BOND GRAPH MODEL OF A WATER HEAT EXCHANGER

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KEYWORDS

Bond graph; Multiport; Thermofluid systems; Plate heat exchanger

ABSTRACT

This paper presents a Bond Graph (BG) modelling approach to add and exploit on existing Modelica models some information on the energy structure of the systems. The developed models in the ThermosysPro library (Modelica-based) are already validated against the experimental data in previous works. A plate heat exchanger (PHE), which is equipment for nuclear power plants, is considered as a case study in this paper. Simulation results of the BG model for the counterflow PHE are compared with simulation results of the tested Modelica model. Comparisons show good agreement between both model results.

INTRODUCTION

Nowadays, the major problems of the numerical computation of mathematical models for complex processes are solved by using different commercial and open source software packages. The representation of the models in these languages is often based on model equations. The bond graph representation allows a physical structural analysis which is based on the system energy structure. This facilitates the exchange of models and simulation specifications. Bond graph is a graphical representation methodology for modelling multidisciplinary physical systems (Jardin et al. 2009).

Heat exchange is an important unit operation that contributes to efficiency and safety of many processes (nuclear power plants, steam generators, automotive, heat pumps, etc.). A plate heat exchanger is a type of heat exchanger that uses metal plates to transfer heat between two fluids. The plate heat exchanger was invented by Dr Richard Seligman in 1923 and revolutionised methods of indirect heating and cooling of fluids (Crepaco 1987). Plate heat exchangers are widely used in many other applications (food, oil, chemical and paper industries, HVAC, heat recovery, refrigeration, etc.) because of their small size and weight, their cleaning as well as their superior thermal performance compared to other types of heat exchangers (Guo et al. 2012).

The plate heat exchanger model is one of over 200 0D/1D models of components belonging to the ThermosysPro library. This open source library, developed by EDF R&D, is used to model energy systems and different types of power plants (nuclear, conventional, solar, etc.) (El Hefni 2014; El Hefni and Bouskela 2006; El Hefni et al. 2011, 2012; Deneux et al. 2013). The Modelica model is developed in Dymola. Modelica

representation leads to static analyses which are based on model equations, while BG representation permits a physical structural analysis which is based on the system's energy structure. The bond graph representation in this paper is built using the graphical editor MS1. MS1, an acronym of Modelling System One, is an interactive environment for modelling, simulation and analysis of non-linear dynamic systems (Jardin et al. 2008).

In the literature, bond graph modelling of heat exchangers is widespread (Shoureshi and Kevin 1983; Hubbard and Brewer 1981; Delgado and Thoma 1999). Due to difficulties in handling entropy and heat transfer rate, many efforts have been made to develop pseudo-bond graph representations of thermo-fluid transport and heat exchange (Karnopp and Azerbaijani 1981; Karnopp 1978, 1979; Ould Bouamama 2003). All these references mentioned above have different assumptions. For instance, in (Shoureshi and Kevin 1983) a temperature-entropy bond graph technique has been proposed based on three lump models to predict the reversal of flow. In this model, the authors have considered that the fluid domain is operated independently from the thermal domain. In (Karnopp 1978), pseudo bond graph strategies have been proposed with using the temperature and heat flow as effort and flow.

This paper uses pseudo bond graph method for heat/mass transfer modelling. Furthermore, multi-port C and multi-port R elements have been used. This method is based on finite volume approach considering the thermal and fluid bonds. First, fundamental theory of thermofluid is given. Then, the plate heat exchanger models are explained: the Modelica model and the BG model. In the section after that, simulation results are discussed. The last section contains conclusion and future research paths.

THERMOFLUID SYSTEM

Thermofluid or thermal fluid sciences involve the study of the thermodynamics, fluid mechanics, heat and mass transfer in complex engineering systems. In the open system case, the energy and mass equations for a thermodynamic system are formulated as (see nomenclature page 339)

$$\frac{dE_s}{dt} = \dot{Q}_{in} + \dot{W}_{in} + \dot{E}_i - \dot{E}_e \qquad (1)$$

where (dE_s/dt) is the rate of increase in energy within the system, $\dot{Q}_{in}$ is the rate at which heat enters the system, $\dot{W}_{in}$ is the rate at which work enters the system, $\dot{E}_i$ is the rate at which energy is brought in by the mass entering the system, and $\dot{E}_e$ is the rate at which energy

is removed by the mass leaving the system.

$$\frac{\mathrm{d}m_s}{\mathrm{d}t} = \dot{m}_i - \dot{m}_e \qquad (2)$$

where $(\mathrm{d}m_s/\mathrm{d}t)$ represents the rate of increase in mass within the system, and m_i and m_e represent the respective rates at which mass entering and leaving the system.

