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Experimental study on defrosting mechanism of intermittent ultrasonic resonance for a finned-tube evaporator

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ABSTRACT

This paper proposed a new defrosting method based on ultrasonic resonance mechanism, to solve the problem of the unknown mechanism of ultrasonic defrosting for a finned-tube evaporator. Dynamic microscopic process of frost crystals formation and growth under the natural frost condition was first investigated. According to the growth characteristics of the frost crystals, the natural frequencies of frost crystals with different height were calculated in COMSOL software. An ultrasonic transducer of 28 kHz/60 W was adopted as an executor to excite the evaporator, then ultrasonic defrosting experiments and laser vibrometer experiments were carried out under the excitation of the ultrasonic transducer. Finally, experiment of ultrasonic resonance based on intermittent operational was studied to optimize ultrasonic loading method. It was found that the height of the frost crystals were about 0.5 mm after growing for 4 min, the average natural frequency of the frost crystals were about 27.95 kHz, the evaporator and frost crystals on the fin surface were forced vibration at the frequency of 28.2 kHz, which was the actual working frequency of the ultrasonic transducer detected in laser vibrometer experiment, and most frost crystals with certain shape and size were immediately broken up when the ultrasonic vibration applied. The main mechanism of ultrasonic defrosting was the resonance effect of natural frequency of frost crystals and excitation frequency, and the optimal working mode of ultrasonic resonance defrosting was intermittent 4 min, vibration 1 min. The experiment's results also showed that ultrasonic shear stress and acceleration effect of ultrasonic also had defrosting performance, but they were not the main mechanism for ultrasonic defrosting.

1. Introduction

Frost formation on the surface of a finned-tube evaporator is often encountered under a low ambient temperature in winter. The thermal resistance increases and air channels blocks the heat-exchanger due to frost deposition, which the heat-exchange efficiency decreased drastically. Even the refrigeration system is shutdown due to the impact of refrigerant droplets against compressor blades. Therefore, developing an effective method to prevent evaporator frosting is crucial in the field of refrigeration and air conditioning.

In the past few years, there are many studies concerning the anti-frost and defrosting technology which uses external fields. For example, Liu and Tang [1] presented a dynamic simulation model of an air-source heat pump during hot-gas defrosting. They set up a nominal 0.88 kW capacity residential air-to-air heat pump during the defrosting, the simulation results are consistent with the experiment data. It also shows that the model is suitable for the simulation of performance characteristics of defrosting cycles. Cho et al. [2] measured the performance of an on–off cycle and hot-gas bypass defrosting of three showcase refrigeration evaporators. The study result showed that the optimum electronic expansion valve (EEV) opening was 75% of the full openings during the hot-gas bypass defrosting. The hot bypass defrosting cycles showed advantages in achieving the appropriate refrigerating capacity and maintaining constant storage temperature compared to the on–off cycling, although it had a relatively higher compressor power. Hoffenbecker et al. [3] proposed a transient model to predict the heat and mass transfer effects for an air-cooling evaporator during a hot gas defrosting cycle. Parametric analysis results showed that an optimum hot gas temperature is a function of both the accumulated mass and density of frost on the evaporator, and the model predicted that the mass of moisture re-evaporated back to the space increased with decreasing hot gas temperature. Qu et al. [4] experimentally studied a novel reverse-defrosting method which used phase change material (PCM) to storage the

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Nomenclature

BLT	bolt-clamped Langevin-type transducer	W×L×H	width(mm) × length(mm) × height(mm)
s	second	μ	=G, shearing modulus
ρ	material density	λ	lame constants
n	=1, 2 layer number	∇^2	$= \partial^2/\partial x_1^2 + \partial^2/\partial x_3^2$, differential operators
t	time	ϕ	dilatation strain
ψ	equivoluminal strain	ω	angular frequency
c_L	longitudinal wave velocity	c_T	shear wave velocity
k_L	=ω/c_L, longitudinal wave number	k_T	=ω/c_T, shear wave number
θ_L	angle of longitudinal wave propagation direction and normal direction	θ_T	angle of shear wave propagation direction and normal direction
C_1, C_2, C_3, C_4	arbitrary constants	a	acceleration
nu	Poisson ratio	T_{zx}, T_{zy}	shear stress in x_1x_2 plane
E	elastic modulus		

thermal energy. Compared to standard defrosting condition, the PCM-based reverse-cycle defrosting method could shorter the defrosting time with higher suction pressure, the defrosting COP was increased and did not degrade the quality of space heating during heating operation, and indoor thermal comfort was improved for occupants during defrosting and heating resumption process. A transient simulation model of an air-coil evaporator to predict and evaluate the performance of the hot-gas defrosting process was developed by Dopazo et al. [5]. A finite difference approach was used to solve the model equations, the defrosting time and energy supply were increased as the refrigerant mass flow rate decreases or the inlet refrigerant temperature increase. The percentage of energy used to warm and melt the frost increases as the refrigerant mass flow rate increases (from 40.36% to 43.52%), and the minimum value of the percentage (32.2%) was found around 294 K.

