INTERNATIONAL JOURNAL OF REFRIGERATION 53 (2015) 101–114

Available online at www.sciencedirect.com

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A comparison between finite volume and switched moving boundary approaches for dynamic vapor compression system modeling

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ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form
16 January 2015
Accepted 19 January 2015
Available online 28 January 2015

Keywords:
Vapor compression system
Heat exchanger model
Moving boundary
Finite volume

ABSTRACT

Most work in dynamic heat exchanger modeling for control design can be classified as either a finite volume or a moving boundary formulation. These approaches represent fundamentally different discretization approaches and are often characterized as contrasting accuracy with simulation speed. This work challenges that characterization by validating finite volume and moving boundary heat exchanger models with experimental data from a vapor compression system in order to demonstrate that these approaches are capable of achieving similar levels of accuracy. However, there are differences. The moving boundary model is found to have faster simulation speed, while the finite volume model is more flexible for adaptation to heat exchangers of different physical configuration. The formulation of each modeling approach used in this work is described in detail and techniques to increase simulation speed and avoid numerical issues in implementation are discussed.

Une comparaison entre le volume fini et les approches par interversion des frontières mobiles pour la modélisation des systèmes dynamiques à compression de vapeur

Mots clés : Systéme de compression de vapeur ; Modéle d'échangeur de chaleur ; Frontiére mobile ; Volume fini

1. Introduction

Advanced control methods for vapor compression systems (VCSs) have been shown to result in more efficient operation, reducing the energy consumption of these systems while improving performance (He et al., 1998). In turn, the use of appropriate system models contributes significantly to effective control design. Three such contributions include: 1) models can be used to study system behavior and dominant

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http://dx.doi.org/10.1016/j.ijrefrig.2015.01.009

List of symbols and subscripts

Symbols

A	Area
c_p	Constant Pressure Specific Heat Capacity
h	Specific Enthalpy
k	Sample Time Index
L	Length
m	Mass
$\dot{m}$	Mass Flow Rate
n	Total Number of Control Volumes
P	Pressure
p	Perimeter
Q	Heat Transfer Rate
T	Temperature
V	Volume
α	Heat Transfer Coefficient
$\overline{\gamma}$	Mean Void Fraction
ζ	Normalized Control Volume Length
ρ	Density

Subscripts

a	Air
cs	Cross Sectional
cv	Control Volume
f	Saturated Liquid
g	Saturated Gas
i	Control Volume Index
r	Refrigerant
s	Surface
SC	Subcool
SH	Superheat
TP	Two-Phase
w	Tube Wall
z	Length along Refrigerant Flow Direction

dynamics, 2) implementing a controller on a model in simulation allows the controller's performance to be evaluated in a cost and time efficient manner, and 3) in the case of model-based controls, the system model is incorporated into the controller. Models used in control design are generally evaluated by the accuracy of the model in predicting the physical systems' behavior and the computational resources required to implement the model. A tradeoff often exists between these two criteria; therefore a challenge of control-oriented modeling is to develop models that are sufficiently accurate yet computationally simple enough to be implemented given the time and processing power available.

Of the components typically incorporated in a VCS, the heat exchangers are the most complex to model due to the highly nonlinear nature of the thermal dynamics that take place and the timescale separation between thermal and mechanical dynamics (Rasmussen, 2012). In recent literature, two approaches have been dominant for control-oriented physics-based modeling of heat exchangers. These are often referred to as the finite volume (FV) and the moving boundary (MB) lumped parameter methods. Both methods involve spatially discretizing the heat exchanger into control volumes and calculating a set of average, or "lumped," parameters for each volume. The discussion that follows on the historical development of these methods draws significantly from the literature review in Rasmussen (2012).

The FV approach, dating to MacArthur (1984) and Gruhle and Isermann (1985), involves discretizing the heat exchanger spatially into an arbitrary number of equally sized control volumes, as shown in Fig. 1. The refrigerant flow in each volume may switch between superheated, two-phase, and subcooled phases as model inputs and states change. In MacArthur et al. (1983) it is demonstrated that in energy transport modeling, increasing the spatial discretization from low values improves accuracy, but as the approximation converges to the true solution, further increases in discretization bring negligible improvements in accuracy. Similarly, increasing the number control volumes of a FV heat exchanger model increases the accuracy up to some limit (Bendapudi et al., 2005). This reveals the inherent tradeoff between accuracy and computational cost, as increasing the discretization also increases the number of states to compute.

The MB formulation results from the desire to maintain a reasonable level of accuracy without resorting to the high level of discretization often required of FV models, and therefore achieve a better balance between accuracy and computational cost. In this approach the heat exchanger is divided into control volumes corresponding to each refrigerant phase, as shown in Fig. 2. Unlike with the FV approach, the size of volumes can vary with time as phase flow lengths change. The calculation of lumped parameters for the two-phase region of the heat exchanger is often facilitated by incorporation of a mean void fraction assumption as proposed in Wedekind et al. (1978), which describes the ratio of the vapor volume to the total volume along the length of the two-

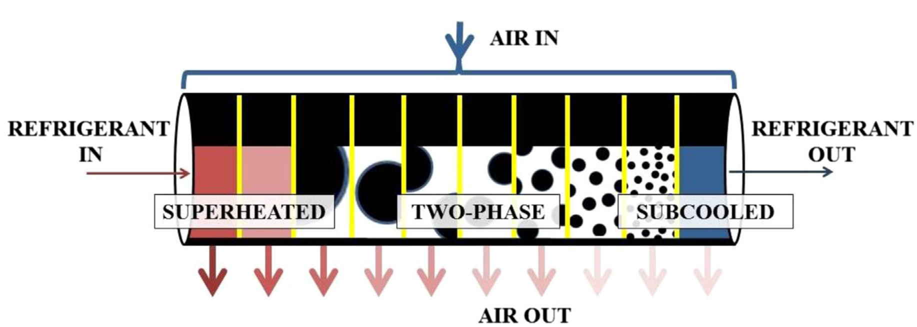

Fig. 1 – FV model with 10 control volumes for a cross-flow refrigerant-to-air condenser.