In many thermal application, the reduced heat equation is used

$$\dot{Q} = \frac{\mathrm{d}Q}{\mathrm{d}t} = mC_p\frac{\mathrm{d}T}{\mathrm{d}t} = KA(\Delta T), \qquad (3)$$

where $\dot{Q}$ is the heat-flow-rate (named just heat rate), C_p is the specific heat capacity, m is the mass flow rate, the global heat transfer coefficient K (associated to a bounding area A and the average temperature jump ΔT between the system and the surroundings). More details about the above equations can be seen in reference (Martìnez 1992).
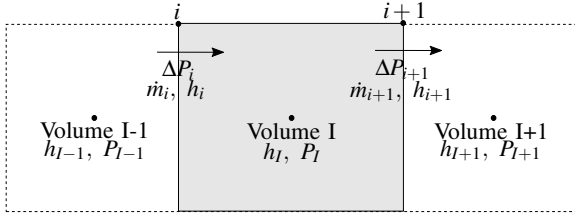

Figure 1: Staggered finite volume scheme

The cooling water heat exchanger used in this study is an equipment for nuclear power plants. Two main approach for the dynamic modelling of the heat exchanger are the moving boundaries (MB) and the discretized models, known as finite-volume models (FVM) (Bendapudi et al. 2004; Desideri et al. 2015). The moving boundary method is useful for developing feedback controllers, in this approach the heat exchanger is divided into zones based on the fluid phase in each region and the location of the boundary between regions vary in time according to the current conditions. In finite-volume models the 1D flow is subdivided into several equal control volumes as shown in Figure 1.

The modelling technique used in this paper is based on finite volumes approach. A pictorial representation of the discretized counterflow heat exchanger is shown in Figure 2.

PLATE HEAT EXCHANGER MODELS
The plate heat exchanger is the component that transforms heat (thermal energy) from one fluid to another. Plate heat exchangers have a high heat transfer rate compared to other types of heat exchangers due to their large surface area.

Modelling of Water/Water Heat Exchangers in Modelica

The dynamic water/water heat exchanger component used belongs to the ThermoSysPro library. The core model of the heat exchanger was written in Modelica
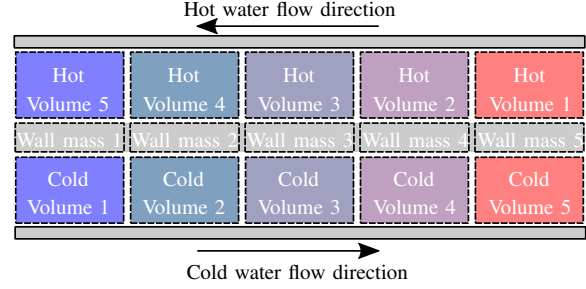

Figure 2: Schematic diagram of a typical discretized counterflow plate heat exchanger

and simulated with the Dymola simulation environment. Figure 3 shows the schematic of the heat exchanger model in Dymola. This model has two parts: the upper part for hot water and the other part for cold water, which are quite similar. The inlets and outlets of the heat exchanger block are shown by the blue and red rectangles, respectively. The red and blue arrows show the cold and hot waters of the two parts respectively.
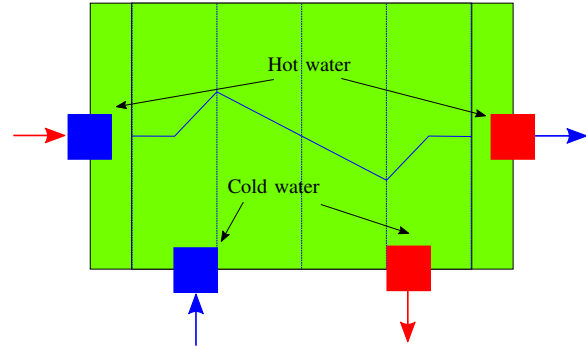

Figure 3: Dymola layout of the heat exchanger

In this model, the rate of mass accumulation within the volume does not incorporate any dynamic effects. This means that the entering mass flow rate is exactly equal to the leaving one i.e. the steady balance for all volumes of the heat exchanger, yields

$$\dot{m}_{b,i-1} - \dot{m}_{b,i} = 0 \qquad (4)$$

where $\dot{m}$ is the mass flow rate. Throughout the paper, the subscript b means the hot part when $(b \leftarrow h)$ or the cold part when $(b \leftarrow c)$.

