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Quick estimation of frost growth on cold fins through thermal network analysis

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ABSTRACT

In this study, applicability of the thermal network analysis (TNA) technique in predicting the frost growth on cold fins was tested. Based on the frost formation model by Lee et al. (1997) and the analogy between the heat and mass transfer, time variations of the thickness and the density of the frost layer were predicted. At the same time, the temperature distributions of the frost layer, air stream and the fin were obtained for each time step. Then, the results were compared with the solutions by full CFD (Computational Fluid Dynamics) analysis as well as with the experimental results for two- and three-dimensional cases that have been reported by others previously. Although the results of the TNA show somewhat lower accuracy compared with those of the CFD analysis, the technique is much simpler and cost-effective in quick estimation of the frost-layer growth.

Estimation rapide de la croissance du givre sur des ailettes froides à travers une analyse du réseau de chaleur

Mots clés : Formation de givre ; Analyse de réseaux de chaleur ; Simulation numérique ; Echangeur de chaleur

1. Introduction

When a frost layer is formed on the fin surface of the evaporators of heat pump systems, the thermal resistance is greatly increased. At the same time, with the growth of the frost layer on the extended surfaces (fins), the air passage between them is narrowed down significantly. Hence, to remove the frost layer, the defrosting cycle has to be operated intermittently, which makes the overall efficiency of the heat-pump systems even worse. Thus quick and accurate prediction of frost formation/growth on the fin surface is essential in designing of evaporators of heat-pump systems with a better performance (Cui et al., 2011a,b; Da Silva et al., 2011a,b; Hermes, 2012; Hermes et al., 2009; Kandula, 2011; Kim et al., 2009; Lee et al., 2003; Moallem et al., 2013; Na and Webb, 2004a,b; Padhmanabhan et al., 2011; Wang et al., 2012; Yang and Lee, 2005; Yang et al., 2006).

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Nomenclature

Roman

c_p	specific heat (J kg^{-1} K^{-1})
D	diffusivity of water vapor (m^2 s^{-1})
h_h	heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (kg m^{-2} s^{-1})
i_{sg}	latent heat of sublimation (J kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
m''	mass flux (kg m^{-2} s^{-1})
Q	volumetric flow rate (m^3 s^{-1})
q''	heat flux (W m^{-2})
R	thermal resistance (K W^{-1})
RH	relative humidity (%)
T	temperature (K)
t	time (s)
u	velocity (m s^{-1})
x	coordinate along the air-flow direction (m)
y	coordinate normal to the fin surface (m)
z	coordinate toward the fin tip from the fin base (m)

Greek letters

α_f	absorption coefficient (s^{-1})
δ	frost thickness (m)
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Superscripts

i	node index for x-direction
k	node index for z-direction

Subscripts

a	air
B	back (negative-z) side of a control volume
E	east (positive-x) side of a control volume
F	front (positive-z) side of a control volume
f	frost layer
fin	fin
in	inlet
ini	initial
N	north (positive-y) side of a control volume
S	south (negative-y) side a control volume
s	surface
sat	saturation
W	west (negative-x) side of a control volume
w	water vapor
δ	frost-layer thickness
ρ	frost density

Dimensionless groups

Le	Lewis number [$=k/(\rho c_p D)$]
Pr	Prandtl number [$=\mu c_p/k$]
Re	Reynolds number [$=\rho u x/\mu$]

Under the frosting condition, nucleation and growth of the embryo take place over a cold surface alternatively and eventually a porous-structured frost layer is formed through which the water vapor can diffuse (Piucco et al., 2008). The growth of such a frost layer is a very complicated phenomenon because the heat and mass transfers as well as the phase change occur simultaneously within the porous structure composed of the ice-crystal particles. Therefore, in modeling the frost-layer growth, appropriate assumptions had to be employed. For example, Hermes (2012), Hermes et al. (2009), Kandula (2011), Lee et al. (1997), Mago and Sherif (2005), Na and Webb (2004b), Padhmanabhan et al. (2011) and Wang et al. (2012) proposed the one-dimensional models assuming that the heat and mass transport within the frost layer occur only in the lateral direction. Although Na and Webb (2004a) showed that, through the laminar concentration boundary layer analysis, the water vapor at the frost surface is supersaturated, the assumption of the saturation of the water vapor at the frost surface is still adopted in many of the subsequent works for simplicity (Hermes, 2012; Kandula, 2011; Mago and Sherif, 2005; Kim et al., 2009; Padhmanabhan et al., 2011; Wang et al., 2012; Yang et al., 2006). Thereby, analytical expressions for distributions of the temperature and the water-vapor density across the frost layer were available. Hence, the growth of the frost layer could be estimated based on the mass transfer coefficient and the water-vapor density difference between the free air-stream and the frost surface. Thus, estimation of the frost-surface temperature is very essential in predicting the frost growth because the saturated water-vapor density depends on the temperature (Even with the super-saturation model of Na and Webb (2004a,b), the frost-surface temperature information should be secured because the water-vapor density at the surface is also related to the temperature.). The predicted results obtained by the simplified models agreed well with experimental results but only with simple flow configurations; and it is still difficult to apply such models to the surfaces having complex shapes.

In recent years, various attempts have been made by using the CFD (Computational Fluid Dynamics) technique to find the temperature and water-vapor distributions accurately for complex geometries or by introducing the turbulence effect in the air stream, or by taking account the fluid flow within the porous frost layer. Lee et al. (2003) have obtained the temperature and water-vapor distributions of the air side using the two-dimensional (2D) CFD technique and predicted the frost-layer growth, but based on their one-dimensional frost-layer model (Lee et al., 1997). They simulated the variations of the frost thickness and density along the air-flow direction, and their results agreed with their own experimental results with the errors of about 10%. Similarly, Yang et al. (2006) estimated the air-flow behavior through the 2D CFD analysis with the turbulence effect taken into account based on the k-ε model. There, they found that the frost-layer growth and the heat transfer were promoted by the turbulence effect. Kim et al. (2009) performed the three-dimensional (3D) CFD analysis, considering the conduction heat transfer inside the fin attached to the cold base in constant temperature. The result showed that the growth rate of the frost layer sharply decreased with the farther distance from the fin base. Recently, Cui et al. (2011a) also carried out the 2D CFD analysis but with considering the air flow inside the porous frost layer. Later, Cui et al. (2011b) extended their own work to the three-dimensional cases to simulate the frost growing behavior on the surface of a fin-tube type heat exchanger.