energy [11]. Thus, non-frosting ASHP unit was widely explored, such as by adding extra heat exchanger coated with a solid desiccant [12,13], or a solution spray subsystem [14] in a conventional ASHP system. However, frost that is present after delaying would have to be removed, which resulting in series of defrosting methods explored, including compressor shutdown [15], electric heat [16], hot water spraying [17], ultrasonic vibration [18], air-particle jet [19], and hot gas bypass [20], etc. Finally, reverse cycle defrosting (RCD) becomes the most widely used method for ASHP units due to its advantages of simple structure, convenient application, high efficiency, system safety, and few modifications [21]. During RCD, when the working mode of an ASHP unit turns from heating to defrosting, the roles of indoor and outdoor coils changed. The outdoor coil acts as a condenser from an evaporator, and in verse for its indoor coil. Energy transfer procession in an ASHP unit during heating and defrosting are further illustrated in Fig. 1 [22,23].

After the mode is turned to defrosting mode, the space heating used energy is changed to be consumed on melting frost and vaporizing water. Not only indoor space heating was interrupted, but

Abbreviations: A/C, Air conditioning; ASHP, Air source heat pump; COP, Coefficient of performance; DEV, Defrosting evenness vale; DX, Direct expansion; EEV, Electronic expansive valve; FEV, Frosting evenness value; MES, Metal energy storage; MS, Manual stop valve; RCD, Reverse cycle defrosting; SV, Solenoid modeling valve.

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Nomenclatures

Variable	Description (unit)
c_{Al}	Specific heat of aluminum (0.88) (kJ/(kg °C))
c_{Cu}	Specific heat of copper (0.39) (kJ/(kg °C))
$c_{i,\ a}$	Specific heat of indoor air (1.004) (kJ/(kg °C))
c_{PMe}	Average specific heat of metal (kJ/(kg °C))
E_{comp}	Electricity input to compressor during defrosting (kJ)
$E_{i,\ fan}$	Electricity input to indoor air fan during defrosting (kJ)
L_{sf}	Latent heat of frost melting (334) (kJ/kg)
L_v	Latent heat of water vaporization (2443) (kJ/kg)
m_{Al}	Mass of aluminum (kg)
m_{Cu}	Mass of copper (kg)
$m_{i,\ a}$	Mass rate of indoor air (kg/s)
m_{cf}	Total mass of the melted frost collected in the cylinders (kg)
m_f	Total mass of the frost accumulated (kg)
m_m	Total mass of the melted frost collected and retained water (kg)
m_{rw}	Total mass of retained water (kg)
m_v	Total mass of vaporized water (kg)
η_d	Defrosting efficiency (%)
η_m	Effect of MES on defrosting performance (%)
$\rho_{i,\ a}$	Density of indoor air (kg/m^3)
$\rho_{o,\ a}$	Density of outdoor air (kg/m^3)
P_{Me}	Rate of heat supply from indoor coil metal (kW)
q_{Me}	Energy used to heat the metal (kW)
Q_f	Energy consumed on frost melting and vaporizing (kJ)
$Q_{i,\ a}$	Heat supply from indoor air (kJ)
Q_m	Energy consumed on melting frost (kJ)
Q_v	Energy consumed on vaporizing water (kJ)
$Q_{i,\ MES}$	Energy discharged from the metal of indoor coil (kJ)
$Q_{o,\ MES}$	Energy discharged from the metal of outdoor coil (kJ)
$Q_{i,MES-0}$	Metal energy storage of indoor coil at defrosting start (kJ)
$Q_{o,MES-0}$	Metal energy storage of outdoor coil at defrosting start (kJ)
$Q_{i,MES-t}$	Metal energy storage of indoor coil at defrosting end (kJ)
$Q_{o,MES-t}$	Metal energy storage of outdoor coil at defrosting end (kJ)
Δt	Measuring time interval (s)
t	Time (s)
t_d	Defrosting duration (s)
t_f	Frosting duration (s)
ΔT_{Me}	Average temperature difference of indoor coil metal (°C)
T	Temperature (°C)
T_{in}	Tube surface temperature at the inlet of indoor coil (°C)
T_{out}	Tube surface temperature at the outlet of indoor coil (°C)
$T_{ind,\ in}$	Air temperature at the entrance of indoor coil (°C)
$T_{ind,\ out}$	Air temperature at the exit of indoor coil (°C)
T_0	Average temperature of indoor coil metal at defrosting start (°C)
T_t	Average temperature of indoor coil metal at defrosting end (°C)
$\omega_{o,\ o}$	Moisture content of air at the outlet of outdoor coil (g/kg (dry air))
$\omega_{o,\ i}$	Moisture content of air at the inlet of outdoor coil (g/kg (dry air))
$V_{o,\ a}$	Volume of outdoor air (m^3)