To simplify the model, the mass flow rate is considered positive in both parts i.e. $\dot{m}_{b,i} > 0$, and the pressure between each two volumes is defined as

$$P_{b,i+1} = P_{b,i} - \Delta P_{b,i}/N \qquad (5)$$

where N is number of segments, $\Delta P_{b,i}$ is the pressure drop.

The pressure drop ($\Delta P_{b,i}$), which has direct relationship to the size of the plate heat exchanger, is defined by

$$\Delta P_{b,i} = k_{b,i} \cdot Nu_{b,i}^{-0.097} \cdot qu_{b,i}^2 + 104.97 \cdot Nu_{b,i}^{-0.25} \qquad (6)$$

where $k_{b,i}$, and correlation for the heat transfer Nu (is called also Nusselt number) and pressure drop qu

characteristics, are defined as

$$\begin{cases} Nu_{b,i} = \dot{m}_{b,i}/(M \cdot \mu_{b,i}) \\ qu_{b,i} = \dot{m}_{b,i}/M \\ k_{b,i} = 14423.2 \left[1472.47 + \dfrac{1.54(M-1)}{2}\right] \dfrac{c_{1,b}}{\rho_{b,i}} \end{cases} \quad (7)$$

where $c_{1,b}$ is a correction coefficient, and $M = (n-1)/2$, n is the number of plates. The formulas above are investigated experimentally in (Cracow 2011).

The energy balance equation in each layer is given by:

$$V_{b,I} \cdot \rho_{b,I} \cdot \frac{dh_{b,I}}{dt} = \pm(h_{b,i} \cdot \dot{m}_{b,i} - h_{b,i+1} \cdot \dot{m}_{b,i+1} - \dot{W}_I) \quad (8)$$

where the plus-minus sign ($\pm$) indicates (+) for the hot part and (-) for cold part.

The global heat exchanged between the both fluids and the wall is

$$\dot{W}_I = K_I \cdot \Delta S \cdot (T_{h,I} - T_{c,I}) \quad (9)$$

The heat exchange surface ΔS, and the global heat transfer coefficient K_I are given by

$$\begin{cases} \Delta S = (n-2) \cdot A/N, \\ K_I = (\overline{h}_h \cdot \overline{h}_c)/(\overline{h}_h + \overline{h}_c + \overline{h}_h \cdot \overline{h}_c \cdot \frac{e_m}{\lambda_m}), \\ \overline{h}_b = 11.245 \cdot |Nu_{b,i}|^{0.8} \cdot Pr_{b,i}^{0.4} \cdot \lambda_{b,i}. \end{cases} \quad (10)$$

where h_b is the convection heat transfer coefficient between the fluid and the wall. The Prandtl number $Pr_{b,i}$ is defined as,

$$Pr_{b,i} = \mu_{b,i} \cdot Cp_{b,i}/\lambda_{b,i} \quad (11)$$

In Equations (7) to (11), $\rho_{b,i}$, $T_{b,I}$, $\lambda_{b,i}$, $\mu_{b,i}$, and $Cp_{b,i}$ are the density, temperature, thermal conductivity, dynamic viscosity, and heat capacity respectively. In Modelica model, water properties are expressed as

$$\begin{cases} \rho_{b,i} = \rho_{b,i}(P_{b,I}, h_{b,I}) \\ \lambda_{b,i} = \lambda_{b,i}(\rho_{b,i}, T_{b,I}, P_{b,I}) \\ \mu_{b,i} = \mu_{b,i}(\rho_{b,i}, T_{b,I}) \\ Cp_{b,i} = Cp_{b,i}(P_{b,I}, h_{b,I}) \end{cases} \quad (12)$$

The presure $P_{b,I}$ and the specific enthalpy $h_{b,I}$ at the volume are given by

$$\begin{cases} P_{b,I} = \dfrac{P_{b,i} + P_{b,i+1}}{2}, \\ h_{b,I} = \dfrac{h_{b,i} + h_{b,i+1}}{2}. \end{cases} \quad (13)$$

