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MoBTES – A new Borehole Thermal Energy Storage model in Modelica

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ABSTRACT

The modeling language Modelica has gained a lot of popularity over the last years due to its conceptual advantages including an object-oriented equation-based design and multi-domain applicability. It has been frequently used for modeling Solar District Heating Systems. However, the consideration of geothermal storage systems is complicated due to a lack of open source and tool-independent Borehole Thermal Energy Storage (BTES) models. To address this problem, a new Modelica BTES model – MoBTES – was designed, using the superposition of the local thermal diffusion process around a single borehole heat exchanger (BHE) and the global temperature field of the storage. The model is radial symmetric and requires therefore much less computational effort than fully discretized 3D models. Moreover, to allow for the consideration of dynamic storage operation scenarios, a Thermal Resistance and Capacity Model (TRCM) of the BHEs is implemented. All model components are derived from elements from the Modelica Standard Library and a strict object-oriented approach was realized, resulting in a tool-box for thermal underground storage systems with a high reusability and extensibility. First simulations show a good fit to the results of established FEM models, especially for large BTES systems, while reducing the computation time significantly.

1. INTRODUCTION

Borehole Thermal Energy Storage Systems are suitable for the large-scale storage of thermal energy over periods of several months, thus facilitating seasonal storage of e.g. solar thermal energy or waste heat (Welsch *et al.*, 2018). For an efficient operation of those systems a careful system design, based on transient numerical system simulations is imperative. A language for multi-domain modeling and simulation of physical systems is Modelica. Due to its intuitive physical modeling approach and conceptual advantages, like being object-oriented and equation-based, it has gained a wide popularity over the last years. While there are numerous analytical and numerical modelling approaches for the stand-alone assessment of BTES (e.g. Schulte *et al.*, 2016), only very few of those models are suited and implemented for transient system simulation software tools (Pahud and Hellström, 1996; Picard and Helsen, 2014). One approach to this problem is the coupling of Modelica and simulation software tools with BTES modeling functionality, like Finite Element Method (FEM) tools (Welsch *et al.*, 2017). This approach enables the use of dedicated and proven BTES models, but results in a high computational effort and is thus not suited for large parameter studies. To enable efficient simulation of BTES in Modelica, a model was created which is in compliance with the Modelica language specification 3.4 (Modelica Association, 2018) and can therefore generally be used in arbitrary Modelica simulation environments. The model extensively utilizes the object-oriented modeling approach, to allow for a high reusability of the BTES model components and an easy extensibility. The applied model reduction approaches result in a model with high computational efficiency, which enables large parameter studies.

2. METHODOLOGY

2.1. Model reduction approach

The proposed model considers conductive heat transport and neglects all other processes, besides the convective transport inside the BHEs. The heat diffusion process inside the storage is thus generally described by Fourier's law of heat conduction:

$$\rho c \frac{\partial T}{\partial t} = \nabla * \lambda \nabla T + Q \quad (1)$$

The simultaneous and accurate representation of the heat transfer processes between the heat carrier medium inside BHEs and their close vicinity, as well as the heat transfer between multiple boreholes and their surroundings constitutes a challenge, due to their different scales and characteristics. Therefor they are often considered separately resulting in the two sub-models called the local problem, which covers the thermal diffusion process in and around single BHEs and the global problem, which thermally connects the BHEs and the underground surrounding the storage volume (Eskilson and Claesson, 1988; Hellström, 1991). The coupling of the two sub-models is achieved by superposition. This approach facilitates a numerically efficient simulation, while ensuring a sufficient level of accuracy and has been applied in many BTES models (Diersch *et al.*, 2009; Picard and Helsen, 2014; Schulte *et al.*, 2015). The proposed MoBTES model therefor takes this approach and applies a number of additional model order reduction (MOR) techniques, to further increase the computational efficiency, resulting in two TRCM models (global & local) which are thermally connected to each other. TRCMs divide bodies into smaller volumes, each with its mass lumped into one single point at its center of mass, representing its volume's thermal capacity. The connection between those lumped masses is done by thermal resistors, which allow for the heat exchange between adjoining volumes by thermal diffusion.

