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A hybrid transient model for simulation of air-cooled refrigeration systems: Description and experimental validation

Jing Wu [a,*], *Emilie Gagnière* [a], *Françoise Couenne* [a], *Boussad Hamroun* [a], *Thierry Latour* [b], *Christian Jallut* [a]

[a] *Université de Lyon, Université Lyon 1, Laboratoire d'Automatique et de Génie des Procédés, UMR 5007, CNRS/UCBL, 43 Bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France*
[b] *CIAT, Avenue Jean Falconnier, 01350 Culoz, France*

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ABSTRACT

In this paper are described a hybrid dynamic model for transient simulation of refrigeration systems as well as dynamic experiments that have been performed on an air/water heap pump. The machine under consideration is made of an evaporator, a condenser, an expansion valve, a variable speed scroll compressor and a receiver. The refrigerant and second fluid flows in heat exchangers are approximated by a cascade of Continuous Stirred Tank Reactors (CSTRs). This model is quite flexible since a unique structure is used for the evaporator and the condenser models according to different boundary conditions. This is due to the use of a switching procedure between different configurations based on a phase stability test that is designed to ensure the continuity of the system simulation. An analytical thermodynamic model of the refrigerant based on an equation of state is used. Good agreement between simulation results and experimental data is achieved.

Modèle hybride transitoire pour la simulation de systèmes frigorifiques refroidis à l'air: description et validation expérimentale

Mots clés : Système frigorifique ; Echangeur de chaleur ; Modèle dynamique hybride ; Thermodynamique

* *Corresponding author*. Tel.: +33 472 431 856.
E-mail addresses: jwu@lagep.univ-lyon1.fr, wujingjiajia@gmail.com (J. Wu).

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Nomenclature

A	heat exchange surface area (m^2)
Bo	boiling number, $Bo = \phi/\Delta h_{lv}$
CSTR	continuous stirred tank reactor
C_d	mass flow coefficient
c_p	specific heat capacity (J K^{-1} kg^{-1})
D_c	fin collar outside diameter ($D_o + 2\delta$) (m)
D_o	tube outside diameter (m)
D_h	hydraulic diameter (m)
F_p	fin pitch (m)
G	mass flux (kg m^{-2} s^{-1})
h	specific enthalpy (J kg^{-1})
L	channel length (m)
m	mass (kg)
q	mass flow rate (kg s^{-1})
N	number of tube row, number of CSTRs
P	pressure (Pa)
Pr	Prandtl number
P_t	transverse tube pitch (m)
Re	Reynolds number
s	fin spacing (m)
S	transversal section (m^2)
T	temperature (K)
t	time (s)
u	specific internal energy (J kg^{-1})
v	configuration index (0 or 1)
V	volume of CSTR (m^3)
V_{air}	air velocity (m s^{-1})
x	vapour mass fraction
Greek symbols	
ρ	refrigerant density (kg m^{-3})
ϕ	heat flux (W m^{-2})
α	heat transfer coefficient (W m^{-2} K^{-1})
δ	fin thickness (m)
Δh_{lv}	vaporization enthalpy (J kg^{-1})
ω	rotation speed (tr min^{-1})
γ	EEV position
Subscripts	
a, b, c, d	characteristic points
a	secondary fluid
comp	compressor
cond	condenser
d	two-phase system
eva	evaporator
EEV	electronic expansion valve
f	fan
iw	inside of tube
l	liquid
m	one-phase system
ow	outside of tube
rec	receiver
v	vapour
w	tube wall

1. Introduction

In the field of buildings refrigeration, the coupling of a Vapour Compression System (VCS) with a cold thermal storage can lead to significant cost savings (Rismanchi et al., 2012). Daytime electricity consumption can be shifted to night time when electricity is cheaper. Cold energy is stored when the cooling demand of the building is low, whereas the storage works in parallel with the VCS when the cooling demand is high. Consequently, the VCS can be subject to a wide range of operating conditions and transient periods. In order to manage automatically and safely such a situation, it is recommended to use first principles dynamic models for the design of automatic controllers (Rasmussen and Alleyne, 2004; Schurt et al., 2009; Wallace et al., 2012; Catano et al., 2013a,b) and to optimize the dynamic operating conditions of such coupled systems (Wang et al., 2007b).

There are other circumstances where the VCS is operated under transient conditions so that dynamic modelling can be necessary. Cycling conditions (Ndiaye and Bernier, 2012) as well as shut-down or start-up severe transients (Li and Alleyne, 2010; Uhlmann and Bertsch, 2012; Schalbart and Haberschill, 2013) are examples of such situations.

The objective of this study is to propose a first principles dynamic model of a VCS provided by the CIAT company. In future works, this VCS will be coupled to a PCM (Phase Change Material) cold thermal storage and then be used for experimental control studies of building refrigeration systems. This model will be used to design a multivariable controller allowing regulating the VCS cooling capacity and the evaporator superheating by using the compressor rotation speed and the valve position as control variables (Romero et al., 2011). Such a control is all the more necessary that the VCS is coupled to a thermal storage in order to satisfy a varying thermal demand.

A detailed review of recent literature on VCS dynamic modelling is presented by Rasmussen (2012). The primary dynamics of these systems are driven by fluctuating states of refrigerant in evaporators and condensers as well as by the thermal inertia of the exchangers' walls. VCS evaporators and condensers are generally represented by an equivalent tubular heat-exchanger, the equivalent parameters of which allowing to represent the real exchanger properties (Rasmussen and Alleyne, 2004; Eldredge et al., 2008). Two approaches are then generally used to derive evaporators and condensers dynamic models (Bendapudi et al., 2008). The first one consists in deriving 1D models from refrigerant mass, energy balances and sometimes momentum balances (Zhang et al., 2009). The resulting PDEs are discretized in order to be numerically solved (Bendapudi et al., 2008; Hermes and Melo, 2008; Ndiaye and Bernier, 2012). A classical approach used in chemical engineering to perform such a discretization consists in approximating a flow by a cascade of Continuous Stirred Tank Reactors (CSTRs). Such a method has already been applied to VCS heat exchangers modelling (Schalbart and Haberschill, 2013). The second approach, the moving-boundary method, has been proposed to get a low order lumped parameter model easier to solve (Willatzen et al., 1998a; Wang et al., 2007a; McKinley and