Object-Oriented Modeling of Switching Moving Boundary Models for Two-phase Flow Evaporators ⋆

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Abstract: The present paper describes the design of switching moving boundary models for two-phase flow evaporators and the development of an object-oriented library written in the Modelica language. The main idea is to design basic models for each flow state: subcooled liquid, two-phase flow and superheated steam, applying the conservation laws. The design must be done in order that the basic models can be interconnected to create complete, flooded or dry-expansion evaporators depending on the particular case. The basic models should consider the balances of mass, energy and momentum, meanwhile the evaporator models should include mechanisms to switch between them, for example from a complete evaporator to a flooded evaporator in case that the superheated region becomes extinct. Several models currently exist although none of them include all the desirable features.

Keywords: Moving boundary model, two-phase flow, evaporator, switching, object-oriented modeling.

1. INTRODUCTION

The most common approaches used in fluid dynamic and heat exchange modeling are the finite-volume distributed-parameter method (Patankar, 1980) and the moving-boundary lumped-parameter method (Dhar and Soedel, 1979). Dynamic modeling is always a challenging task in which the trade-off between accuracy and speed must be evaluated. In Bendapudi et al. (2008), both methods for a centrifugal chiller system were studied and analyzed. The conclusion is that the moving boundary method is much faster although not as accurate and robust as the finite volume method. Despite of the loss of accuracy of the moving boundary method, in the context of real-time simulation, dynamic system optimization and model-based control, where fast computation is required, the moving boundary method seems to be the appropriate one.

The moving boundary method divides the evaporator in different regions, also called Control Volumes (CVs), depending on the fluid phase. In each CV, the lumped thermodynamic properties are average in some way, the barrier is not fixed and it may move between the CVs. Table 2 summarizes some of the most relevant moving boundary models (MBMs), showing if models for evaporators and condensers were developed, what modes apply (see Table 1), if the models support switching and if they consider the mean void fraction ($\bar{\gamma}$) to be time variant. An outstanding review is presented in Mancini (2011).

Table 1. Modes in moving boundary models

Abbvs.	Description	Flow states in evaporator	Flow states in condenser
SC	Subcooled liquid	SC	SC
TP	Two-phase flow	TP	TP
SH	Superheated steam	SH	SH
G	General	SC - TP - SH	SH - TP - SC
D	Dry	TP - SH	SH - TP
F	Flooded	SC - TP	TP - SC

When the inlet and outlet qualities are constant, the mean void fraction can be considered time invariant (Wedekind et al., 1978) (Beck and Wedekind, 1981), otherwise its calculation describes more accurately the total amount of steam at the output of the evaporator (Åström and Bell, 2000). Some authors neglect the time derivative of the mean void fraction because its change tends to be small during transients, and also because its time

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Table 2. Comparison of moving boundary models in two-phase flows.

Moving Boundary Model	Evaporator	Condenser	Switching	$d\bar{\gamma}/dt$
Dhar and Soedel (1979)	TP[1]	D,F,SH	Yes[2]	No
Grald and MacArthur (1992)	D	-	-	No
He et al. (1998)	D,TP	G	Yes[3]	No
Willatzen et al. (1998) Pettit and Willatzen (1998)	G,D,F,TP	-	Yes[4]	No
Jensen and Tummescheit (2002)	G,D,F	-	No	No
Leducq et al. (2003)	D	G	-	No
Yebra et al. (2005)[5]	G	-	-	-
Rasmussen (2006)	D	G	-	No
Zhang and Zhang (2006)	D,TP	-	Yes	Yes[6]
Kumar et al. (2008)	D	F	-	No
McKinley and Alleyne (2008)	-	G,D	Yes[7]	Yes
Bendapudi et al. (2008)	D,TP	G,D,SH	Yes[8]	Yes
Eldredge et al. (2008)	TP	D	-[9]	Yes
Li and Alleyne (2010)[10]	D,TP	G,D,F,TP,SH	Yes	Yes
Mancini (2011)[11]	D,TP	-	Yes	Yes

dependence is related to dynamic modes that are faster than the dominant system dynamics (Rasmussen, 2006). It is widely extended to assume a uniform pressure along the evaporator and hence neglecting the conservation of momentum. However, this assumption does not always hold, for instance if solar evaporators are considered, since some solar facilities have up to 1400-m-long evaporators (Yebra et al., 2005).