As concluded in the research results above, hot gas and reverse cycle defrosting can remove frost effectively and inhibit frost deposition on the evaporator. With the common disadvantage of seriously penalizing the overall heat pump or air-conditioner efficiency, for they not only release cryogenic energy to the room, but also use energy during defrosting. Before defrosting, the heat pump or air-conditioner operated in low efficiency because of deposition frost which increases the thermal resistance and decreases air mass flow.

Relative to the hot gas defrosting, numerous researchers focused on the frost formation subjected to the influence of electric field. Munakata et al. [6] have studied the effect of electric fields on frosting phenomenon in 1998. They found a critical value, which the frosting rate was gradually decreased by increasing the electric field strength up to this certain value. After this critical value, the frosting rate was increased by increasing the field strength. Wang et al. [7] found that with the presence of electro hydrodynamics (EHD), the frost crystal was pulled up towards the electrode and the structure was relatively skinny and fragile to easily break up and fall off due to the influence of gravity. The speed of the frost growth and the break-off frequency under negative polarity was roughly 30–50% higher than those with the positive polarity. This phenomenon is related to the opposite direction of the dielectrophoretic force and the electrostrictive force at a positive polarity, whereas the direction of the dielectrophoretic force and the electrostrictive force are the same at a negative polarity. Tudor and Ohadi [8] firstly studied the effect of stationary and sweeping frequency AC electric fields on frost crystals growth and frost control/removal. They used electric field with sweeping frequencies (from 370 Hz to 7.5 kHz) at an applied voltage of 14.5 kV, the 46% reduction of frost was obtained, and most crystals were pulled by the applied oscillating electric force in the first 10–60 s. Zhang et al. [9] investigated the influences of direct current (DC) electric fields on the initial form of the frost crystal on a cold vertical plate. The experimental results showed that at the initial stages of the frost formation that the stronger the electric field, the smaller the water drops formed on the cold plate. They also found the frost mass increases with the electric field intensity. Joppolo et al. [10] experimentally studied the influence of a DC electric fields on the performance of a finned-tube evaporator under frosting condition and found that the electric field can reduce the frost mass and air-side pressure drop. To conclude, the use of the EHD technique could provide beneficial results for applications where frost insulating effect and air flow blocking effects were important and detrimental for the system working conditions. Generally speaking, the use of applied electric field could not remove frost completely, but it could delay or suppress frost deposition under certain condition. Therefore, exploration of a long-term effective frost suppression technology and application of it into practice was very important, which could achieve the purpose of energy saving and system performance optimization for the foundation of commercial application.

In addition to the above frost suppression technology, ultrasonic frost suppression technology was firstly studied by Adachi [11,12] in 1998. They used ultrasonic flexural vibration to excite a rectangular duralumin plate (20 mm × 92.6 mm) in almost 100% relative humidity at 2 °C. The defrosting experimental showed that the frost was decreased by almost 60% with the frequency of approximately 37 kHz and amplitude of 3.1 μm. The authors attributed this effect to the movement of small frost crystal nuclei which cannot stay on the plate to grow when the vibration amplitude is high. Yan et al. [13] experimentally studied the ultrasonic defrosting on a heat-exchange with a 40 m^2 refrigeration fan. The results proved that ultrasonic defrosting technology is feasible for refrigeration fan, and the transverse wave defrosting effect is better than vertical wave. Li et al. [14] investigated the initial frost nucleation, structure and thickness on a plate surface with and without 20 kHz noncontact ultrasound wave for 10 min. The experimental results showed that the sizes of deposited freezing droplets on the cold surface with the effect of ultrasound are much smaller than that without ultrasound and the shape is relatively inerratic. The ultrasound has a strong ability to restrain the initial frost nucleation and frost growth process. However, the impacted area of noncontact ultrasonic was small, the noncontact ultrasound cannot effective remove when the whole evaporator had frosted. Wang et al. [15] used dynamic microscopic process to investigate the frost formation and growth with and without ultrasonic vibration. They concluded that the mechanism of ultrasonic frost suppression was mainly attribute to the mechanical vibration effect, but the reason why low-frequency mechanical vibration have not frost suppression effect was not explained yet.