Then the temperature at the volume is calculated from the a tables of the water thermodynamic properties, and it is defined as

$$T_{b,I} = T_{b,I}(P_{b,I}, h_{b,I}) \quad (14)$$

In Modelica model, water temperature T and density ρ are calculated from tables of water thermodynamic properties, depending on water pressure P and specific enthalpy h. However, for most of the elements presented above, the calculation of pressure depends on water density, which introduces an algebraic loop in the calculation scheme.
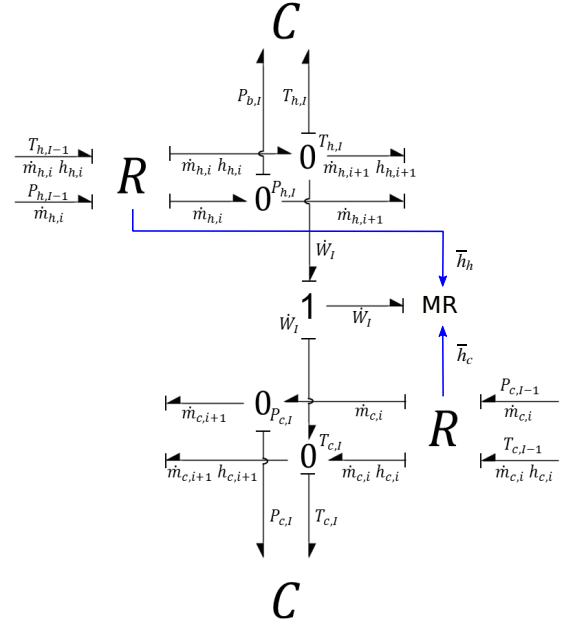

Figure 4: Pseudo bond graph of a small heat exchanger

Modelling of Watet/Water Heat Exchangers using Bond Graph Approach

The bond graph model of this complex dynamic behavior and nonlinear system in thermofluids engineering allows to non-expert to get a better understanding of the model and to analyse the properties of this physical system (Karnopp et al. 1990, 2012). In this approach, the specific enthalpy and some other properties of water are calculated from tables depending on pressure and temperature. The bond graph developed here has more degree of freedom compared with the Modelica model due to the consideration of the rate of mass accumulation within the volume.

The same finite volume method used in previous section is applied, where the heat exchanger has to be divided into n small successive heat exchangers, where each has uniform hot and cold temperature. Figure 4 shows the causal bond graph representation for one small heat exchanger. For modelling of each lump, the following elements were used

- **Multi-port C-element,**

The multi-port C-element is used here for a thermodynamic accumulator, and is in its pseudo-bond graph form since the variables at its ports are not strictly power variables (Fig. 5). The thermodynamic accumulator has two degrees of freedom (2-DOF) since its volume is fixed here. The two state variables chosen are the water mass (m) for the fluid domain, and the specific enthalpy (h) for the thermal domain. Therefore, several modifications must be done compared to the Modelica model. The outputs from the multi-port C-element are the pressure and temperature, which are given by following relations:

$$\textbf{\textit{Fluid Bond}} \quad P_{b,I} = P_{b,I}(\rho_{b,I}, h_{b,I}) \quad (15)$$
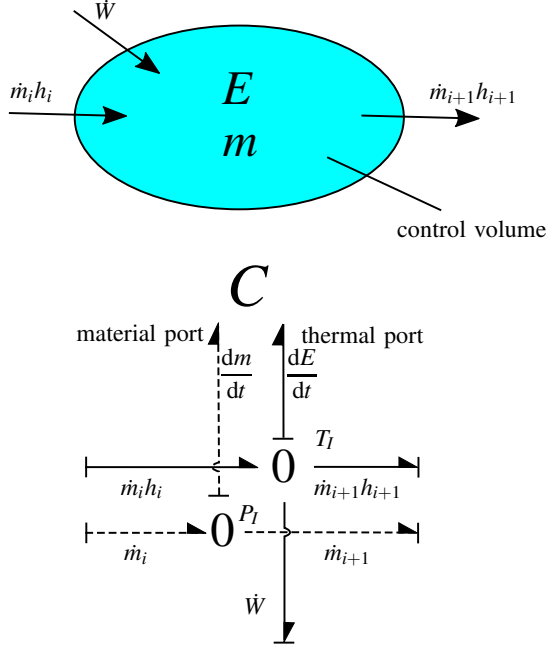
Figure 5: Control volume and its corresponding bond graph of the thermodynamic accumulator