[1] It consists of a liquid zone and a vapor zone, which are not in thermal equilibrium, the liquid and vapor phases then exchange heat. [2] Discontinuities and numerical instability. [3] The switching criteria is presented in Cheng and Asada (2006). [4] Auxiliary equations to ensure relatively smooth state variables using pseudo-state tracking on inactive state variables. [5] Model based on Jensen and Tummescheit (2002), including the momentum conservation equation discretized by the finite volume method and the staggered-grid method (Harlow and Welch, 1965). [6] Introduced the time-dependent mean void fraction showing an improved robustness and smoother state parameters curves during large transients. [7] Introduced a novel switching criteria based on void fraction. Pseudo-state variables were used (Pettit and Willatzen, 1998), it was demonstrated the consistency of results with the mass and energy conservation integral equations through several cases. [8] The switching approach is based on the initialization of newly created dynamic states, which claims that smooth transitions are ensured without introducing large energy imbalances at the transition. Mean refrigerant density integration implies time-variant mean void fraction. [9] Introduced the pseudoquality variable to predict the formation of subcooled liquid / superheated setam region at the condenser / evaporator, experimental validation presented. [10] Extended condenser model from McKinley and Alleyne (2008) to allow five modes and development of a switching evaporator model, experimental validation considering two cases. [11] Use of the pseudo-state variables introduced in Pettit and Willatzen (1998). New switching criteria and choice of the state variables to ensure mass and energy conservation when simulating low mean void fraction start-ups. Temporal integration is applied to the mean density leading the mean void fraction to be time variant.

2. MODELING

2.1 Assumptions and Goals

In order to develop a low order model but reflecting the principal dynamics, a number of assumptions must be performed: one-dimensional flow, average properties in each CV, negligible gravitational forces, negligible changes in the kinetic energy, constant cross-sectional area in the pipe, constant heat flux per unit length in each CV, axial heat conduction in the fluid and pipe wall is also negligible and homogeneous two-phase flow. The pipe geometry considered is cylindrical and the heat transfer fluid is the steam-water two-phase flow.

The main goal is to design a moving boundary model for two-phase flow evaporators with the following features: support for the 6 modes for evaporators described in Table 1, inclusion of switching mechanisms between them. Development of the model in a object-oriented equation-based way. Consider the pressure drop in the evaporator (Yebra et al., 2005) and the time-variant mean void fraction. Use in some way pseudo-state variables, which represent states in inactive zones (Willatzen et al., 1998) (McKinley and Alleyne, 2008).

The two common choices of state variables, in the published moving boundary models for the two-phase flow volume, are: $(p, h_{tp,out}, L_{tp})$ (Pettit and Willatzen, 1998; Zhang and Zhang, 2006; Bendapudi et al., 2008) and $(p, \bar{\gamma}, L_{tp})$ (Li and Alleyne, 2010), nomenclature is shown in Table 3. In this work, the $(p, h_{tp,out}, L_{tp})$ state variables are considered in the development of the two-phase flow volume model.

2.2 Modeling achievements

Presently, the following goals have been achieved: start-up of the development of the library, development of the base models for the CVs and the pipe wall. Models for subcooled liquid, two-phase flow volumes together with the flooded evaporator model. The momentum balance equation has not been considered yet. Switching between subcooled liquid model and flooded evaporator model has been also implemented. The next subsections introduce only some of these models because of space limitation.

Two-phase Flow Volume Model. The straightforward way to derive the model equations is using the unsteady-state equations for conservation of mass and energy. The equations are shown in its final form due to space limitation. The process to obtain the equations is similar to the performed in Jensen and Tummescheit (2002), but considering a time-variant mean void fraction. The conservation of mass and energy in the two-phase flow volume are defined by (1) and (2) respectively, the nomenclature is described in Table 3.

Table 3. Nomenclature

Variable	Description	Units
A	Cross-sectional area	[m^2]
d	Diameter	[m]
α	Heat transfer coefficient (HTC)	[W/(m^2·K)]
$\dot{m}$	Mass flow rate	[kg/s]
x	Steam quality	[-]
L	Length	[m]
p	Pressure	[Pa]
γ	Void fraction	[-]
$\bar{\gamma}$	Mean void fraction	[-]
h	Specific enthalpy	[J/kg]
h'	Enthalpy of evaporation	[J/kg]
h''	Enthalpy of condensation	[J/kg]
ρ	Density	[kg/m^3]
ρ'	Density of evaporation	[kg/m^3]
ρ''	Density of condensation	[kg/m^3]
T	Temperature	[K]
T'	Temperature at evaporation	[K]