also the thermal comfort level was adversely affected [17]. Because the low temperature for ambient air always comes out at night, sleep thermal comfort is always degraded due to frequent defrosting operations of the ASHP unit [24]. Energy transfer procession directly affects the defrosting performance, which is key problem for the application of ASHP units. Therefore, to improve the defrosting performance, various experimental studies were conducted, including (1) changing outdoor coil installation style [25], (2) adjusting refrigerant distribution [26], (3) eliminating uneven defrosting [27], (4) improving frosting evenness values (FEVs) [28], (5) improving defrosting evenness values (DEVs) [19], (6) controlling frost distribution to match defrosting heat distribution [29], (7) fin surface treatment for eliminating the retained water [30,31], and (8) adding phase change material thermal energy storage (PCM-TES) in system [32,33], etc. As the latest development, Wang et al. used superhydrophobic surface treatment material to improve the defrosting performance of fin-tube heat exchanger [30]. Experimental results indicated that, compared with the hydrophilic and bare units, the defrosting duration of the superhydrophobic unit was shortened by 41.7% and 43.2%, and the energy consumed on defrosting was reduced by 47.2% and 61.9%, respectively. Also in 2017, Hrnjak et al. experimentally investigated the effect of louver angle on performance of heat exchanger with serpentine fins and flat tubes in frosting and defrosting. As indicated, the overall heat transfer coefficient at the beginning of the first frosting cycle for louver angle 27° with fin pitch 18 fpi was about 0.7% higher than 39° and about 8% higher than 15° [34].

It was also demonstrated that the energy consumptions for heating outdoor coil metal accounted for 16.5% of the total defrosting energy consumption by Dong et al. [35]. And thus, the metal energy storage (MES) was considered in the model development of defrosting for an ASHP unit [36]. Furthermore, authors previously experimentally investigated that, after the outdoor coil enlarged 50%, the MES effect changed from positive (0.33%) to negative (−2.18%). Defrosting efficiency was also improved about 6.08%, from 42.26% to 48.34% [19]. Therefore, the MES effects on defrosting performance for an ASHP unit are very important. It is meaningful to quantitatively explore the two energy transfer equations shown in Fig. 1.

On the other hand, the negative effects of melted frost on defrosting were demonstrated in previously reported experimental studies [19,22]. It was demonstrated that much thermal energy consumed during defrosting, when melted frost flew downward along the surface of multi-circuit outdoor coil, or was kept on the downside of outdoor coil due to surface tension [24]. After water collecting trays installed between circuits in two-circuit and three-circuit outdoor coils, the total defrosting energy consumption could be saved by 10.3% and 10.4%, respectively [37]. Compared to a traditional outdoor coil, after the melted frost was locally removed during defrosting, the effect of uneven refrigerant on defrosting efficiency was improved from 6.9% to 7.4% [38]. By comparing the test data in the first 11 cycles with the later 5 cycles, Wang et al. experimentally demonstrated the defrosting water retention on the surface of evaporator negatively impacting the performance of ASHP during periodic frosting-defrosting cycles. The heating capacity and the heating efficiency both dropped 11% and 10%, respectively [39]. Park et al. carried out experiments of repeated frosting/defrosting cycles of a louvered fin heat exchanger,