The basic concept of the MOR is similar to the techniques presented by Hellström (1991) and revives the idea of Franke (1998) to implement them in Modelica. The main ideas are:

1) reducing the 3D heat diffusion process of the BTES to 2D due to its symmetry
2) reducing the number of modeled BHEs (local problems) due to their similarity
3) assuming that the overall heat transport between BHEs and the surrounding is mainly driven by the average temperatures of the local problems
4) assuming that the actual shape of the storage volume affected by a single local problem is less important for the thermal energy transfer between BHEs and their surrounding ground than the size of the affected volume
5) reducing the 3D heat diffusion process around BHEs to 2D due to the symmetric shape of the heat plume surrounding BHEs, allowing their representation by TRCMs

Thermal energy storage systems are usually most efficient when they have a small surface-to-volume ratio, favoring compact and symmetric storage geometries. In the case of BTES systems a cylindrical shape is common. The axial symmetry of the cylindric BTES volume allows for a reduction by one dimension (see Fig. 1-1). Assuming a ring-shaped distribution of the BHEs inside the storage volume and a lack of physical effects like groundwater flow, which hinder symmetry, the BHEs which share a common ring can be considered to have an equal behavior and must therefore not be modeled individually (see Fig. 1-2). Furthermore, the global problem's heat transfer between the different rings of the storage volume and the surrounding, is assumed to be mostly driven by the volume elements average temperature, rather than their actual temperature distribution (see Fig. 1-3).

The local problems temperature distribution, which results from the heat transfer between a single BHE and its surrounding volume element can be modeled very efficiently by using the finite line source approach as presented in (Carslaw and Jaeger, 1959). This approach allows for the analytical calculation of the temperature distribution of a heat source with a negligible radius in comparison to its length inside a cylindrical volume. In contrast to this, the actual shape of the volume which can be assigned to one single BHE, has not a circular cross section like a cylinder. However, for the average temperature inside the volume element, which is needed for the coupling between the local and global problem, the actual shape of the cross section is again much less important than the volume affected by the BHE (see Fig. 1-4). Since the heat transport of the global problem is only dependent of the average volume temperature and Eq. 5-8 give us an expression for the local problem's heat transfer, which contains the average volume temperature, it is possible to connect the two model parts.