Subscript	Description	Subscript	Description
in	Input	*out*	Output
sc	Subcooled	*tp*	Two-phase
i	Inner	*w*	Pipe wall

$$
\begin{aligned}
&A\left(\left(\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}-\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}\right)\frac{dL_{sc}}{dt}+\right.\\
&L_{tp}\left(\left(\bar{\gamma}\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}+(1-\bar{\gamma})\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}\right)\frac{dp}{dt}+\right.\\
&\left.\left.\frac{d\bar{\gamma}}{dt}\left(\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}+\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}\right)\right)+\right.\\
&\left.\left(\bar{\gamma}\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}+(1-\bar{\gamma})\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}\right)\frac{dL_{tp}}{dt}\right)\\
&=\dot{m}_{tp,in}-\dot{m}_{tp,out},
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
&A\left((\rho'h'-\rho''h'')\frac{dL_{sc}}{dt}+(1-\bar{\gamma})(\rho'h'-\rho''h'')\frac{dL_{tp}}{dt}+\right.\\
&L_{tp}\left(\left(\bar{\gamma}\left(\rho''\frac{\partial h''}{\partial p}+h''\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}\right)+\right.\right.\\
&\left.(1-\bar{\gamma})\left(\rho'\frac{\partial h'}{\partial p}+h'\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}\right)-1\right)\frac{dp}{dt}+\\
&\left.\left.\frac{d\bar{\gamma}}{dt}\left(\left.\frac{\partial\rho''}{\partial p}\right|_{h_{tp}}h''-\left.\frac{\partial\rho'}{\partial p}\right|_{h_{tp}}h'\right)\right)\right)=\\
&\dot{m}_{tp,in}h'-\dot{m}_{tp,out}h_{tp,out}+\pi d_{i,w}L_{tp}\alpha_{tp}(T_{tp,w}-T_{tp}).
\end{aligned}
\tag{2}
$$

A and α_{tp} are parameters, A is computed as $\pi d_{i,w}^2/4$. The thermodynamic properties: ρ', ρ'', h', h'' and its partial pressure derivatives are computed by the pressure (p), using the Modelica.Media library, which follows the IAPWS (the International Association for the Properties of Water and Steam) recommendations in its latest IF97 formulation, (Industrial Formulation 1997) (IAPWS, 1997). This formulation is optimized for short computing times and low CPU load.

It is assumed a linear distribution of specific enthalpy in the CV, therefore,

$$h_{tp}=\frac{h_{tp,in}+h_{tp,out}}{2}. \tag{3}$$

The steam quality considering a homogeneous flow is,

$$x=\frac{h_{tp}-h'}{h''-h'}. \tag{4}$$

The $d\bar{\gamma}/dt$ has been calculated considering (5),

$$\frac{d\bar{\gamma}}{dt}=\frac{\partial\bar{\gamma}}{\partial p}\frac{dp}{dt}+\frac{\partial\bar{\gamma}}{\partial h_{tp,out}}\frac{dh_{tp,out}}{dt}+\frac{\partial\bar{\gamma}}{\partial h_{tp,in}}\frac{dh_{tp,in}}{dt}, \tag{5}$$

and calculating symbolically the partial derivatives: $\partial\bar{\gamma}/\partial p$ $\partial\bar{\gamma}/\partial h_{out}$ and $\partial\bar{\gamma}/\partial h_{in}$ from (6) (this expression is analogous to the obtained in Åström and Bell (2000)),

$$
\begin{aligned}
&\bar{\gamma}=\frac{1}{h_{tp,out}-h_{tp,in}}\int_{h_{tp,in}}^{h_{tp,out}}\gamma\, dh_{tp}=\\
&\frac{1}{h_{tp,out}-h_{tp,in}}\int_{h_{tp,in}}^{h_{tp,out}}\frac{x\rho'}{x\rho'(1-x)\rho''}\, dh_{tp}=\\
&\frac{1}{(\rho'-\rho'')^2}\left(\rho'\left(\left(h_{tp,out}-h_{tp,in}\right)\rho'+\rho''\left(h_{tp,in}-h_{tp,out}\right.\right.\right.\\
&+\left(h'-h''\right)\left(\ln\left(\rho''\left(h_{tp,in}-h'\right)+\rho'\left(h''-h_{tp,in}\right)\right)\right.\\
&-\left.\left.\left.\left.\ln\left(\rho''\left(h_{tp,out}-h'\right)+\rho'\left(h''-h_{tp,out}\right)\right)\right)\right)\right)\right),
\end{aligned}
\tag{6}
$$

resulting after isolating γ from (7) (Jensen, 2003),

$$x=\frac{\rho''\gamma}{\rho'(1-\gamma)+\rho''\gamma}, \tag{7}$$

and integrating over the $[h_{tp,in},h_{tp,out}]$ interval.

