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An intrinsically mass conservative switched evaporator model adopting the moving-boundary method

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ABSTRACT

This paper presents a generalized intrinsically mass conservative evaporator model based on the moving-boundary approach. The heat exchanger model is based on a numerical scheme which can switch between the two-zone (two-phase and superheated) and one-zone (two-phase) representations. The switching algorithms adopt *pseudo-state* equations in order to track the un-active variables and ensure reasonable initial conditions when rezoning, keeping the robustness whenever superheated region appears or disappears. State variables are chosen to have an intrinsically mass conservative model. This choice is well suited when the evaporator operates at low mean void fraction conditions. Numerical results show that the simulation is consistent with integral forms of energy and continuity equations. The numerical stability to changing flow regimes is demonstrated through simulation test cases. A validation case is presented showing that the model transient behaviour can well predict the performance of an experimentally validated finned coil finite-volume evaporator model.

Modèle d'évaporateur à conservation de masse faisant appel à une méthode de limites mobiles

Mots clés : Comparaison ; Contrôle ; Évaporateur ; Modélisation ; Froid ; Régime transitoire

1. Introduction

The energy consumption of refrigeration and air conditioning installations contributes to CO_2 emissions and reduces global energy resources. Efforts implemented by refrigeration stakeholders focus on the reduction of energy consumption thanks to increasing energy efficiency of vapour compression cycles. This can be accomplished by designing advanced refrigeration equipment control systems (Beghi and Cecchinato, 2011). It is generally agreed that, in spite of the advancements made in computer technology and its impact on the development of new control methodologies for Heating, Ventilation, and Air Conditioning and refrigeration systems (HVAC&R), the process of operating HVAC&R

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Nomenclature

A	flow area [m^2]
L	length [m]
d	tube diameter [m]
F	surface efficiency
h	enthalpy [J kg^{-1}]
$\dot{m}$	mass-flow rate [kg s^{-1}]
NTU	number of transport unit
p	pressure [Pa]
x	quality [–]
s	thickness [m]
t	time [s]
T	temperature [°C]
u	internal energy [J kg^{-1}]
w	specific humidity [kg kg^{-1}]
X	states vector
Y	solution vector
z	spatial coordinate [m]
c_p	specific heat [J kg^{-1} K^{-1}]
U	global transmittance [W m^{-2} K^{-1}]

Greek letters

α	heat transfer coefficient [W m^{-2} K^{-1}]
γ	void fraction [–]
$\bar{\gamma}$	void fraction mean [–]
η	fin efficiency [–]
ρ	density [kg m^{-3}]
Ω	fin efficiency [–]
φ	air relative humidity [–]

Subscripts

s	secondary fluid (air)
e	evaporator
g	vapour
i	inlet
int	interface
l	liquid
o	outlet
sat	saturation
w	wall
1	two-phase zone
2	superheated zone

equipment in dwelling and in commercial and industrial buildings is still a low efficient and high-energy consumption process (Yaqub and Zubair, 2001). Classical control techniques such as ON/OFF controllers (thermostats) and proportional–integral–derivative (PID) controllers are still very popular, due to their low cost and ease of tuning and operation (Astrom and Hagglund, 1995; ASHRAE, 2003). However, more advanced control systems that are able to efficiently track the actual cooling/heating power requests from the plant, such as predictive or adaptive controllers, are best suited to meet the challenge of reducing the overall energy consumption for refrigeration and building climatisation.

Dynamic modelling is an efficient and useful approach to the control-oriented design of HVAC&R equipment and of vapour compressor machines in particular. This approach can be valuable for hardware-in-the-loop/software-in-the-loop simulation and embedded control and diagnostic applications (Rasmussen et al., 2005).

Bendapudi and Braun (2002) pointed out that two different modelling schemes are commonly adopted for vapour compression cycles dynamic simulation: finite-volume/difference distributed parameter and moving-boundary lumped parameter schemes. Bendapudi et al. (2008) presented a study of a centrifugal chiller system. The authors compared a finite-volume and moving boundary flooded shell-and-tube heat exchanger model in the analysis of the unit start-up and load-change transients. Bendapudi (2004) and Bendapudi et al. (2008) found that the moving-boundary system model executed about three times faster than the finite-volume while maintaining nearly identical accuracy in the predictions of system steady-state and transient-performance. This confirmed what already stated by Grald and MacArthur (1992). Moving-boundary techniques have already been shown to provide reasonably accurate transient predictions against experimental data (Grald and MacArthur, 1992; Leducq et al., 2003; Bendapudi, 2004; Rasmussen, 2006; Li and Alleyne, 2010). The moving-boundary method fastness makes it the most suitable simulation technique for control-oriented applications and studies (He et al., 1998; Jensen and Tummescheit, 2002; Lei and Zaheeruddin, 2005; Cheng and Asada, 2006; Rasmussen, 2006, Qi and Deng, 2008; Schurt et al., 2009).

Different authors developed heat exchanger or vapour compression cycle simulation models adopting the moving-boundary method (Dhar and Soedel, 1979; Grald and MacArthur, 1992; He et al., 1995; Willatzen et al., 1998; Jensen and Tummescheit, 2002; Zhang and Zhang, 2006; Rasmussen, 2006; McKinley and Alleyne, 2008; Kumar et al., 2008; Bendapudi et al., 2008; Li and Alleyne, 2010). This approach consists in dividing the heat exchanger into control volumes (or zones), each volume corresponds to a refrigerant phase and model parameters are lumped for each of these volumes. The length of each zone, thus the boundary position between refrigerant phase, is dynamically determined and its correctness is mandatory to actually predict refrigerant mass, pressure and heat transfer. One of the main drawbacks of this technique is that, being constant the number of zones, if the length of a zone tends to zero, the corresponding set of mass and energy conservation equations becomes singular. This is the case of a unit start-up and shut-down operations both for the evaporator and the condenser. In order to avoid simulation fails, some authors (Dhar and Soedel, 1979; Willatzen et al., 1998; Zhang and Zhang, 2006; McKinley and Alleyne, 2008; Bendapudi et al., 2008; Li and Alleyne, 2010) adopted multiple modelling frameworks in the same simulation, introducing switching criteria between the models. Dhar and Soedel (1979) adopted three model representations or modes for condenser and one for the evaporator to correctly simulate evaporator start-ups. Unfortunately only general remarks on the proposed model switching technique are given. Willatzen et al. (1998) developed an evaporator model introducing auxiliary equations (Pettit et al., 1998) to ensure that state derivatives remained relatively smooth during large transients resulting in destruction or creation of dynamic states.