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Transient simulation of a two-door frost-free refrigerator subjected to periodic door opening and evaporator frosting ☆

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HIGHLIGHTS

- Transient behavior of a refrigerator under periodic door opening is simulated.
- The refrigeration loop is modeled following a semi-empirical quasi-steady approach.
- Energy and moisture transfer into and within the compartments are modeled.
- Key heat and mass transfer parameters were derived from in-house experiments.
- Predictions followed closely the experimental trends for power and temperatures.

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ABSTRACT

This paper describes a quasi-steady-state simulation model for predicting the transient behavior of a two-door household refrigerator subjected to periodic door opening and evaporator frosting. A semi-empirical steady-state model was developed for the refrigeration loop, whereas a transient model was devised to predict the energy and mass transfer into and within the refrigerated compartments, and also the frost build-up on the evaporator. The key empirical heat and mass transfer parameters required by the model were derived from a set of experiments performed in-house in a climate-controlled chamber. In general, it was found that the model predictions followed closely the experimental trends for the power consumption (deviations within ±10%) and for the compartment temperatures (deviations within ±2 K) when the doors are opened periodically and frost is allowed to accumulate over the evaporator.

1. Introduction

Modern refrigerator design is aimed at energy savings and also at product robustness in relation to evaporator frosting. In this regard, standardized tests [1,2] as well as tests under real usage conditions, that is, with doors opened regularly [3,4] allowing moisture to enter the refrigerated compartment and frost to accumulate on the evaporator [5] are procedures commonly carried out by most manufacturers.

Nevertheless, since the experimental procedures for frost-free refrigerators and freezers are costly and time consuming [6,7], simulation models have been devised to improve the product development process [8–15]. None of them, however, can predict the refrigerator performance degradation due to periodic door opening and consequent evaporator frosting.

Recently, Mastrullo et al. [16] put forward a transient simulation model that is suitable to predict the time evolution of the compartment air temperature and the power consumption taking into account the door opening, and the resulting evaporator frosting. The model was developed and validated for a single-door upright freezer, which represents a small niche in the realm of household refrigeration if compared with two-door frost-free appliances, the so-called "Combi" refrigerators [11,14].

To the best of the authors' knowledge, none of the models available in the literature [8–16] are able to predict the performance of two-door frost-free refrigerators under periodic door opening, which not only affect the sensible and the latent loads, but also allows frost to build-up on the evaporator, thus decreasing the air flow rate supplied by the fan.

To advance a simulation model for predicting the transient behavior of a two-door frost-free refrigerator subjected to periodic

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Nomenclature

Roman

A	heat transfer area, m^2
C	thermal capacity, J K^{-1}
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
D	inner diameter, m
D_{fr}	effective vapor diffusivity in frosted media, m^2 s^{-1}
G	mass flux, kg/m^2 s
H	height, m
h	specific enthalpy, J kg^{-1}
Ha	Hatta number, dimensionless
h_{lv}	latent heat of evaporation, J kg^{-1}
h_{sv}	latent heat of sublimation, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
k_{fr}	effective thermal conductivity in frosted media, W m^{-1} K^{-1}
L	length, m
Le	Lewis number, dimensionless
m	mass flow rate, kg s^{-1}
N	compressor speed, Hz
NTU	number of transfer units, dimensionless
p	pressure, Pa
Q	heat transfer rate, W
r	air flow ratio, dimensionless
S	compressor swept volume, m^3
T	temperature, K
UA	thermal conductance, W
v	specific volume, m^3 kg^{-1}
V	volumetric air flow rate, m^3 s^{-1}
W	compression power, W
w	humidity ratio, kg$_v$ kg$_a^{-1}$
W	width, m

Greek

α	heat transfer coefficient, W m^{-2} K^{-1}
δ	frost thickness, m
ε_c	emissivity of the condenser wall, dimensionless
ε_x	heat exchanger effectiveness, dimensionless
ϕ	correction factor, kg$_v$
Δp	pressure drop, Pa
Δt	time-step, s
η_g	global compression efficiency, dimensionless
η_v	volumetric compression efficiency, dimensionless
ρ	density, m
σ	Stefan-Boltzmann constant, W m^{-2} K^{-4}
ζ	evaporator dry-out position, m

Subscripts

1	compressor inlet
2	condenser inlet
3	condenser outlet
4	evaporator inlet
5	evaporator outlet
a	ambient, air
c	condenser
cap	capillary tube
d	door
e	evaporator
f	flash-point
ff	fresh-food
fr	frost
fz	freezer
g	saturated vapor at the evaporating pressure
i	inlet
k	compressor
l	saturated liquid
lat	latent thermal load
m	mullion
o	outlet
r	refrigerant
s	isentropic process
sat	saturation
sen	sensible thermal load
ss	steady-state
sub	subcooling
suc	suction line
sup	superheating
v	saturated vapor
x	internal heat exchanger

door opening is therefore the main aim of this study. The proposed model follows a quasi-steady-state approach [14], with a steady-state sub-model for the refrigeration loop and a transient sub-model for the energy and moisture transfer into and within the refrigerated compartments. An additional frost growth and densification sub-model was developed to predict the frost accumulation on the evaporator over time.

2. Simulation model

2.1. Refrigeration loop

A 433-liter top-mount refrigerator, running with R-134a and comprised of a 6.76-cm^3 hermetic reciprocating compressor, natural draft wire-on-tube condenser, tube-fin evaporator and capillary tube-suction line heat exchanger, illustrated in Fig. 1, was adopted in this study.

2.1.1. Compressor

The compressor sub-model uses the volumetric (η_v) and overall (η_g) efficiencies to calculate the compression power and the refrigerant mass flow rate for a given operating condition. The compressor shell thermal conductance (UA$_k$) is also required for the heat transfer calculation [12]. The refrigerant specific enthalpy at the compressor outlet is thus obtained from the following energy balance [13]:

$$h_2 = h_1 + \frac{h_{2,s} - h_1}{\eta_g} - \frac{UA_k(T_2 - T_a)}{m_k} \tag{1}$$

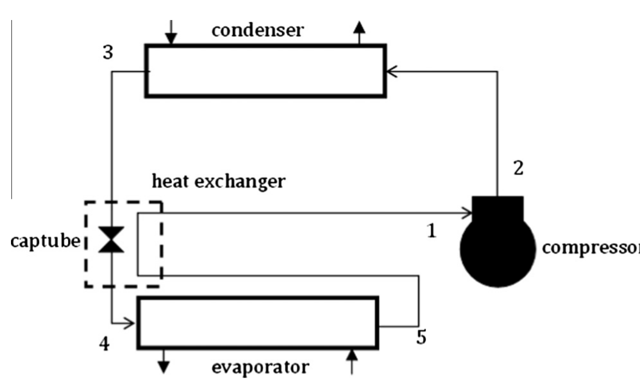

Fig. 1. Schematic representation of the refrigeration loop.