# OpenModelica implementation of PCM ventilation unit.

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## Abstract

The OpenModelica-compatible package for a specific type of PCM ventilation unit is developed. The model is built of components from Modelica Standard Library (MSL) and IBPSA library as a part of Termonet library aiming at opensource models for household owners and utility companies to help to integrate sustainable technologies into district energy networks. The PCM heat exchanger model instantiating IBPSA library fluid components are compared to MSL PCM implementation with no fluid components and the Matlab-inspired textual Modelica model. MSL-based and textual models are shown to produce identical results, whereas account of fluid properties leads to only a slight deviation. This can motivate the use of the MSL and IBPSA-based models as a control and emulator models in Model Predictive Control. Essential fluid models from IBPSA library can be compiled and simulated using OpenModelica with minimal tuning, which shows the potential of the IBPSA library as a fully opensource building performance simulation tool.

*Keywords: OpenModelica, Phase change material, HVAC, sustainable energy, building energy modeling*

## 1 Introduction

Modelica is an excellent tool for grey-box modeling of novel technologies and can be used for analysis of their integration into modern energy market. When the PCM heat exchangers are a technology of choice, their modeling attracts large interest both in HVAC and Modelica communities (Faraj, Khaled et al., 2019; Qiao, Nabi et al., 2019; Emhofer, Barz et al., 2018; Fiorentini, Cooper et al., 2015). Due to its efficiency and energy flexibility, PCM heat exchangers can be anticipated to gain popularity at the single household level, which already happened in some locations in form of PCM underfloor heating (Thermavar, 2019). It is therefore important to have a simple model, which can be used by a residential building management system to optimize energy consumption and create market value.

To promote larger availability of such building simulation tools, IBPSA Project 1 creates open-source software that builds the basis of next generation computing tools for the design and operation of building and district energy and control systems (IBPSA project 1, 2019). Dymola (Dassault Systemes, 2019) is the most popular tool among the project contributors for its robustness, convenience and good documentation available. Multiple Modelica models are developed in Dymola to analyze PCM heat exchangers for building applications (Halimov, Lauster et al., 2019; Maccarini, Hultmark et al., 2018). Dymola license can however be expensive for a private household, therefore, there is a need for opensource modeling tools to promote individual integration of sustainable technologies.

On the other hand, OpenModelica (2019) proposes a free of charge platform, where the models developed in the IBPSA project 1 can be tried out by anyone familiar with Modelica Language. The obstacle, however, for doing so is the difference in compilation of Modelica code and initialization of compiled models supported by OpenModelica and Dymola. This especially concerns fluid components, which are the primary interest in building performance simulation. In this paper the challenge is addressed and the PCM heat exchanger model was developed to be compatible with OpenModelica. The model is built using MSL library tools with added IBPSA components and included in Termonet library developed at the Center of Energy Informatics, University of Southern Denmark.

## 2 Methodology

### 2.1 PCM ventilation unit model

The implementation of PCM heat exchanger as a core component of the ventilation unit is based on the theory developed by Ljungdahl et al. (2020) and adopted here to build quasi-RC model shown in Figure 1.

The idea of the quasi RC implementation is to convert the nonlinear differential equation of the PCM heat exchanger to the usual state-space form and model it by using the standard thermal RC-components from MSL. The non-linear 0D PCM heat exchanger equation has in the simplest case the following form:

$$C(T)\,\frac{dT}{dt} = UA\,(T_f - T),$$

where T is the PCM temperature, C(T) is the temperature-depend PCM heat capacity, UA is the flow-dependent convective heat transfer coefficient and $T_f$ is the temperature of the heat exchanger fluid. C(T) depends on the phase transformation processes occurring in PCM and cannot therefore be modeled without considering the heating/cooling thermodynamic cycle. This fact makes the thermal storage in the PCM dependent on temperature in a complex way and cannot be described by linear thermal mass component. However, by rewriting the equation in the form

$$C_s \frac{dT}{dt} = (T_f - T)/R(T),$$

where $R(T) = UA \times C_s/C(T)$ and $C_s$ is a heat capacity of the PCM solid phase, the dynamics of the system can be considered as a combination of storage in solid phase and heat loss with temperature dependent effective resistance $R(T)$.

