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Research on frost formation in air source heat pump at cold-moist conditions in central-south China

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HIGHLIGHTS

- ▶ A dynamic evaporator model is built up.
- ▶ The model involves the ratio of the latent heat to sensible heat of wet air.
- ▶ A correlation considering d_{eq} is shown below to predict frost accumulation: $\frac{M_{fr}v^3}{\Psi d_{eq}^2} = (\frac{T_a}{T_w})^{0.1}(\frac{v\tau}{d_{eq}})^{0.7}(\frac{l}{d_{eq}})^{1.378}X_a^{1.228}$.
- ▶ The changing ratio can characterize the early development of system performance.
- ▶ The changing ratio can characterize the early development of frost accumulation.

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ABSTRACT

A dynamic evaporator model of air source heat pump (ASHP), considering the ratio of the latent heat to sensible heat of wet air, is presented to analyze the performance of ASHP under frosting. The performance parameters, such as the heating capacity, COP and the outlet temperature of compressor, are simulated with CYCLEPAD. Then a semi-empirical correlation that predicts frost accumulation on the air-side of fin-tube heat exchanger is developed with dimensionless analysis and also modified by a test conducted under cold-moist conditions in winter. In addition, eight influence factors are considered involving the ambient conditions and structures of heat exchanger, whose effects are analyzed as well. Among them, the equivalent diameter of air flow cross-section in fin-tube d_{eq} is especially proposed. Lastly, the relationships between the ratio, the performance parameters and the frost accumulation are discussed in this paper, followed by an evaluation of an optimal defrosting time interval to improve the ASHP's energy efficiency and operational reliability at cold-moist conditions in central-south China.

1. Introduction

Air source heat pump (ASHP) unit is the major cooling and heating source for buildings in central-south China. However, cold and moisture are the major climate characteristics of this region in winter. When such a unit is operated under cold-moist conditions in winter, the frost formation will occur as the wet air flows through the cold surface of ASHP whose temperature is lower than the dew point. At the same time, the process of frost formation or accumulation will decrease the heat transfer significantly and increase the pressure drop rapidly, which leads to an undesirable performance degradation of the unit [1–3]. Therefore, it is necessary to launch a detailed investigation on the frosting characteristics of its air-side for the sake of its operational efficiency and reliability at cold-moist conditions.

Currently, a large number of works have been available on frost formation and its characteristics [4–12]. Also, many theoretical and experimental researches on the frosting characteristics and the heat transfer process involved in frost formation have been carried out for simple geometry heat exchangers. Schneider [4,5] has studied the frost formation on cylinder. Trammel et al. [6], Jones and Parker [7], Schulte and Howell [8] and Hosoda and Zuhashi [9] have tested it on flat plates; Brian et al. [10], Yamakawa et al. [11] and O'Neal and Tree [12] have demonstrated it on parallel flat plates. However, for such a more complex geometry than fin-tube heat exchanger, the works already done so far are still limited. The reason for this is probably that it involves many such variables as the complicated geometric surface of heat exchangers and the intricate thermo-physical characteristics of wet air during the frosting process.

Meanwhile, Kondepudi and O'Neal [13] have simulated the performance of heat exchanger with the change of frost layer based on a numerical model. Yao et al. [14] have studied the performance of

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Nomenclature

A	the area of front surface of the evaporator (m^2)
A_i	the total heat exchanger inside area (m^2)
A_{tot}	the total heat exchanger surface area (m^2)
a, b, c, d	index in correlation
c_p	specific heat of air at constant pressure (J/kg K)
$d_{a,i}$	the absolute moisture content of inlet air flow (kg/kg_{air})
$d_{a,o}$	the absolute moisture content of outlet air flow (kg/kg_{air})
$d_{a\cdot ave}$	the average moisture content of air flow (kg/kg_{air})
d_0	tube outer diameter (m)
d_{eq}	equivalent diameter of cross-section fin-tube (m)
d_s	the surface humidity of heat exchanger
d_f	fin thickness (mm)
e	fin pitch (mm)
G_a	air flow volume through the heat exchange (m^3)
l	the length of fin in the direction of air flow (m)
l_p	the length of single pipe (mm)
M_{fr}	frost accumulation per unit length (g/m)
$\dot{m}_{fr}$	the frost mass accumulation rate per unit length (kg/m s)
$\dot{m}_\rho$	the frost density accumulated rate (kg/m s)
$\dot{m}_\delta$	the thickness accumulated rate (kg/m s)
$\dot{Q}$	the total heat transfer rate (w/s)
$\dot{Q}_{con}$	the conduction heat transfer rate through the frost layer (w/s)
$\dot{Q}_{sub}$	the latent heat of condensation heat transfer rate through of frost layer (w/s)
R_{ash}	the attached thermal resistance of fin tube surface (m^2 K/W)
r_{sub}	the latent heat of sublimation (J/kg)
s_1	the tube spacing (mm)
T_a	the temperature of ambient or inlet air (K)
$T_{a,ave}$	the average temperature of air flow (K)
$\dot{T}_s$	the surface temperature of frost layer with time (K)
T_w	the surface temperature of tube outside (K)
v	face velocity of air flow through tube pipes (m/s)
v_a	the average velocity of air flow (m/s)
X_a	relative humidity
x	the direction (m)