Thermal Bond $\quad T_{b,I} = T_{b,I}(P_{b,I}, h_{b,I}) \quad$ (16)

where the temperature table $T_{b,I}(P_{b,I}, h_{b,I})$, thermodynamic property of the water, is well detailed in reference (Wagner and Kretzschmar 2008) and the ThermoSysPro model. The function $P_{b,I}(\rho_{b,I}, h_{b,I})$ is calculated by an iterative resolution given in Algorithm 1 described in the appendix section. The algorithm provides an easiest way to obtain the pressure, as a function of a given density and specific enthalpy. To obtain the density the dynamic continuity equation, in which the total stored mass equals the net integrated mass flow rate, is used

$$\frac{dm_{b,I}}{dt} = \dot{m}_{b,i} - \dot{m}_{b,i+1} \quad (17)$$

where $m_{b,I}$ is the mass, $\dot{m}_{b,i}$ and $\dot{m}_{b,i+1}$ are respectively the control volume entering and leaving mass flow rates, as shown in Figure 5 by the dashed bonds.

To convert Equation (17) into a more useful form to obtain the density in the control volume, the following relationship is used

$$\rho_{b,I} = \frac{m_{b,I}}{V_{b,I}} \quad (18)$$

where $V_{b,I}$ is the volume of the control volume.

Assuming a C-element with a constant volume, which leads to

$$\frac{d\rho_{b,I}}{dt} = \frac{\dot{m}_{b,i} - \dot{m}_{b,i+1}}{V} \quad (19)$$

In Equations (16) and (15), the specific enthalpy $h_{b,I}$ is calculated from the following one-dimensional energy equation

$$V_{b,I} \cdot \rho_{b,I} \cdot \frac{dh_{b,I}}{dt} = \pm(h_{b,i} \cdot \dot{m}_{b,i} - h_{b,i+1} \cdot \dot{m}_{b,i+1} - \dot{W}_I) \quad (20)$$

- **Multi-port R-element,**

The Multi-port R-element is used for a thermodynamic resistance and in its pseudo-bond graph form. The structure of the multiport pseudo-bond graph model R-element is defined in Figure 6.
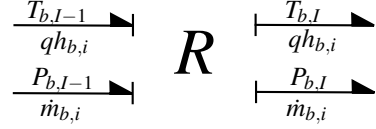

Figure 6: The pseudo bond graph of the R-field of the heat exchanger

The relationships between the efforts (temperatures and pressures) and flows (mass flow rate and specific enthalpy flow rate) in R-elements are given by

$$\begin{cases} \dot{m}_{b,i} = \dot{m}_{b,i}(T_{b,I-1}, T_{b,I}, P_{b,I-1}, P_{b,I}), \\ qh_{b,i} = qh_{b,i}(T_{b,I-1}, T_{b,I}, P_{b,I-1}, P_{b,I}). \end{cases} \quad (21)$$

where the specific enthalpy flow rate $qh_{b,i}$ is represents the quantity $\dot{m}_{b,i}h_{b,i}$ shown in the Figure 6.
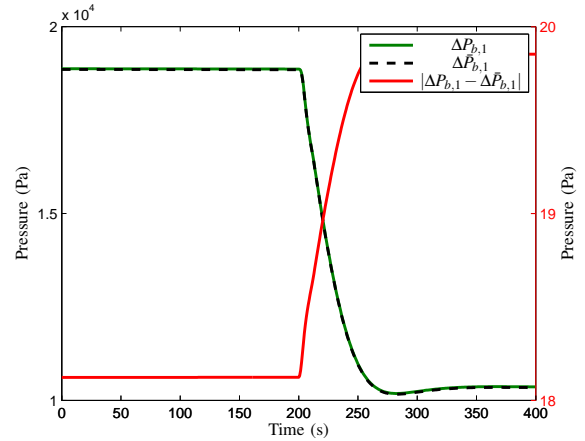