The RC-model consisting of MSL components is shown in Figure 1, where the effective resistance is calculated from the heating/cooling cycle of the PCM. The solid phase of PCM is thermally coupled to external fluid flow (heat port in the bottom) through the MSL convection component representing the Newton's law of cooling, which accepts the calculated $R(T)$ as a time-varying input. Although this approach may appear artificial, it is adequate to the physics of the process, since the convective heat transfer in real PCM heat exchanger depends on the thermodynamic state of the system. The parameters of the thermodynamic state, in their turn, depend on the system location on the heating and cooling curves at a specific moment of time.

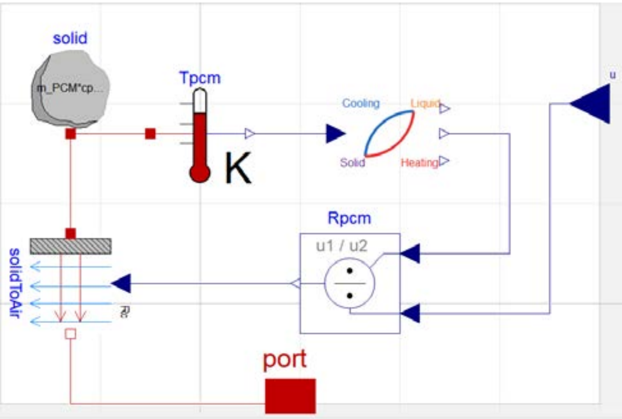


**Figure 1.** MSL-based component of PCM heat exchanger (Termonet library).

The temperature independent part of the effective resistance is calculated as the regular convective heat transfer coefficient based on fluid flow properties modeled in the external PCM ventilation unit component shown in Figure 2.

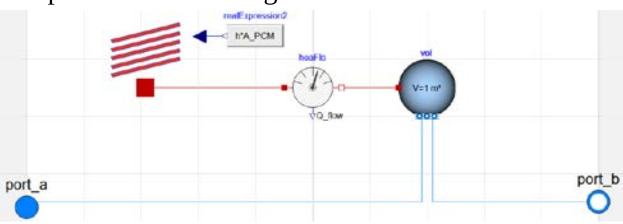


**Figure 2.** Termonet- and IBPSA-based PCM ventilation unit component.

In this component, the above PCM heat exchanger is located in the upper left corner and has a red icon representing the PCM plates separated by the air gaps.

Heat port of the heat exchanger is connected to the fluid mixed volume component from the IBPSA library (International Building Performance Simulation Association, 2019) and its causal input port is connected to the real expression source block from MSL. The block supplies the convective heat transfer coefficient value calculated based on the air flow properties extracted from the inlet fluid port, denoted as **port_a** in the figure.

## 2.2 Test models

Two models were created to test the difference between the MSL PCM implementation of Figure 1 with prescribed temperature and mass flow rate boundary conditions against the same component coupled to the IBPSA fluid models in Figure 2.