The boundary variables of the volume model are: dL_{sc}/dt, $dh_{tp,in}/dt = dh_{sc,out}/dt$, obtained from the subcooled liquid volume model, and $T_{tp,w}$ which is calculated in the pipe wall model, both models are not described in this manuscript due to space limitations, but the subcooled liquid volume model is derived from Jensen (2003) considering a variable outlet specific enthalpy and the pipe wall model is described in Zhang and Zhang (2006). The state variables in the two-phase flow volume model are $(p, h_{tp,out}, L_{tp})$.

Switching Flooded Moving Boundary Model. The flooded moving boundary model is composed by the subcooled liquid volume model and the two-phase flow volume model, previously introduced, as shown in Fig. 3.

The switching from the flooded evaporator to the subcooled liquid volume is performed when,

$$x \leq 0, \tag{8}$$

is true, the criteria reads, when the steam fraction is zero the model must switch to the single-phase volume mode. The switching criteria from the subcooled liquid volume to the flooded evaporator is the following,

$$x \geq \epsilon. \tag{9}$$

The global switching criteria uses then a hysteresis, with a certain threshold, ϵ set to 10^{-3}. This has been introduced in order to minimize the effects of chattering in the switching process, further research must be devoted to study the chattering in this switching process.

When the single-phase volume mode is activated, (1) is replaced by,

$$\dot{m}_{tp,out} = \dot{m}_{tp,in}, \tag{10}$$

and (2) is replaced by,

$$\frac{dh_{tp,out}}{dt} = \frac{dh_{tp,in}}{dt}, \tag{11}$$

$\frac{dL_{sc}}{dt}$ is set to zero (in the subcooled liquid volume model), then,

$$L_{sc} = L_{tot}, \tag{12}$$

where L_{tot} is the total length of the evaporator, and therefore, $L_{tp} = 0$. In this configuration also, $\bar{\gamma} = 0$ and $x = 0$.

2.3 MBMs Library

An object-oriented equation-based library for moving boundary models in two-phase flow evaporators (MBMs Library) is being develop to organize, reuse and maintain the models. Modelica 3.2 (Modelica Association, 2010) has been chosen as the modeling language. The Modelica.Fluid and Modelica.Thermal libraries from the Modelica Standard Library have been widespread used in order to establish heat and fluid ports and interfaces. The Modelica.Media library has been used to obtain the thermodynamic properties of the steam-water two-phase flow. Fig. 1 shows the different packages which compose the library. Fig. 2 shows the two-phase flow volume model icon. Fig. 3 shows the component diagram of the flooded evaporator model which also includes a switching mechanism. An example model to test the switching flooded evaporator model can be seen in Fig. 4.

3. SIMULATION

This section presents the simulation of a switching flooded evaporator example model (see Fig. 4). The model is fairly simple, a source of direct solar irradiance is modeled as the Irradiance table shown in Fig. 4, a parabolic-trough collector concentrates the irradiance considering a angle of incidence which is zero. The concentrated solar irradiance (see Fig. 5) is uniformly distributed along a absorber