Figure 7: Comparison between the pressure difference

To calculate the mass flow rate $\dot{m}_{b,i}$ as a funtion of $\Delta P_{b,i}$ using the Equation (6) is quite difficult. Hence, to obtain an approximate solution, we ignore the second term $104.97 \cdot (Nu_{b,i})^{-0.25}$ in the Equation (6) because its effect on $\Delta P_{b,i}$ is negligible (see Figure 7). The pressure drop can be written as

$$\begin{aligned} \Delta \bar{P}_{b,i} &= k_{b,i} \cdot Nu_{b,i}^{-0.097} \cdot qu_{b,i}^2 \\ &= k_{b,i} \cdot \left(\frac{\dot{m}_{b,i}}{\mu_{b,i} \cdot M}\right)^{-0.097} \cdot \left(\frac{\dot{m}_{b,i}}{M}\right)^2 \\ &= \bar{k}_{b,i} \cdot \dot{m}_{b,i}^{1.903} \end{aligned} \quad (22)$$

where $\bar{k}_{b,i} = k_{b,i} \cdot \mu_{b,i}^{0.097} \cdot M^{-1.903}$. Thus, the mass flow rate $\dot{m}_{b,i}$ can be calculated by using the following formula

$$\dot{m}_{b,i} = \exp\left(\frac{\ln(\Delta \bar{P}_{b,i}) - \ln(\bar{k}_{b,i})}{1.903}\right) \quad (23)$$

Figure 8 shows the comparison between both mass flow rates of the hot water in Dymola and MS1, in which
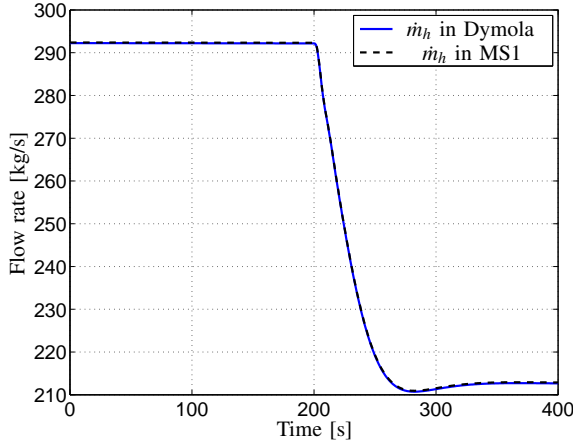
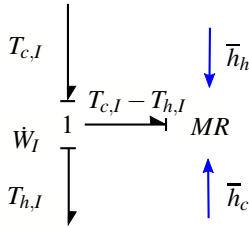Figure 8: Comparison between both mass flow rates in Dymola and MS1

Figure 9: Modulated 1-port R-element and 1-junction

calculated by Equation (23). The blue curve represents the mass flow rate obtained by the ThermoSysPro model, and dashed black curve represents the mass flow rate obtained by BG model. As a result, both curves are similar because the pressure drop obtain by Equation (22) is quite equal to that obtained by Equation (6).

- **Modulated 1-port R-element,**

The rate of heat transfer in each segment occurs between two C-fields at higher and lower temperatures. The heat flow between C-fields (from higher temperature to lower temperature) is proportional to the difference of temperatures, and is given by

$$\dot{W}_I = K_I \cdot \Delta S \cdot (T_{h,I} - T_{c,I}) \tag{24}$$

where K_I and ΔS are given in Eq (10). K_I is a function of the convection heat transfer coefficient $\overline{h}_b$, the latter is calculated in R-Element and materialized by the blue arrows in Figure 9.

In Figure 9, the 1-junction means that the rate of heat transfer $\dot{W}$ (flow) through all connected bonds is the same, and that the temperatures (efforts) sum to zero. The sign of each temperature is related to the power direction (i.e. direction of the half arrow) of the bond.

In the bond graph model, the calculation of some thermodynamic properties of water is different compared to Equation (12). Here, the thermodynamic properties of water are given in terms of the pressure and the

temperature as following

$$\begin{cases} \rho_{b,i} = \rho_{b,i}(P_{b,i}, T_{b,i}) \\ h_{b,i} = h_{b,i}(P_{b,i}, T_{b,i}) \\ \lambda_{b,i} = \lambda_{b,i}(\rho_{b,i}, T_{b,i}) \\ \mu_{b,i} = \mu_{b,i}(\rho_{b,i}, T_{b,i}) \\ Cp_{b,i} = Cp_{b,i}(P_{b,i}, T_{b,i}) \end{cases} \tag{25}$$

where, the pressure $P_{b,i}$ and the temperature $T_{b,i}$ at the multi-port R-element are given by

$$\begin{cases} P_{b,i} = \dfrac{P_{b,I-1} + P_{b,I}}{2} \\ T_{b,i} = \dfrac{T_{b,I-1} + T_{b,I}}{2} \end{cases} \tag{26}$$

The functions in Equation (25) of the water properties are based on the Industrial Formulation IAPWS-IF97 which consists of a set of equations for different water regions (more details are given in (Wagner and Kretzschmar 2008)).