Greek letters

Ψ	the heat flux of inner surface (w/m^2)
$\dot{\alpha}_{lat}$	the latent heat exchange coefficient of wet air
$\dot{\alpha}_{sen}$	the sensible heat exchange coefficient of wet air
$\dot{\alpha}_{ls}$	the ratio of the latent heat to sensible heat
λ_{fr}	the thermal conductivity of frost (w/m K)
σ	the mass transfer coefficient (kg/m^2 s)
δ_{fr}	the frost thickness (m)
θ	the tilt angle of corrugated fins
τ	frosting time(s)

ASHP under different ambient conditions, but at a constant evaporation temperature; Oskarsson and Krakow [15,16] have presented a finite evaporator model to simulate the frosting conditions, with only one row, which is a large difference from the practical one. In addition, the most widely used defrosting method for ASHP is reverse cycle defrosting [17,18]. Its outdoor fin-tube heat exchanger acts as a condenser and its indoor heat exchanger as an evaporator when a heating ASHP is operated in a reverse cycle defrosting mode. Hence there is no heating provided during defrosting, thus degrading indoor thermal comfort while consuming electrical energy for melting frost [19,20]. Moreover, low-pressure cutoff or wet compression may take place, which may cause an ASHP unit to shut down and potential compressor damage. However, Qu et al. [21] have studied further this method, they have employed an electronic expansion valve to regulate the flow volume of refrigerant, but the reverse cycle defrosting is a complex process and also the technology is complicated.

Previous researches have revealed that the frosting characteristics and the performances of heat exchanger are mostly influenced by the ambient parameters such as the ambient temperature, humidity, face velocity and cold surface temperature; Schneider [22] has presented a correlation of frost thickness on the circular tube, yet where the effect of face velocity is ignored. Empirical correlations for the frost thickness and density have been proposed by Cremers and Mehra [23] and Sengupta et al. [24], which, however, are obtained with a fixed air flow volume and cold surface temperature. Lee et al. [25] have developed a correlation of frost accumulation in wet air of low humidity; Tokura et al. [26], Biguria and Wenzel [27] have provided the correlations for thickness, density of frost layer in the inlet air of high temperature. Nevertheless, they are seemly not fitted well in central-south China of cold-moist conditions. Mao et al. [28,29] have proposed dimensionless correlations of frosting characteristics, but which cannot predict the test data well. These works that deal with correlations of frosting characteristics did not involve all the practical influence factors; and especially, a kind of new evaporator model considering the ratio of the latent heat to sensible heat has not been developed so far. Thus, more influence factors and their relationships based on this model are to be investigated.

2. Research object

Our research object is an ASHP water heating/chilling unit tested in central-south China in January 2008. The test unit and flowchart are shown in Figs. 1 and 2 respectively. The test loop is composed of a hot water storage tank and a CXAH0125A type ASHP unit with rated heating capacity of 38.5 kW, R22 as refrigerant. The evaporator is comprised of a heat exchanger with two rows of corrugated fin tubes arranging as U type detailed in Table 1, which is divided into 15 passages. The fin-tube heat exchanger on the view

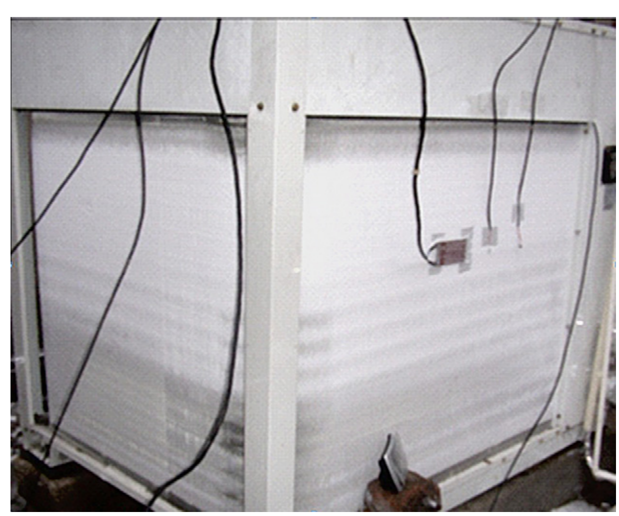

Fig. 1. The evaporator tested of ASHP.