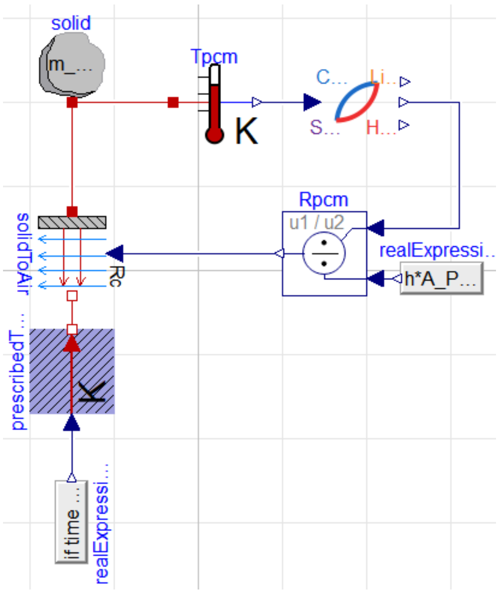


**Figure 3.** Testing of the PCM heat exchanger component.

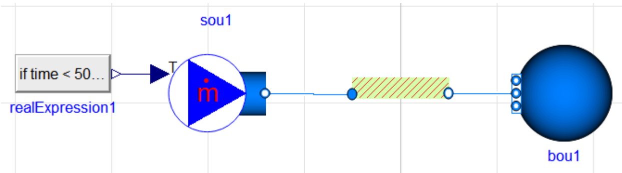


**Figure 4.** Testing of the PCM ventilation unit component.

The first test model is shown in Figure 3 in expanded form to emphasize that it is built completely from MSL components. The second test model is shown in Figure 4, where the PCM ventilation unit component (green rectangle) is connected to the prescribed mass flow rate source and the fixed pressure/temperature sink. These two implementations are further compared to the third test model, which is the "flat" implementation obtained by writing all parameters and equations in a single Modelica model and simulating it directly. This "flat" model is a direct translation of the Matlab model validated by Ljungdahl et al. (2020) and is limited to the fixed mass flow rate values.

In all three models, the piecewise temperature boundary condition as function of time is supplied to the system shown as a step function in Figure 5 (blue solid line). The same condition is used in all test models to maintain the same reference conditions when comparing the three implementations.

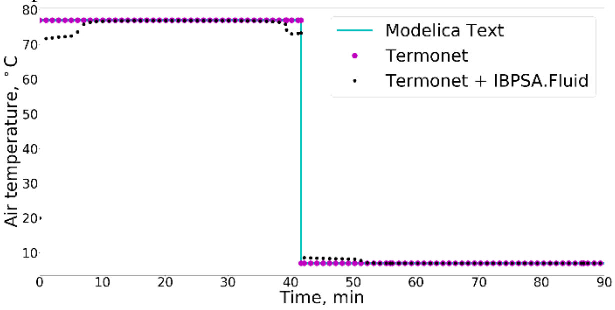


**Figure 5.** Air temperature profile used for model testing.

In the Termonet (first) and textual (third) test models, this temperature is used as a fixed far-field air temperature, when calculating the amount of heat convected in the heat exchanger. In the Termonet + IBPSA (second) test model, this boundary condition prescribes the temperature of the air flowing into the mixed volume. However, a part of heat transferred from PCM to the air is stored in the mixed volume, changing the momentary values of temperatures and their derivatives both in the solid and in the outflowing air compared to two other test models.

This fact is reflected in the distorted shape of the fluid temperature profile in Figure 5 compared to the step profile prescribed at the inlet. In order to initialize the three test models in the same state of the phase transition, the "full" PCM temperature in the textual model is set equal to the solid phase temperature $T_s = 5$ °C used to initialize other test models. To make the two initializations equivalent, it was assumed that all PCM layers in the heat exchanger are initially in the solid state. This implies that the heating curve of the thermodynamic cycle is activated at the simulation start and the temperature increases as simulation progresses.

## 3 Results and discussion

The comparison of OpenModelica simulation results produced by the three implementations of the PCM ventilation unit are shown in Figure 6. The temperature of the solid material is increasing until the simulation time reaches 2500 s (42 min), at which point the jump in the curves in Figure 5 occurs. Beyond this moment, the thermodynamic cycle inside the material enters a cooling process and gradually returns the material to its solid state.

If at least 0.999 of the total PCM is converted to liquid, which is true in Figure 6, the transition from the heating curve to the cooling curve accompanies the temperature jump. This transition is modeled within the cooling/heating cycle block in Figure 1 depending on the liquid fraction. After the cooling process converts all material back into solid, the similar transition occurs from cooling curve to heating curve (not shown). This induces hysteretic behavior of the PCM material by changing its state periodically between the solid and the liquid phase. If, however, the percentage of fluid is lower than 0.999 at the time of the jump, the cooling occurs along the same (heating) curve and no hysteresis is observed.

