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A first-principles simulation model for the start-up and cycling transients of household refrigerators

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ABSTRACT

A first-principles model for simulating the transient behavior of household refrigerators is presented in this study. The model was employed to simulate a typical frost-free 440-l top-mount refrigerator, in which the compressor is on–off controlled by the freezer temperature, while a thermo-mechanical damper is used to set the fresh-food compartment temperature. Innovative modeling approaches were introduced for each of the refrigerator components: heat exchangers (condenser and evaporator), non-adiabatic capillary tube, reciprocating compressor, and refrigerated compartments. Numerical predictions were compared to experimental data showing a reasonable level of agreement for the whole range of operating conditions, including the start-up and cycling regimes. The system energy consumption was found to be within ±10% agreement with the experimental data, while the air temperatures of the compartments were predicted with a maximum deviation of ±1 °C.

Modèle de simulation fondé sur les principes fondamentaux utilisé pour étudier les phénomènes transitoires lors du démarrage et du cyclage des réfrigérateurs domestiques

Mots clés : Réfrigérateur domestique ; Modélisation ; Simulation ; Régime transitoire ; Comparaison ; Consommation d'énergie

1. Introduction

A household refrigerator is basically composed of a thermally insulated cabinet and a vapor–compression refrigeration loop, as illustrated in Fig. 1. The energy consumption of a typical refrigerator is around 1 kWh/day, which is equivalent to the energy consumption of a 40 W light-bulb continuously running. Although the energy consumption of a unitary refrigerator is reasonably low, commercial and household refrigeration appliances are responsible for 11% of the total energy produced annually in Brazil (PROCEL, 1998), which amounts to 2.86 TWh/year. Such a high energy consumption may be easily accounted for considering that there is a large amount of household refrigerators currently in use, and their

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Nomenclature

A	area, m^2
A_{min}	minimum flow passage, m^2
c	specific heat, $J\,kg^{-1}\,K^{-1}$
C	thermal capacity, $W\,K^{-1}$
c_p	specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
D	diameter, m
G	mass flux, $kg\,s^{-1}\,m^{-2}$
h	specific enthalpy, $J\,kg^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	length, m
M	mass, kg
N	number of control volumes of the cabinet wall
n	number of control volumes of the coil
NTU	number of transfer units
P	pitch, m
p	pressure, Pa
q	heat flux, $W\,m^{-2}$
Q	heat transfer rate, W
T	temperature, K
t	time, s
u	specific internal energy, $J\,kg^{-1}$
UA	overall conductance, $W\,K^{-1}$
v	specific volume, $m^3\,kg^{-1}$
V	volume, m^3
w	mass flow rate, $kg\,s^{-1}$
W	power, W
x	normal coordinate of the cabinet walls, m
z	axial coordinate of the coil, m

Greek symbols

α	thermal diffusivity, m^2/s
γ	void fraction, dimensionless
ε	temperature effectiveness, dimensionless
η	efficiency, dimensionless
θ	crank angle, rad
λ	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
μ	viscosity, Pa s
ρ	specific mass, $kg\,m^{-3}$
σ	solubility, dimensionless
τ	shear stress, Pa
ϕ	partial derivative of the density with respect to the specific internal energy
ψ	partial derivative of the density with respect to the pressure
ω	angular speed, $rad\,s^{-1}$

Subscripts

a	air-side
c	compressor, condenser
ct	capillary tube
d	discharge
e	entrance, external, evaporator
en	entrance
es	outer liner
ex	exit
f	fin
hx	heat exchanger
i	inlet, internal
in	inflow
k	k-th control volume
l	saturated liquid
is	inner liner
o	oil, outlet
r	refrigerant-side, radiation
rc	refrigerated compartment
s	suction
sl	suction line
t	tube
tp	two-phase
v	saturated vapor
w	tube wall, cabinet walls

Superscript

$\dot{y}$	time-derivative ($=dy/dt$)

thermodynamic efficiency is intrinsically low, barely reaching 15% of Carnot's COP. The major part of the energy is wasted by the system components (compressor, condenser, evaporator and capillary tube) due to irreversible losses. Studies carried out to understand such thermodynamic losses shall lead to the development of higher efficiency products.

The performance of a household refrigerator is usually assessed using one of the following approaches: (i) simplified calculations based on component characteristic curves; (ii) numerical analysis via commercial CFD packages; and (iii) standardized experiments. Although the first two techniques play important roles in component design, they do not provide enough information about component matching and system behavior, which are only obtained by testing the refrigerator in a controlled environment chamber. However, such tests are time consuming and expensive. A faster and less costly alternative is the use of first-principles models to simulate the thermal- and fluid-dynamic behavior of refrigeration systems. Steady-state and transient approaches can both be used. The former is mainly applied for component matching, whilst the second is essential to define the controlling strategies and to optimize the system performance.

Former transient models for refrigeration systems date back to the early 80s and were mostly focused on heat pump and air conditioning equipment (Dhar, 1978; Chi and Didion, 1982; Yasuda et al., 1983; MacArthur, 1984; Murphy and Goldschmidt, 1985; Sami et al., 1987; MacArthur and Grald, 1989; Wang, 1991; He et al., 1994; Vargas and Parise, 1995; Rossi and Braun, 1999; Browne and Bansal, 2002; Kim et al., 2004; Lei and Zaheeruddin, 2005) (see Table 1). The development of dynamic models for household refrigerators was stimulated by the CFC-12 phase-out in the late 80s (Melo et al., 1988; Jansen et al., 1988, 1992; Lunardi, 1991; Chen and Lin, 1991; Yuan et al., 1991; Vidmar and Gaspersic, 1991). These models were developed based on the experience acquired for large systems (Dhar, 1978; Chi and Didion, 1982; Yasuda et al., 1983; MacArthur, 1984; Murphy and Goldschmidt, 1985; Sami et al., 1987; MacArthur and Grald, 1989), although refrigerator modeling strategies may differ substantially from those adopted for air conditioning/heat pump (AC/HP)