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Modeling and performance analyses of evaporators in frozen-food supermarket display cabinets at low temperatures

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Abstract

This paper presents modeling and experimental analyses of evaporators in ''in situ'' frozen-food display cabinets at low temperatures in the supermarket industry. Extensive experiments were conducted to measure store and display cabinet relative humidities and temperatures, and pressures, temperatures and mass flow rates of the refrigerant. The mathematical model adopts various empirical correlations of heat transfer coefficients and frost properties in a fin-tube heat exchanger in order to investigate the influence of indoor conditions on the performance of the display cabinets. The model is validated with the experimental data of ''in situ'' cabinets. The model would be a good guide tool to the design engineers to evaluate the performance of supermarket display cabinet heat exchangers under various store conditions.

Keywords: Frozen product; Display cabinet; Evaporator; Modelling; Simulation; Flow; Refrigerant; Temperature; Relative humidity; Pressure; Frost

Modélisation et analyse de la performance des évaporateurs utilisés dans les meubles de vente de supermarché employés pour les surgelés

Mots clés : Produit congelé ; Meuble de vente ; Évaporateur ; Modélisation ; Simulation ; Débit ; Frigorigène ; Température ; Humidité relative ; Pression ; Givrage

1. Introduction

Supermarket refrigeration systems, mainly refrigerated display cases, consume roughly 20% of the total energy use of the store (Getu [1]). The field (defrosting, anti-sweat resistance heaters, display cabinet lights and fans) energy consumption contributes to an additional 14%. The energy consumption due to the air-conditioning system of the building is as much as 17% of the entire energy use of the supermarket. The rest of the supermarket energy use, which is around 49% attributes to water heating and lighting systems of the establishment. Supermarkets often use multi-compressor systems/racks, which are situated in remote machine rooms. The compressors operate in parallel at the same saturated suction temperature, and are piped with

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Nomenclature

A_f	fin surface area [m^2]
$A_{reg,tube}$	bare tube surface area of superheated/two-phase region [m^2]
$A_{reg,i}$	internal tube surface area of superheated/two-phase region [m^2]
$A_{reg,o}$	overall surface area of superheated/two-phase region [m^2]
A_{sp}	air-side total surface area in superheated region [m^2]
A_{tp}	air-side total surface area in two-phase region [m^2]
A_{total}	air-side total surface area [m^2]
C	ratio of minimum to maximum capacity rate of heat exchanging fluids [−]
C_a	capacity rate of air [$W\,K^{-1}$]
C_{max}	maximum heat capacity rate [$W\,K^{-1}$]
C_{min}	minimum heat capacity rate [$W\,K^{-1}$]
C_r	capacity rate of refrigerant [$W\,K^{-1}$]
C_p	specific heat at constant pressure [$kJ\,kg^{-1}\,K^{-1}$]
D	diameter [m]
D_H	frosted hydraulic diameter [m]
f	friction factor [dimensionless]
f_f	friction factor due to fins
f_t	friction factor due to tubes
Fo_{DH}	Fourier number based on frosted surface [−]
GFF	glass-door-frozen-food
G	mass flux [$kg\,s^{-1}\,m^{-2}$]
h	enthalpy [$J\,kg^{-1}$]/heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
h_c	fin-tube contact conductance [$W\,m^{-2}\,K^{-1}$]
$h_{f,a}$	air-side fouling conductance [$W\,m^{-2}\,K^{-1}$]
$h_{f,ref}$	refrigerant-side fouling conductance [$W\,m^{-2}\,K^{-1}$]
h_{sg}	sublimation latent heat [$J\,kg^{-1}$]
I_0	modified zero-order Bessel function of the first kind [−]
K_0	modified zero-order Bessel function of the second kind [−]
I_1	modified first-order Bessel function of the first kind [−]
K_1	modified first-order Bessel function of the second kind [−]
j	colburn factor
k	conductivity [$W\,m^{-1}\,K^{-1}$]
L	length [m]
L_D	frost length in the direction of air flow [m]
L_{reg}	tube length in superheated/two-phase region [m]
Lewis	Lewis number [−]
m	mass [kg]/constant [−]
$\dot{m}$	mass flow rate [$kg\,s^{-1}$]
m_{fst}	frost mass accumulation [$kg\,m^{-2}$]
N_t	total number of tubes
NTU	number of transfer units [dimensionless]
Nu	Nusselt number [dimensionless]
P	pressure [Pa]
Pr_D	Prandtl number based on tube inside diameter [−]
Pr_{DH}	Prandtl number based on frosted surface [−]
$\dot{Q}$	rate of heat transfer [W]
r_f	fin tip radius [m]
r_o	tube outer radius [m]
Re	Reynolds number [dimensionless]
Re_D	Reynolds number based on tube inside diameter
Re_{DH}	Reynolds number based on frosted surface [−]
RH	relative humidity [%]
S_F	fin spacing [$fin\,m^{-1}$]
S_L	longitudinal tube spacing [m]
S_T	transverse tube spacing [m]
t	time [s]/thickness [m]
T	temperature [°C]
Ti	the temperature difference between triple point and coil surface [K]
TFF	through-frozen-food
U	overall heat transfer coefficient [$W/m^{-2}\,k^{-1}$]
x	quality [dimensionless]

Greek letters

Δ	change [−]
ε	heat exchanger effectiveness [−]
φ	efficiency [−]
ω	humidity ratio [kg moisture/kg dry air]
ω_∞	free air stream humidity ratio [kg/kg]
ρ	density [$kg\,m^{-3}$]
ς	constant [dimensionless]
μ	viscosity [$kg\,s^{-1}\,m^{-1}$]

Subscripts

a	air
ave	average
ain	air inlet
aout	air outlet
case	display cabinet
D	tube diameter
e	evaporator
ein	evaporator inlet
eout	evaporator outlet
exvin	expansion valve inlet
f	liquid refrigerant/fin
fst	frost
i	inner
ice	ice
in	inlet
lat	latent