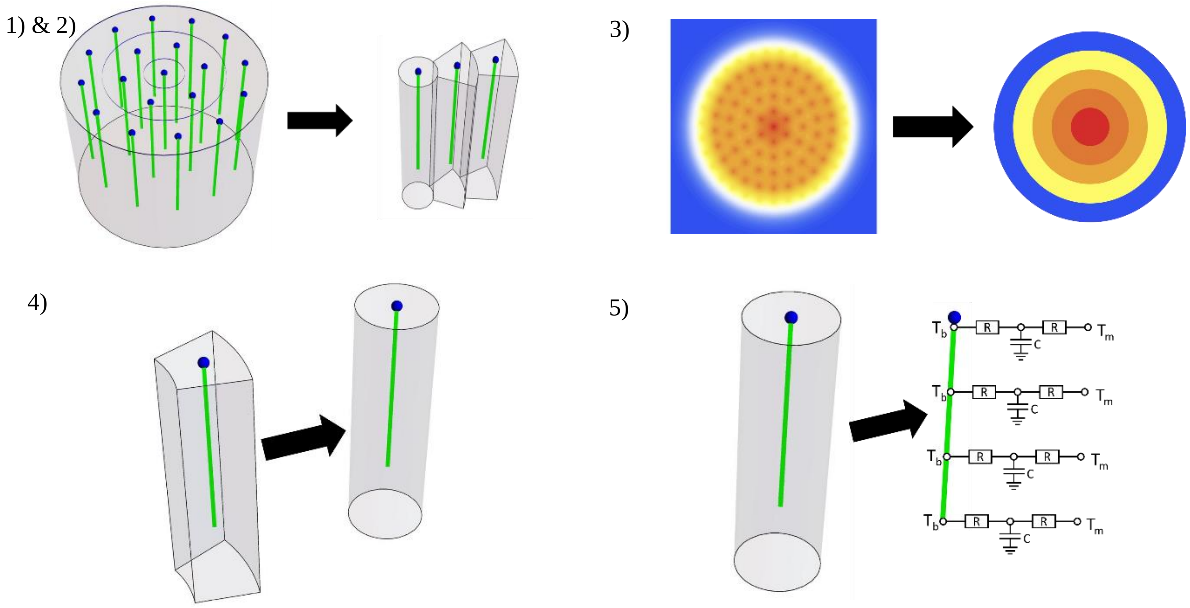

Figure 1: The main model reduction approaches in MoBTES (green: BHEs)

As shown by Carslaw and Jaeger (1959), the line source approach can be used to derive an expression for the time- and space-dependent temperature response to a step pulse heat flux $\dot{Q}_{sf}$ (sf=steady flux, see Eq.2) inside a cylinder with the radius r_{eq}. The first term inside the brackets on the right-hand side of Eq. 2 contains the volume thermal capacity C and can be interpreted as the increase of the average volume temperature T_m (Eq. 3). The second and third term can be interpreted as thermal resistances R between the heat source at r=0 and a specific point at radius r. Both their shapes are defined by the parabolic characteristics of the underlying heat equation. The former represents the steady state part of the thermal resistance R_0 and is thus independent of time (Eq. 4) and the latter can be interpreted as the transient part of the thermal resistance. The transient part is given by a sum with rapidly decreasing time constants for succeeding elements of the sum. Since BTES systems are generally operated rather steadily, only the first term with the biggest time constant τ_1 is considered. (Franke, 1998)

$$T(r,t) = \dot{Q}_{\mathrm{sf}} \left[\frac{1}{C} t + R_0(r) - \sum_{i=1}^{\infty} R_i(r) e^{-\frac{t}{\tau_i}} \right] \tag{2}$$

$$T_m(t) = \frac{\dot{Q}_{\mathrm{sf}}}{C} t = \frac{\dot{Q}_{\mathrm{sf}}}{c_p \rho \pi ({r_{eq}}^2 - {r_b}^2)} t \tag{3}$$

$$T_o(r) = \dot{Q}_{\mathrm{sf}} R_0(r) = \frac{\dot{Q}_{\mathrm{sf}}}{2\pi\lambda} \frac{{r_{eq}}^2}{{r_{eq}}^2 - {r_b}^2} [\ln(\frac{r_{eq}}{r}) - \frac{3}{4} + \frac{2r^2 - {r_b}^2}{4{r_{eq}}^2} + \frac{{r_b}^2}{{r_{eq}}^2 - {r_b}^2} \ln(\frac{r_{eq}}{r_b})] \tag{4}$$

Eq. 3 and 4 can be used to calculate the difference between the borehole wall (T(r$_b$,t)) and the average volume temperature at steady state (Eq. 5-8). This temperature difference is equivalent to the temperature difference between the local and the global model part and is therefore needed to calculate the heat flux between those two model parts. (Franke, 1998)

$$T(r_b, t) - T_m(t) = T_0(r_b) \tag{5}$$

$$= \frac{\dot{Q}_{\mathrm{sf}}}{2\pi\lambda} [(\frac{{r_1}^2}{{r_{eq}}^2 - {r_b}^2})^2 \ln(\frac{r_{eq}}{r_b}) - \frac{3{r_{eq}}^2 - {r_b}^2}{4({r_{eq}}^2 - {r_b}^2)}] \tag{6}$$

$$= \frac{\dot{Q}_{\mathrm{sf}}}{2\pi\lambda} [\ln(\frac{r_{eq}}{r_b}) - \frac{3}{4}], \qquad r_{eq} >> r_b \tag{7}$$