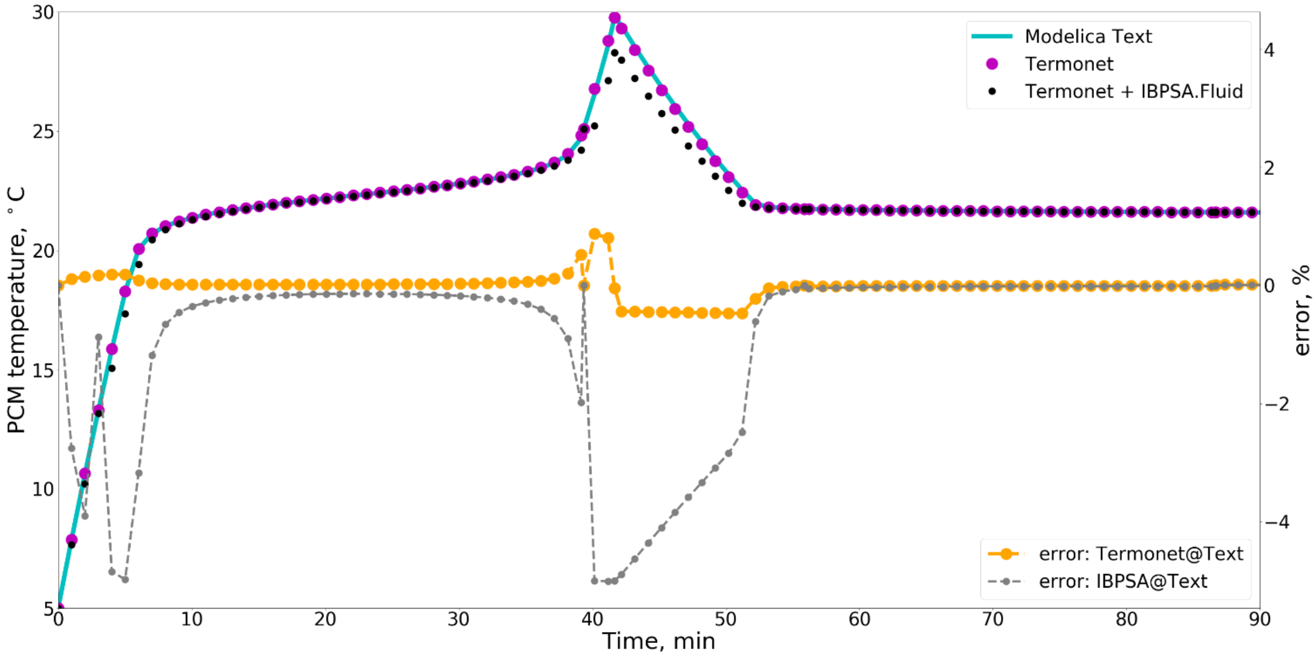


**Figure 6.** PCM temperature as function of time corresponding to the three test models: Termonet (MSL-based), IBPSA.Fluid and "flat" textual MSL model.