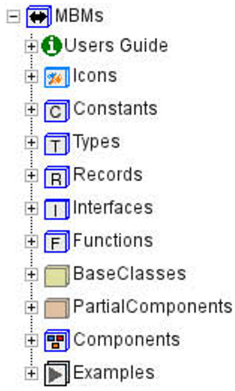

Fig. 1. Library packages

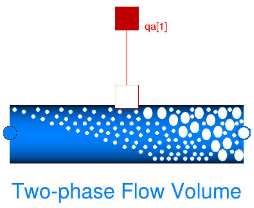

Fig. 2. Two-phase volume model icon

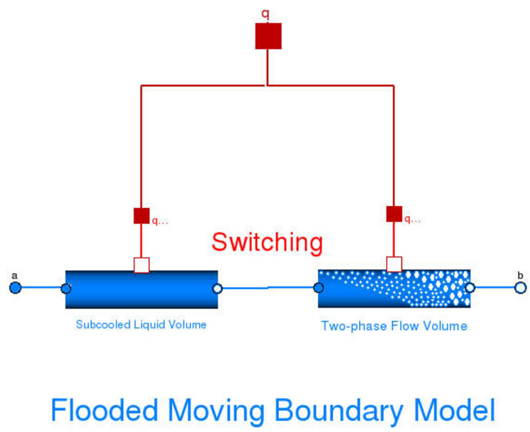

Fig. 3. Switching flooded MBM component diagram

tube located in the geometrical focal line of the parabolic-trough receiver, the absorber tube is composed of a glass cover and a cylindrical steel pipe, which has a selective coating with low emissivity, between both elements there is high vacuum to minimize the thermal loses by conduction and convection. Therefore, the steel pipe heats the water circulating inside it and loses energy to the ambient by radiation.

Table 4 summarizes the model parameters whereas Table 5 shows the simulation parameters and simulation statistics, where can be seen that the simulation is performed in 0.64 s. The Dymola 2012 FD01 tool (Dassault Systèmes AB, 2011) has been used in order to simulate the Modelica model.

Fig. 5 shows the heat over the pipe and the evaporator mode: subcooled liquid mode = 200, flooded evaporator mode = 400. Fig. 6 shows the subcooled liquid and two-phase zone lengths during the simulation, it can be seen

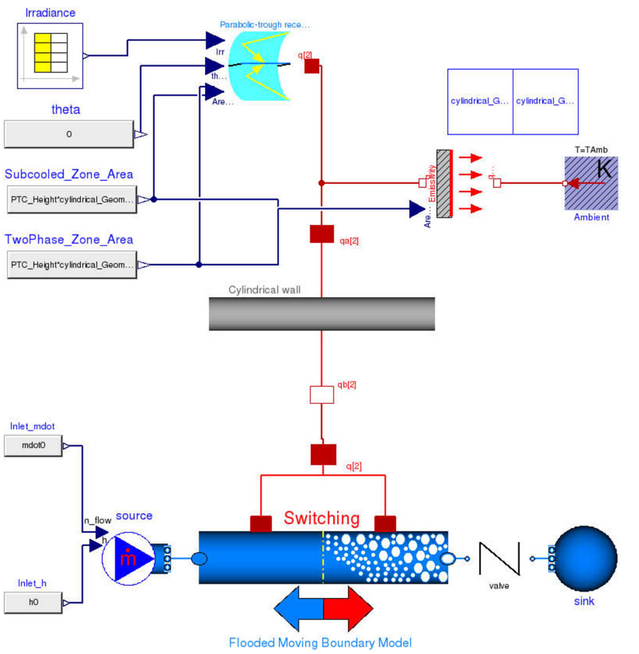

Fig. 4. Switching flooded evaporator example model

how the two-phase zone length is zero when the evaporator is in the subcooled liquid mode. The mean void fraction and the steam quality in the two-phase region can be seen in Fig. 7. Fig. 8 shows the pressure and the outlet mass flow rate. Fig. 9 shows specific enthalpy values, when the model is in the subcooled liquid mode it can be seen how the outlet specific enthalpy is just slightly lower, in this case, than the enthalpy of evaporation. Fig. 10 shows the outlet temperature and the temperature at evaporation, it can be also seen that the outlet temperature is also slightly lower than the temperature at evaporation when the model is in the subcooled liquid mode.

Table 4. Switching flooded evaporator model parameters

Parameter	Description	Value	Units
$\dot{m}_{in}$	Inlet mass flow rate	0.5	[kg/s]
T_{amb}	Ambient temperature	290	[K]
T_{in}	Inlet water temperature	350	[K]
p_0	Initial evaporator pressure	6	[MPa]
p_{sink}	Sink pressure	5.9	[MPa]
L_{tot}	Evaporator length	500	[m]
d_i	Inner pipe diameter	0.05	[m]
d_o	Outer pipe diameter	0.07	[m]
α_{sc}	SC convective HTC	2500	$[W/(m^2{\cdot}K)]$
α_{tp}	TP convective HTC	8000	$[W/(m^2{\cdot}K)]$
ρ_w	Pipe density	7780	$[kg/m^3]$
$c_{p,w}$	Pipe specific heat capacity	500	[J/(kg·K)]
ε_w	Pipe emissivity	0.065	[-]

