INTERNATIONAL JOURNAL OF REFRIGERATION 34 (2011) 2018–2030

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/ijrefrig

Modeling non-uniform frost growth on a fin-and-tube heat exchanger

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ARTICLE INFO

Article history:
Received 19 November 2010
Received in revised form
28 May 2011
Accepted 3 June 2011
Available online 12 June 2011

Keywords:
Frost
Modeling
Finned tube
Air distribution

ABSTRACT

A semi-empirical model that predicts non-uniform frost growth on heat exchangers is developed and experimentally validated. The model is based on a scaling approach that uses the average frost layer properties to predict growth in a quasi-steady state, heat and mass balance based segment-by-segment coil simulation. The air redistribution algorithm in the model improved frost thickness predictions by 20%–50% and coil capacity predictions by 42% compared to the same model without air redistribution. The model along with an empirical frost delay predicted the frost thickness for different inlet refrigerant temperatures, air relative humidities and air velocities under non-uniform frosting with a root mean square error of 3.7%, 9.8% and 5.2% respectively.

Modélisation de la formation de givre non uniforme sur un échangeur de chaleur à tubes ailetés

Mots clés : Givre ; Modélisation ; Tube aileté ; Distribution de l'air

1. Introduction

Air source heat pump systems are used for heating and cooling buildings all year around. They are energy efficient, compact and have low installation cost. An air source heat pump exchanges heat directly from the indoor environment to the outdoor ambient air, and during winter operation, the outdoor coil might accumulate frost on its surface. Defrost cycles are periodically executed in between the heating time to melt the ice, drain the water from the outdoor coil, and free its surface from accumulated frost before the heating service could start again. Thus, air source heat pumps suffer from a drop in energy efficiency, that is, a degradation of the actual heating seasonal performance factor. Due to the fact that frost and defrost are inherently transient phenomena, steady state models, which are often employed to predict the performance of heat pump systems, do not adequately describe heat pump behavior when operating in frosting conditions.

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0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2011.06.005

Nomenclature

$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{m}''$	mass flux (kg m^{-2} s^{-1})
$\dot{Q}$	heat transfer rate (W)
A	area (m^2)
C_p	specific heat (J kg^{-1} K^{-1})
d	diameter (m)
D_{AB}	Binary diffusion coefficient (m^2 s^{-1})
D_{eff}	effective diffusion coefficient (m^2 s^{-1})
G	mass flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (m s^{-1})
h_{sg}	latent heat of ablimation (J kg^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
K_e	exit loss coefficient
K_i	inlet loss coefficient
Le	Lewis number
P	pressure (Pa)
R	specific gas constant for water vapor (J kg^{-1} K^{-1})
S_{fi}	fin spacing (m)
T	temperature (°C)
t	time (s)
v	coil face velocity (m s^{-1})
y	coordinate variable
z^*	Graetz number based on distance from inlet

Greek symbols

δ	thickness (m)
ρ	density (kg m^{-3})
σ	area ratio
τ	tortuosity
ϑ	Specific volume (m^3 kg^{-1})

Subscripts

∞	bulk air
a	air
cond	conduction
diff	diffusion
f	frost
fi	fin
fs	frost surface
i	inner
ice	ice
l	latent
ref	refrigerant
s	surface; sensible
sat	saturation
tp	triple point
v	vapor

This paper presents an experimentally validated quasi-steady state heat exchanger frost growth model that is both computationally efficient and sufficiently accurate to be useful in practical engineering design of heat pump outdoor coils. The heat exchanger frost growth model is modular and when integrated with a whole vapor compression system simulation program assists in predicting the time-dependent heat transfer rate, air, frost, and refrigerant properties, and air pressure drop across the outdoor coil due to flow blockage from frost accumulation.

Frost growth is a coupled heat transfer, mass transfer, and fluid dynamic phenomenon. The performance of a heat exchanger working in frosting conditions is difficult to estimate because the rate of frost growth varies from inlet to outlet of the heat exchanger circuits. This results in a continuous redistribution of the airflow over the frontal face of the heat exchanger during the frost accumulation process. In addition, as frost grows on the fin and tube surfaces, the heat transfer area changes along with the free flow area. The direct effect of frost is increased air side resistance to both flow and heat transfer thereby reducing heat transfer performance. Previous models have either neglected the dynamic redistribution of airflow due to non-uniformity of frost thickness at various locations or assumed uniform frost thickness over the entire surface of the heat exchanger. Such assumptions introduce significant error if the fin/tube temperatures vary considerably. In order to effectively integrate the frost growth model in a heat exchanger simulation algorithm, all variables of interest should be solved with the boundary conditions set on the air and refrigerant side. Typically this means that air and refrigerant inlet flow rates and temperatures are the only direct inputs to the heat exchanger model; the surface temperature of the fins is not used as the control variable. A unique feature of our model is the ability to simultaneously update fin and tube heat transfer areas, air free flow area and the air flow map across the face of the coil due to the direct and indirect effects of frost growth on the heat exchanger during each time step of the frosting simulation period.

Previous studies pertaining to frost growth on simple geometries such as flat plates and cylinders focused either on the development of empirical correlations for frost properties or on modeling the heat and mass transfer within the frost layer. Yonko and Sepsy (1967) presented empirical correlations for frost thermal properties as a function of frost density. The relation of Hayashi et al. (1977) which expressed the density of frost as a functions of the frost surface temperature is used in this study. Schneider (1978) claimed that the properties of the frost layer were not affected by the Reynolds number or the difference in vapor pressure water in the air and frost layers. Their conclusion that the water vapor pressure differential did not affect the frost growth did not agree with the observations of other researchers. Jones and Parker (1974) developed an analytical model for the rate of frost growth on a heat exchanger. They provided closed form solutions for the frost surface temperature and the temperature gradient inside the frost layer. The model was able to predict the frost growth for varying environmental parameters, but was not validated for a heat exchanger. Yun et al. (2002) proposed an empirical model for frost parameters and heat and mass transfer rate based on the average frost roughness. They compared the results from the model to experimental data. The trends predicted by the model matched the experiments well. However, for some parameters like frost density and frost surface temperature, the