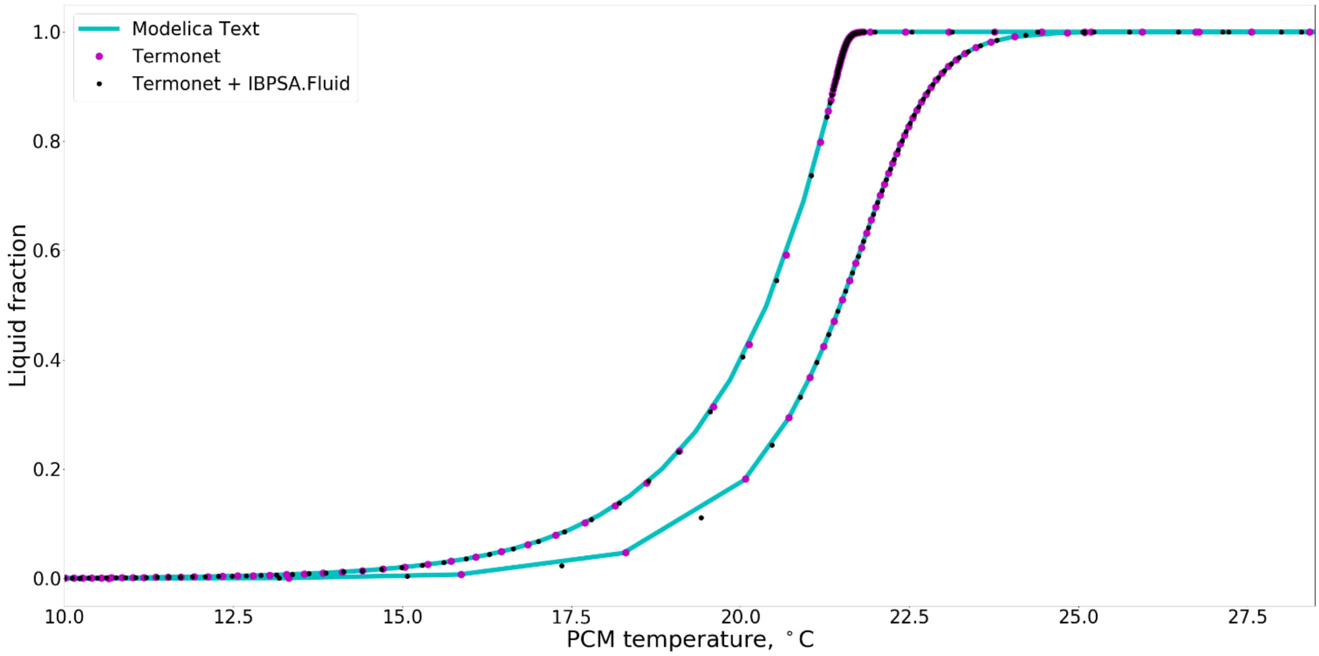


**Figure 7.** Comparison of PCM liquid fraction in the three implementations.

Figure 6 shows that results of the Termonet test model (solid cyan curve) and the textual MSL test model (magenta dots) are in good agreement with a relative error staying below 1% (orange dots). The results of the Termonet model with added IBPSA fluid components (black dots) experience larger deviations from the textual model, which is indicated by the relative error increase beyond 5%. As was mentioned in previous section, this happens due to the heat storage included in the mixed volume, which lumps together the air in the gaps between PCM plates. This deviation may be important if the ventilation unit component is a part of the white-box model. However, in model predictive control applications, this difference is less important, since the parameters of the quasi-RC model can be dynamically calibrated from the measured data or from the data simulated by a validated white-box model.

To illustrate that the models adequately reproduce PCM physics, the liquid fraction is shown in Figure 7 as a function of the PCM/solid temperature through one full cycle of phase transformation. The basic hysteresis loop is reproduced associated with heating and cooling curves discussed above. As for the temperature curve, the liquid fraction values are closer for the Termonet and textual implementations, whereas the model with IBPSA.Fluid components deviates at certain points of the cycle. The overall character of the curve is however unchanged and allows to consider all three as equivalent grey-box implementation to be applied in simulation and model-predictive control.

## 4 Conclusion

In this paper, the opensource Termonet library package for a specific type of PCM ventilation unit has been developed, compiled and simulated in OpenModelica. The developed heat exchanger model using MSL and IBPSA libraries is verified against the “flat” Modelica model reproducing the validated Matlab code. Comparison of the models with and without the fluid components shows minor deviations due to the included storage effects in the fluid system. The model is a grey-box quasi-RC model, where the solid capacitance and PCM-air convective heat transfer coefficient can be estimated to fit the measured time series. Heating and cooling curves’ parameters can be also accessed to be estimated or optimized, if different thermodynamic cycles need to be compared.

It has been demonstrated that the IBPSA project 1 library components can be used for fluid-based heating without proprietary license. The produced model can be converted to the Function Mockup Unit and used for parameter estimation and optimal control due to small simulation time and acceptable accuracy. It can be useful for private households with PCM ventilation systems to increase its efficiency and flexibility and is planned for MPC implementation in future work.

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