4. FUTURE WORK

Future work includes, design the superheated volume model, the switching dry-expansion model and a general model which can switch to flooded, dry-expansion or any of the basic models. Consider the pressure drop in the evaporator by means of the momentum conservation equation. Check the models stability and integrity. Calibration and validation of the models with experimental data and develop a new version of the library using bond-graphs

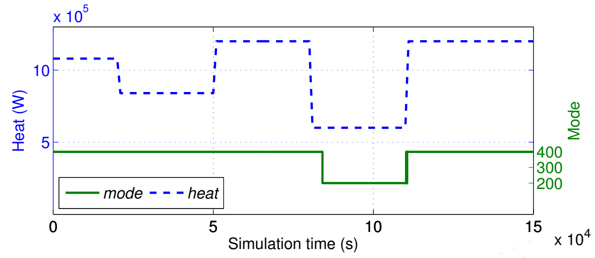

Fig. 5. Inlet solar irradiance and evaporator mode (SC mode = 200, F mode = 400)

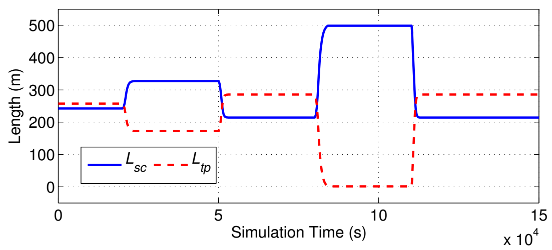

Fig. 6. Subcooled and two-phase zone lengths

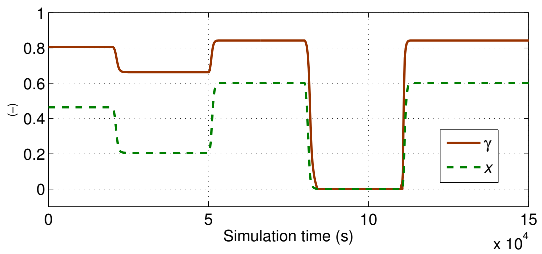

Fig. 7. Mean void fraction and steam quality

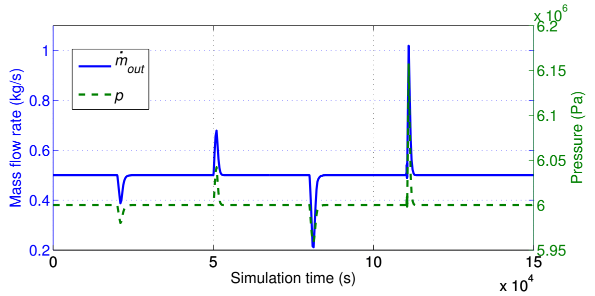

Fig. 8. Pressure and outlet mass flow rate

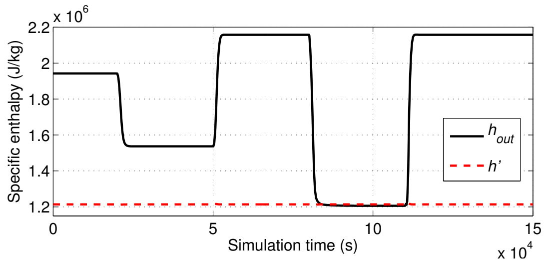

Fig. 9. Specific enthalpies

Table 5. Simulation parameters and statistics

Simulation parameters	
Numerical integrator	DASSL (Petzold, 1983)
Tolerance	10^{-6}
Simulated time	$15 \cdot 10^4$ s
Simulation statistics	
CPU-time for integration	0.64 s
Number of state events	37
Minimum integration stepsize	$6.29 \cdot 10^{-5}$
Maximum integration stepsize	$9.89 \cdot 10^3$
Maximum integration order	5

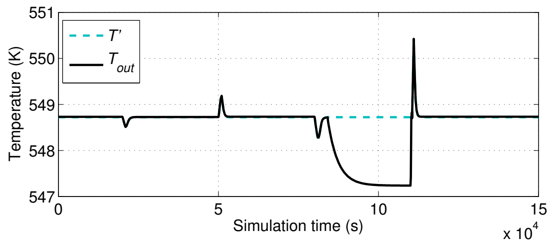

Fig. 10. Temperatures

in order to reflect physical reality more precisely, furthermore facilitating the reuse and maintenance of the library (Cellier, 1991).

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