RESULTS AND DISCUSSION

The bond graph model of the exchanger has been validated by simulations. Figure 10 shows the bond graph model of the PHE. The PHE model consists of total ($N = 5$) numbers of plates, each layer being represented as a small heat exchanger (shown in Figure 4). The inputs of bond graph model are the pressure and the temperature, while the outputs are the mass flow rate and enthalpy flow rate for hot and cold parts.

The Modelica and the BG models were run for 400 seconds of simulation time. Figure 11 shows the pressures, where the black curves represent the pressure at the boundaries, the blue curves represent the pressure at each volume in the ThermoSysPro model, and the dashed green curves represent the pressure at each volume (C-element) in the BG model. Figure 12 shows the error between obtained pressures (Dymola and MS1) at first volume. From the comparison of the simulation results, the conclusion that can be made is that the both models have similar dynamic behavior.

CONCLUSION

In this paper, a multi-port pseudo BG model of a plate heat exchanger system has been presented. The model can be used in transient system simulations and can be extended to cover other heat exchanger types. The comparison of the simulation results of bond graph model with the Modelica model indicates that the model predicts the dynamic behavior of the heat exchanger well.

Future developments will include developing bond graph models of centrifugal pump, regulating valve, feeding on-off valve, and pipes for nuclear power plants. The main objective is to study the observability, initial conditions, structural inversibility by physical structural analysis to improve systems diagnosis and operation.
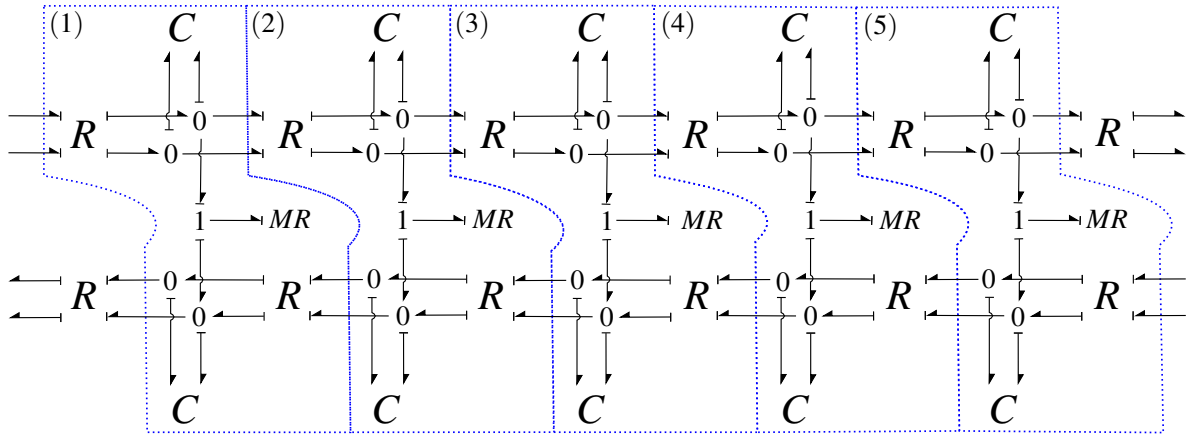
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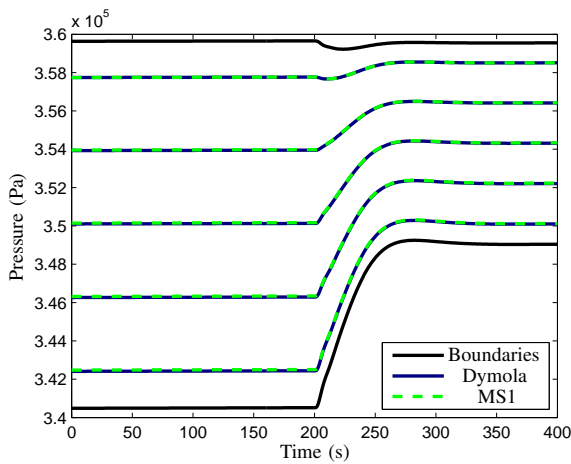Figure 10: Pseudo bond graph of the plate heat exchanger (counterflow)