$$= \dot{Q}_{\mathrm{sf}} * R_{\mathrm{sf}} \tag{8}$$

Finally the thermal capacity C$_{sf}$ is introduced, to consider the biggest time constant of the dynamic resistance (Eq. 9), which allows for a simple TRCM for the local problem (Fig. 1-5). (Franke, 1998)

$$C_{\mathrm{sf}} = \frac{\tau_1}{R} \simeq \frac{{r_{eq}}^2}{15 a R_{\mathrm{sf}}} \tag{9}$$

2.2. Modelica component library

With the implementation of the above-mentioned modelling approaches, a Modelica component library was created. The models are built using components from the Modelica standard libraries Thermal FluidHeatFlow and HeatTransfer. The designed components are in conformity with the Modelica language specification (version 3.4) and have been successfully tested in SimulationX version 4.0 (ESI ITI, 2017) and OpenModelica version 1.13.2. (Fritzson *et al.*, 2005). Fig. 2 shows a detail of the structural view of a MoBTES model, with the structural views of the components for the local and the global problem. The BTES model parameters for heat exchangers, grouts, location lithologies and different ground types are stored in according parameter record collections.

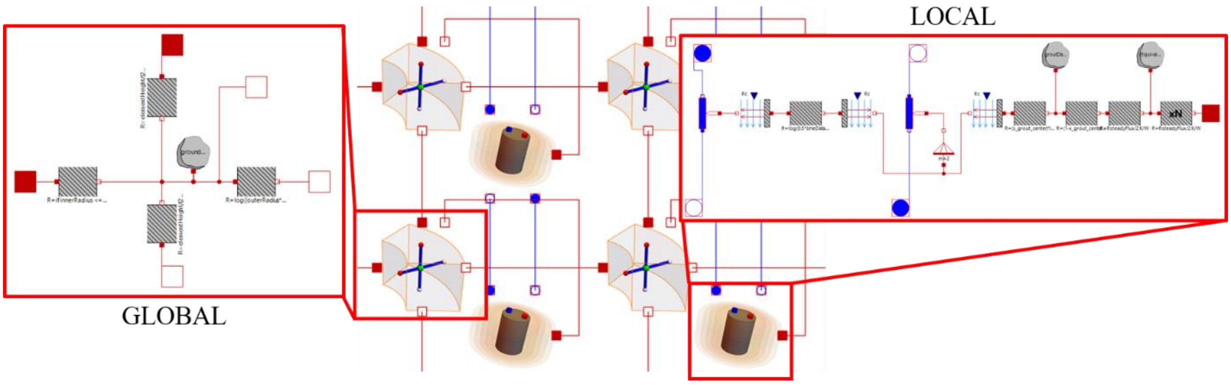

Figure 2: Partial structural view of a MoBTES model and the contained models for the global and local problem (red connections: conductive heat transport; blue connections: convective heat transport).

2.3. Benchmark

For a first assessment of the accuracy of MoBTES a benchmark study was carried out, in which four different BTES system were simulated with MoBTES in SimulationX, FEFLOW (Diersch *et al.*, 2011) and DST in TRNSYS (Pahud and Hellström, 1996). The FEFLOW model was considered to be the most accurate model and is therefore regarded as the benchmark. The model settings can be seen in Table 1. The four different BTES systems, consisting of 7, 19, 37 and 62 BHEs, were simulated over a period of 20 years. The BTES were operated with a constant volume flow of 3 l/s per BHE and were charged during the first 182.5 days of the year and discharged over the remaining 182.5 days. Inlet temperatures were set to 80 °C for the charging period and 20 °C for the discharging period.

