INTERNATIONAL JOURNAL OF REFRIGERATION 65 (2016) 154–171

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

An advanced switching moving boundary heat exchanger model with pressure drop

Hongtao Qiao [a,*], *Christopher R. Laughman* [a], *Vikrant Aute* [b],
Reinhard Radermacher [b]

[a] *Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA 02139, USA*
[b] *Center for Environmental Energy Engineering, University of Maryland, College Park, 4164 Glenn L. Martin Hall Bldg., MD 20742, USA*

ARTICLE INFO

Article history:
Received 25 October 2015
Received in revised form 15 January 2016
Accepted 30 January 2016
Available online 25 March 2016

Keywords:
Transient
Modeling
Moving boundary
Heat exchanger
Flash tank vapor injection
Finite volume

ABSTRACT

This paper presents an advanced heat exchanger model based on the moving boundary approach. Significant improvements have been made to overcome the deficiencies of the extant models. Air flow propagation is taken into account to provide a more accurate prediction of air side heat transfer for multi-row coils. Refrigerant pressure drop is calculated in a reasonably simple manner by solving the global momentum balance equation. The choice of state variables shows the benefits of mass conservation and good computational efficiency. Generalized switching schemes capable of supporting dynamic transition between all possible flow configurations are developed. Model integrity and stability are verified through simulations. The model is applied to explore the start-up transients of an R410a flash tank vapor injection system. Favorable agreement between simulation results and experimental data demonstrates that the proposed model can adequately capture the main transient heat transfer and fluid flow phenomena of the system.

Un nouveau modèle d'échangeur de chaleur à frontière mobile avec chute de pression

Mots clés : Transitoire ; Modélisation ; Frontière mobile ; Échangeur de chaleur ; Injection de vapeur avec un réservoir instantané ; Volume fini

1. Introduction

The thermal inertia of the components, and more importantly the dynamics of the refrigerant flow, dictate the transient behavior of vapor compression systems. Under normal operating conditions, most refrigerant resides inside heat exchangers, which are the major components that experience the exchange of mass, energy and momentum with other components, including the compressor and the expansion

---

[*] Corresponding author. Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA 02139, USA. Tel: +1 617 621 7586; Fax: + 1 617 621 7550.
E-mail address: qiao@merl.com (H. Qiao).

http://dx.doi.org/10.1016/j.ijrefrig.2016.01.026

Nomenclature

Symbols

A	area [m^{2}]
C	heat capacity per unit length [J m^{-1} K^{-1}]
c_p	specific heat [J kg^{-1} K^{-1}]
d	diameter [m]
f	friction loss factor [-]
FPI	number of fins per inch [-]
G	mass flux [kg m^{-2}]
h	enthalpy [J kg^{-1}]
$\bar{h}$	enthalpy mean [J kg^{-1}]
i	tube index [-]
K	gain in the pseudo-state equations [s^{-1}]
L	length [m]
Le	Lewis number [-]
$\dot{m}$	mass flow rate [kg s^{-1}]
M	mass [kg]
N	number [-]
p	pressure [N m^{-2}]
$\bar{p}$	pressure mean [N m^{-2}]
P_r	row pitch [m]
P_t	tube pitch [m]
q	heat transfer rate [W]
q'	heat transfer rate per unit length [W m^{-1}]
t	time [s]
T	temperature [K]
x	vapor quality [-]
Δ	difference [-]
Δz	actual zone length [m]

Greek letters

α	heat transfer coefficient [W m^{-2} K^{-1}]
β	percentage of a tube contributing to a specific zone [-]
δ	thickness [m]
ε	minimum threshold [-]
γ	void fraction [-]
$\bar{\gamma}$	void fraction mean [-]
φ	two-phase pressure drop multiplier [-]
ρ	density [kg m^{-3}]
$\bar{\rho}$	density mean [kg m^{-3}]
ω	humidity ratio [kg H$_2$O / kg dry air]
ζ	normalized zone length [-]

Superscript

i	tube index

Subscripts

a	air
act	active
cir	circuit
dry	dry condition
eff	effective
f	saturated liquid
fg	liquid to gas
fin	fin
g	saturated vapor
h	enthalpy
i	internal
in	inlet
j	zone index (1, 2 or 3)
L	length
lo	liquid only
min	minimum
nz	new zone
o	external
out	outlet
pseudo	pseudo
pz	parent zone
r	refrigerant or tube row
row	tube row
sat	saturation
sc	subcooled
sh	superheated
suc	suction
t	tube
tot	total
tp	two-phase
tpz	total parent zone
w	wall
water	condensate water
wet	wet condition
ρ	density
γ	void fraction
1, 2, 3	zone index
12, 23	zone boundary

device as well as other auxiliary components, and with the secondary fluids (Björk and Palm, 2006a, 2006b). Consequently, it is essential to obtain accurate mathematical and physical representations for the main transient heat transfer and fluid flow phenomena in heat exchangers (Jakobsen et al., 1999; Kærn et al., 2011).

In general, there are two commonly used heat exchanger modeling paradigms, i.e., phase-independent finite volume method and phase-dependent moving boundary method (Bendapudi et al., 2008). Although they render more accurate predictions in heat transfer and fluid flow phenomena, distributed-parameter finite volume models are not well suited for controls design due to computational complexity, whereas low-order moving boundary models are more favorable in this regard. The moving boundary method is characterized by dividing the heat exchanger into different control volumes, each of which exactly encompasses a particular fluid phase (vapor, two-phase or liquid) and is separated by a moving boundary where refrigerant phase transition occurs. The objective of moving boundary models is to capture the thermodynamic behavior inside these control volumes and the time-varying positions of phase boundaries.

The moving boundary method is based on the concept of the system mean void fraction model (Wedekind and Stoecker, 1968), which allows the two-phase flows to be analyzed in a simplified lumped-parameter manner. By casting the resulting equations into a linearized state-space form, moving