Figure 11: Comparison of bond graph model with Dymola model in hot flow
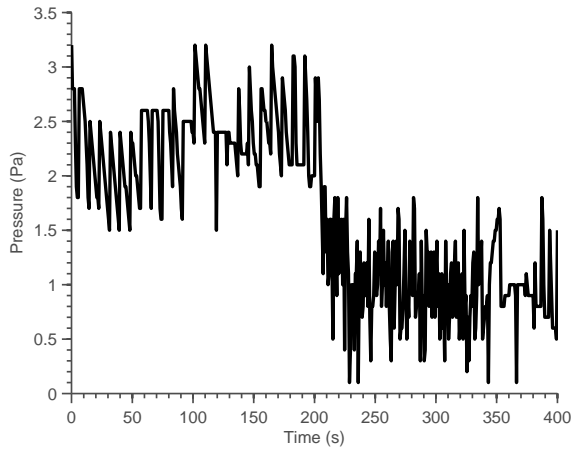

Figure 12: Error between obtained pressures (Dymola and MS1) at first volume

APPENDIX

The following algorithm has been developed for pressure calculation in the C-accumulator of the heat exchanger. Based on the density function it was developed to determine water pressure in terms of specific enthalpy and density. The structure of the algorithm is shown in Algorithm 1. This is a very fast and accurate method in all regions except solid region of the water. This algorithm is used because, as far as we know (Wagner and Kretzschmar 2008), there are no tables to calculate the water pressure directly in terms of specific enthalpy and density. In the solid region, the calculation of the water pressure is based on incompressibility consideration.

> **Data:** ρ, h;
> $p_{min} = 0.00611657$; $p_{max} = 1000$;
> $p_s = 100$; $\rho_s = \rho_s(p_s, h)$;
> **while** $|\rho - \rho_s| > 1E - 7$ **do**
> $\rho_s = \rho_s(p_s, h)$;
>   **if** $\rho_s \geq \rho$ **then**
> $p_{max} = p_s$;
>   **else**
> $p_{min} = p_s$;
>   **end**
> $p_s = (p_{min} + p_{max})/2$;
> **end**
> $p = p_s$;

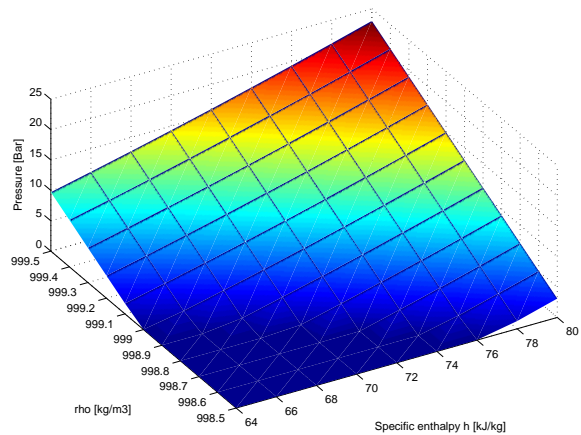**Algorithm 1:** Calculation of the water pressure using the density function

Figure 13: Pressure as a function of h and ρ

Figure 13 shows how the thermodynamic propriety of the water pressure is very sensitive to small changes in density of the water.

NOMENCLATURE

λ_m	Metal thermal conductivity	P	Pressure
$\dot{m}$	Mass flow rate	ΔP	Pressure drop
h	Specific enthalpy	ρ	Density
ΔS	Heat transfer surface	C_p	Heat capacity
L	Heat exchanger length	T	Temperature
n	Number of plates	Pr	Prandtl number
μ	Dynamic viscosity	$\dot{Q}$	Heat flow rate
e_m	Metal wall thickness	$\dot{W}$	Thermal power
K_I	Heat transfer coefficient	V	Volume
N	Number of segments	Nu	Nusselt number

Chosen abbreviations

PHE	Plate Heat Exchanger
BG	Bond Graph
FVM	Finite-Volume Method
MB	Moving Boundaries

Subscripts

I	in the volume I	$b = c$	Cold side
i	entering the volume I	$b = h$	Hot side

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