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Experimental investigation on the defrosting performance of a finned-tube evaporator using intermittent ultrasonic vibration

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HIGHLIGHTS

- The defrosting area of a single ultrasonic transducer is 0.165 m^2.
- There is only a basic frost layer on the fin surface with ultrasonic vibration.
- The COP increment percentage is between 6.51% and 15.33% with ultrasonic vibration.

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ABSTRACT

When an air-source heat pump (ASHP) was operated in heating mode under certain ambient conditions, frost always accumulated on the fin surface of its outdoor coil. Frosting may increase the energy consumption and deteriorate the performance of the ASHP, and hence, periodic defrosting is necessary. In this study, a new defrosting method using intermittent ultrasonic vibration was investigated. First, the vibration attenuation characteristics of a double-row outdoor coil and the frost growth characteristics under different ambient conditions were determined. Next, the average frost thickness with and without the application of intermittent ultrasonic vibration was calculated using MATLAB software. Finally, the decrease in defrosting energy consumption, the increase in heating capacity, and the increase in the coefficient of performance were analysed. The experimental results indicate that intermittent ultrasonic vibration could effectively remove the frost accumulated on the fin surface, and the effective defrosting area of an single ultrasonic transducer was 0.165 m^2 for a double-row finned-tube evaporator on which an ultrasonic transducer with a rated power of 50 W and resonant frequency of 40 kHz was applied. The defrosting energy consumption of the ASHP unit with ultrasonic vibration was 3.14–5.46% lower than that without ultrasonic vibration, whereas the heating capacity increased by 2.2–9.03% and the COP increased by 6.51–15.33%. In addition, the thermal comfort of the indoor side was clearly improved.

1. Introduction

Frost deposition on the evaporator surface during the operation of an air-source heat pump (ASHP) in heating mode is an undesirable and common phenomenon. The growth of the frost layer will increase the air pressure drop and heat transfer resistance of the evaporator, which reduces the heating capacity and increases the energy consumption of the ASHP unit. In addition, the ASHP unit may suffer from an unscheduled shutdown due to the overheating protection and low-pressure protection of the compressor. To ensure the normal operation of an ASHP, periodical defrosting is required. Therefore, it is of great practical significance to develop an effective defrosting or frost suppression method for energy conservation.

Currently, the most widely used standard method of frost removal is reverse cycle defrosting (RCD) [1,2]. RCD is a procedure that switches the heating mode of an ASHP to cooling mode. When a space heating ASHP is operated in RCD mode, its outdoor coil acts as a condenser and its indoor coil acts as an evaporator. As a result, a space heating ASHP actually cools the surrounding space during defrosting, degrading indoor thermal comfort. Therefore, the defrosting period should be controlled to be as short as possible

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Nomenclature

$L \times W \times H$	Length (m) × Width (m) × Height (m)	p_i	the pixels of the ith image
δ	double sides' average frost thickness (m)	p_L	the pixels of the image's vertical edge = 1136
p_1	the pixels of the first image	p_c	the pixels of calibration circle's diameter
D_c	the diameter of calibration circle	Φ_h	total heat output of indoor heat exchanger
n	the number of fin in one image	V'_n	specific volume of humid air at test point
q_{ml}	volume air flow rate of indoor side	h_1	inlet air-enthalpy of indoor side
h_2	outlet air-enthalpy of indoor side	q_0	heat leakage of air volume device
W_n	air humidity at test point	t_2	average temperature of outlet section
t_1	average temperature of inlet section	AEC	average energy consumption
d	air humidity ratio	AED	average enthalpy difference
ESP	energy saving percentage	COP	coefficient of performance
EDIP	enthalpy difference increment percentage	W_{net}	net power supply for the ASHP unit
Q_H	the quantity of heat supply for indoor air		
s	second		

[3,4]. In addition, most melted frost drains off from the outdoor coil surface, and the retained residual water is frozen when the ASHP returns to heating mode. Therefore, a complete defrosting process should involve both melting the frost and drying the coil surface. Furthermore, pressure shock of the compressor often occurs due to the switching of the four-way valve, and hence, the reliability and service life of the ASHP unit is reduced [5,6].

