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A dynamic model of a vapor compression cycle with shut-down and start-up operations

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ABSTRACT

This paper presents an advanced switched modeling approach for vapor compression cycle (VCC) systems used in Air Conditioning and Refrigeration. Building upon recent work (McKinley and Alleyne, 2008), a complete dynamic VCC model is presented that is able to describe the severe transient behaviors in heat exchangers (condenser/evaporator), while maintaining the moving-boundary framework, under compressor shut-down and start-up operations. The heat exchanger models retain a constant structure, but accommodate different model representations. Novel switching schemes between different representations and *pseudo-state* variables are introduced to accommodate the transitions of dynamic states in heat exchangers while keeping track of the vapor and liquid refrigerant zones during the *stop–start* transients. Two model validation studies on an experimental system show that the complete dynamic model developed in Matlab/Simulink can well predict the system dynamics in shut-down and start-up transients.

Modèle dynamique d'un cycle à compression de vapeur en fonctionnement marche/arrêt

Mots clés : Système frigorifique ; Système à compression ; Control ; Modélisation ; Simulation ; Pression ; Condenseur ; Évaporateur ; Échangeur de chaleur ; Régime transitoire ; Comparaison ; Expérimentation

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Nomenclature

Symbols

a	weight value [dimensionless]
A	area [m^2]
c	specific heat [$kJ\,kg^{-1}\,K^{-1}$]
D	refrigerant-side hydraulic diameter [m]
f	forcing function
h	refrigerant enthalpy [$kJ\,kg^{-1}$]
k	refrigerant thermal conductivity [$kW\,m^{-1}\,K^{-1}$]
K	gain in the *pseudo-state* equations; currently set to five [s^{-1}]
M	refrigerant mass [kg]
$\dot{m}$	mass flow rate [$kg\,s^{-1}$]
$\ddot{m}$	time derivative of mass flow rate [$kg\,s^{-2}$]
(mc)	thermal capacitance in the heat exchanger structure (wall) [$kJ\,K^{-1}$]
P	refrigerant pressure [kPa]
$\dot{Q}$	heat transfer rate [kW]
T	temperature [K]
t	time [s]
U	overall heat transfer coefficient [$kW\,m^{-2}\,K^{-1}$]
u	input
V	volume [m^3]
x	state vector
$\dot{x}$	time derivative of the state vector
Z	coefficient matrix
α	refrigerant heat transfer coefficient [$kW\,m^{-2}\,K^{-1}$]
$\bar{\gamma}$	mean void fraction [dimensionless]
ρ	refrigerant density [$kg\,m^{-3}$]
τ	time constant [s]
ζ	fraction of heat exchanger length covered by zone, also called normalized zone length [dimensionless]
$\Delta\zeta$	normalized length of the liquid–vapor mixture [dimensionless]

Subscripts

A	air
alt	alternative
c	condenser
c1, c2, c3	superheated, two-phase, sub-cooled zone in the condenser
c23	boundary between the two-phase and sub-cooled zone in the condenser
comp	compressor
ctot	complete condensation from saturated vapor to saturated liquid
e	evaporator
e1, e2	two-phase, superheated zone in the evaporator
e12	boundary between the two-phase and superheated zone in the evaporator
etot	complete evaporation from saturated liquid to saturated vapor
f	saturated liquid
g	saturated vapor
h	enthalpy *pseudo-state* equation
i	zone number; for the condenser, $i \in \{1,2,3\}$ (1 = superheated, 2 = two-phase, 3 = sub-cooled); for the evaporator, $i \in \{1,2\}$ (1 = two-phase, 2 = superheated)
iA	heat exchanger structure-to-air for zone i
iR	heat exchanger structure-to-refrigerant for zone i
in	inlet
iwt	transported wall temperature across the rightmost boundary of zone i
min	minimum value before switching occurs
o	outlet
pool	pool boiling effect
PA	air at constant pressure
R	refrigerant
SR	refrigerant-to-structure surface
w	heat exchanger structure (wall)

1. Introduction

The primary goal of any vapor compression cycle (VCC) system, such as a refrigeration and/or air-conditioning system, is to move energy from one physical location to another. Most VCC systems operate in a mode in which they stop and start the refrigerant flow to modulate the amount of cooling/heating capacity provided to some enclosed environmental spaces. Here, this is termed the ‘compressor cycling with shut-down and start-up operations’ or, for short the ‘*stop–start*’ problem for dynamic modeling and control with application to VCC systems. This paper focuses on dynamic modeling of the *stop–start* operating characteristics for control purposes, such as hardware-in-the-loop/software-in-the-loop simulation, and embedded system applications.

VCC system dynamic modeling is a challenging task in which the balance between complexity and accuracy must be considered. Two heat exchanger modeling approaches are commonly used in the VCC system modeling: finite-volume distributed-parameter and moving-boundary lumped-parameter methods (Bendapudi and Braun, 2002). A validated system model of a centrifugal chiller system using the finite-volume formulation was reported to predict transient performance including start-up (Bendapudi et al., 2005). More recently, Bendapudi et al. (2008) presented a comparative study of centrifugal chiller system behaviors for start-up and load-change transients with flooded shell-and-tube heat exchanger models. In Bendapudi et al. (2008) both finite-volume and moving-boundary methods were quantitatively compared and the tradeoffs between the two formulations were carefully identified. While the moving-boundary methods were found to be computationally faster, they were not as computationally robust or accurate as the finite volume approaches. Considering the target control applications of the current VCC *stop–start* system model, we choose to use the