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Energy transfer procession in an air source heat pump unit during defrosting

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HIGHLIGHTS

- Energy transfer procession in an ASHP unit during defrosting was explored.
- Effect of metal energy storage on defrosting was proposed and calculated.
- Metal energy storage effect was changed from positive (0.33%) to negative (−2.18%).
- Defrosting efficiency was improved about 6.08%, from 42.26% to 48.34%.
- Contributions of this study can guide the design optimization of two ASHP's coils.

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ABSTRACT

Air source heat pump units have found their wide applications in recent decades due to their high efficiency and low environmental pollution. To solve their undesired frosting problem, reverse cycle defrosting is always employed. As a transient and nonlinear heat and mass transfer procession, defrosting performance directly affects the occupants' thermal comfort. During defrosting, the metal energy storage values of indoor and outdoor coils are varied as their temperature fluctuations. It is therefore necessary to investigate the energy transfer procession in an air source heat pump unit and the effect of metal energy storage during defrosting. However, scarce of attentions were paid to this fundamental problem. In this study, two experimental cases with two-working-circuit and three-working-circuit outdoor coils were conducted basing on frost evenly accumulated on their surfaces. After four types of energy supply and five types of energy consumption during defrosting were calculated, a qualitative and quantitative evaluation on the metal energy storage effect was then given. As concluded, after the outdoor coil enlarged 50%, the metal energy storage effect can be changed from positive (0.33%) to negative (−2.18%). The percentages of energy consumed on melting frost and vaporizing retained water were both increased. Defrosting efficiency was improved about 6.08%, from 42.26% to 48.34%. Contributions of this study can effectively guide the design optimization of indoor and outdoor coils and promote the energy saving for air source heat pump units.

1. Introduction

Global warming, ozone layer depletion and high-levels of pollution, especially the PM 2.5 air pollution in Beijing in China, make air source heat pump (ASHP) units widely used over the recent decades as heating source for building heating and hot water supply [1,2]. Meanwhile, governmental subsidies support customers using ASHP units, for example, *Coal to Electricity in North China*. However, 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, it is hard to avoid frost formed and accumulated there. As frost thickness increases, it reduces the airflow passages and thus increases the airside pressure drop, reduces the heat transfer rate and thus adversely degrades the coefficient of performance (COP) of system [3].

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Nomenclature

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}	power input to compressor during defrosting (kJ)
$E_{i,fan}$	power 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 frost accumulated over outdoor coil surface (kg)
m_m	total mass of the melted frost collected in the cylinders 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 melting the accumulated frost and evaporating the retained water (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)
$Q_{i,MES-0}$	energy stored at the metal of indoor coil at the start of defrosting (kJ)
$Q_{o,MES-0}$	energy stored at the metal of outdoor coil at the start of defrosting (kJ)
$Q_{i,MES-t}$	energy stored at the metal of indoor coil at the end of defrosting (kJ)
$Q_{o,MES-t}$	energy stored at the metal of outdoor coil at the end of defrosting (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 inlet of indoor coil (°C)
$T_{ind,out}$	air temperature at the outlet of indoor coil (°C)
T_0	average temperature of indoor coil metal at the start of defrosting (°C)
T_t	average temperature of indoor coil metal at the end of defrosting (°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)

Abbreviations

ACS	air conditioning system
ASHP	air source heat pump
COP	coefficient of performance
DAS	data acquisition system
DX	direct expansion
EEV	electronic expansive valve
FEV	frosting evenness value
LGU	load generating unit
MES	metal energy storage
PVC	polyvinyl chloride

In order to improve the operating performance of an ASHP unit, various frost retarding measures were explored, including (1) reducing inlet air humidity [4], (2) improving inlet air temperature [5], (3) increasing inlet air flow rate [6], (4) adjusting fin geometry and type [7,8], (5) undertaking fin surface treatment [9], and optimizing the refrigerant distribution [10,11], etc. While the use of frost retarding measures can delay frost formation or growth, they are always expensive or consume additional energy. Frost that is present after delaying would have to be removed. Therefore, periodic defrosting becomes necessary for guaranteeing the satisfactory operation of an ASHP unit [10]. Defrosting may be realized by a number of methods, consisting of (1) compressor shutdown defrosting [12], (2) electric heat defrosting [13], (3) hot water spray defrosting [14], (4) ultrasonic vibration defrosting [15], (5) air-particle jet defrosting [16], and (6) hot gas bypass defrosting [17], etc. Currently, the most widely used standard defrosting method for ASHP units is revere cycle defrosting, due to its advantages of simple structure, convenient application, high efficiency, system safety, and few modifications [11].

As shown in Fig. 1, when the ASHP unit turns from heating mode to reverse cycle defrosting mode, the outdoor coil changes to act as a condenser from an evaporator, and inverse for its indoor coil. The energy that should have been used for space heating is consumed on melting frost and vaporizing water. Not only the indoor space heating was interrupted, but also indoor thermal comfort level may be adversely affected [18,19]. Because the low temperature for ambient air always comes out at night, sleep thermal comfort is always degraded due to frequent defrosting operations of an ASHP unit [20,21]. As a transient and nonlinear heat and mass transfer procession, energy transfer processions directly affect the defrosting performance. Consequently, to improve the defrosting performance of ASHP units, many experimental studies were reported in recent decades, such as, (1) changing the installation style of outdoor coil [22], (2) adjusting the refrigerant distribution [23], (3) eliminating uneven defrosting [24,25], (4) improving frosting evenness values (FEVs) [26,27], and (5) adding PCM-TES in defrosting system [28], etc. Among these mentioned studies, two indexes, defrosting duration and defrosting efficiency, were simply used to evaluate system defrosting performance [29–31]. However, dynamic and complicated energy transfer procession is always neglected and not given.

It is easy to understand that energy transfer procession can be calculated with numerical method. Notably, Cole built a defrosting model for large commercial freezers, and reported the heat and mass transfer and fluid flow mechanisms. Meanwhile, the resultant refrigeration loads due to defrosting were theoretically estimated