To overcome these problems in RCD, the hot-gas bypass defrosting (HGBD) method was proposed in 2000 [7,8]. In the HGBD process, the hot-gas released from the compressor is used to melt the frost on the outdoor heat exchanger surface; therefore, the HGBD can supply continuous heat without the need to switch the four-way valve. However, because low-quality heat is used in the HGBD process, the defrosting time is much longer than that associated with RCD [9]. Although the HGBD method has many advantages for frost removal, few studies on the HGBD cycle have been reported; thus, further investigations are required to enable its actual application. In addition, many researchers have studied electric heat defrosting and hot water defrosting for an ASHP system. However, these methods require additional expenses, and some safety issues should be considered, such as electric shock, short circuit and risk of fire [10,11].

Using developments in advanced materials science, some researchers have attempted to prevent frost formation by modifying material surface, such as by the introduction of hydrophobic and hydrophilic materials on the fin-surface [12–15]. Huang et al. [16] and Lee et al. [17] investigated the effects of hydrophobic and hydrophilic surfaces on frost formation, respectively. Their experimental results indicated that a super-hydrophobic surface can not only retard initial frost formation but can also reduce the defrosting time, whereas a hydrophilic surface has a lower frost thickness and a higher density than the hydrophobic surface. Although hydrophobic and hydrophilic surfaces have distinct effect in preventing frost formation during the early stage of frosting, the effect of frost suppression is not appreciable when the cold surfaces are covered with a frost layer. Therefore, a hydrophilic layer and the RCD system are currently combined in commercial air conditioning evaporators.

In recent years, studies concerning the effect of ultrasonic vibration on de-icing or defrosting have attracted the attention of many scholars. Palacios et al. [18,19] and Overmeyer et al. [20] performed experimental and numerical studies to investigate interfacial stress and ice bonding strength under ultrasonic excitation at different frequencies and amplitudes. They found that ultrasonic vibration could effectively promote instantaneous ice delamination under specific excitation frequencies and amplitudes and that ultrasonic vibration could also prevent water freezing on a cold surface at temperatures below −15 °C. Zhu et al. [21] theoretically analysed ultrasonic guided wave propagation along a multi-layer composite plate with an ice layer. They found that transverse shear stress at the interface between the ice layer and the substrate could be induced by choosing an optimal ultrasonic guided wave mode and frequency and that de-icing could also occur as a result of interface fatigue, thermal melting and cracking. Tan et al. [22] and Li et al. [23] analysed the optimal de-icing frequency and the installation intervals of transducers for wind turbine blades. They found that the shear stress excited by ultrasonic vibration exceeded the adhesion strength of the frozen ice and that de-icing was caused by the interfacial shear stress produced by the velocity difference when an ultrasonic wave was propagated through two different media. Although some thought-provoking conclusions pertaining to ultrasonic de-icing have been drawn, the technique is still not applicable for commercial use.

The literature shows that the number of research articles related to ultrasonic defrosting for a heat exchanger is relatively less compared to that of studies related to ultrasonic de-icing for blades. Adachi et al. [24,25] investigated the effects of high- amplitude ultrasonic vibrations on the frosting process in an environment with nearly 100% relative humidity at 2 °C. The experimental results indicated that ultrasonic vibration could suppress the accumulation of frost, although the frost suppression mechanism was not explained clearly in the authors' paper. Yan et al. [26] tested the defrosting effect on a heat exchanger under single and double ultrasonic sound sources with different frequencies. The study results indicated that the transverse wave defrosting effect is better than the longitudinal wave effect, and a double ultrasonic sound source is better than a single sound source. Barelli et al. [27] placed piezoelectric chips on the evaporator fins for defrosting. This system can inhibit frost deposition on the evaporator fins during chilling operation, and the defrosting effect can be optimized by tuning the operation frequency and voltage according to mass of deposited frost. The effects of ultrasonic waves on frost formation on a cold surface were investigated by Li et al. [28]. They found that the sizes of the deposited freezing droplets under the effects of ultrasound are smaller than those without ultrasound and that the shapes of the freezing droplets are relatively similar. However, the impacted area of the noncontact ultrasonic system is small. Wang et al. [29] investigated the effect of frost release from a finned-tube evaporator using a microscope imaging system. The experiments demonstrated that individual frost crystals were fractured and removed effectively, but the ice layer on the fins could not be removed with ultrasonic vibration. Current research indicates that ultrasonic defrosting is a high-efficiency and energy-saving defrosting method.