Table 1: Settings for the benchmark study

Parameter description	Value	Parameter description	Value
Number of BHEs	7,19,37 & 62	Outer pipe outer diameter	127 mm
Length of BHEs	100 m	Outer pipe wall thickness	5.6 mm
Depth of BHE heads	1 m	Pipe thermal conductivity	54 W/(m K)
Min. distance between BHEs	5 m	Inner pipe outer diameter	87.2 mm
BHE type	coaxial	Inner pipe wall thickness	5.5 mm
Ambient temperature	10 °C	Grout thermal conductivity	2 W/(m K)
Geothermal gradient	0.03 K/m	Grout thermal capacity	1300 J/(kg K)
Soil thermal conductivity	1.4 W/(m K)	Grout density	1500 kg/m³
Soil density	2500 kg/m³	Constant volume flow per BHE	3 l/s
Soil thermal capacity	800 J/(kg K)	Constant charging temperature	80 °C
Borehole diameter	152.2 mm	Constant discharging temperature	20 °C

3. RESULTS

The results for the average thermal energy stored into and out of the different BTES models can be seen in Fig. 3. Generally, the FEFLOW models and MoBTES models show very similar results, while the DST models in TRNSYS result in smaller charged and discharged amounts of thermal energy. The larger difference between FEFLOW and MoBTES models on the one side and the DST models on the other side could be partly caused by the different ways the models are set up. While in FEFLOW and MoBTES the storage geometry is defined by positioning the individual BHEs i.e. defining their distances, a DST model in TRNSYS is defined by setting the affected storage volume and number of BHEs and automatically distributing the BHEs inside this volume.

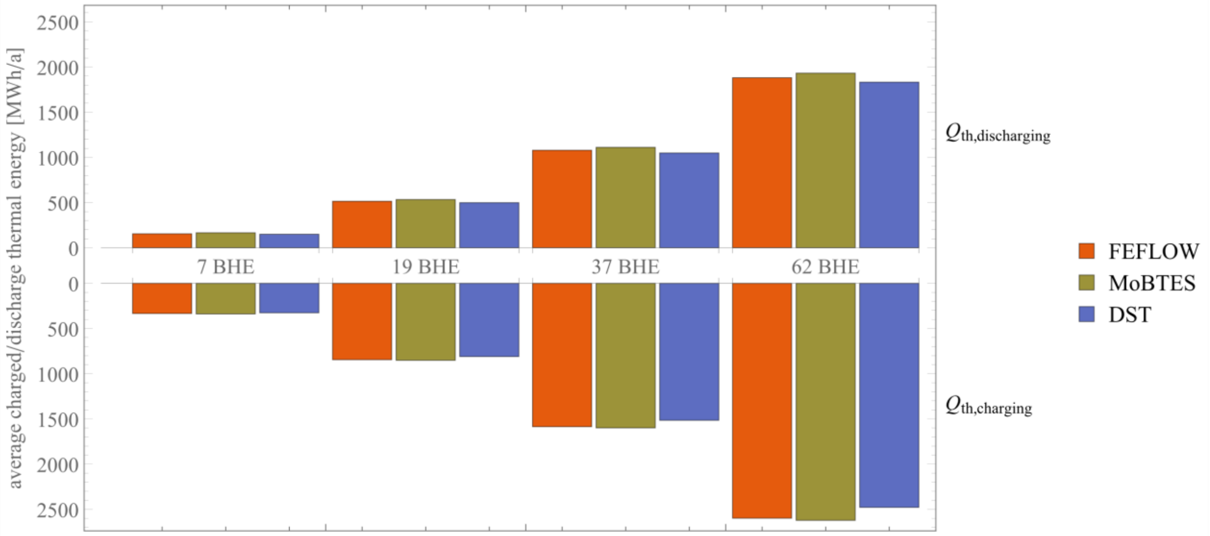

Figure 3: Average charged and discharged thermal energy for different BTES sizes

In general, the model reduction approaches applied in MoBTES are more valid for large BTES systems which consist of many BHEs. The line source representation of the BHEs is based on the assumption of a symmetric temperature distribution around BHEs, which is more accurate or BHEs on inner rings of the BTES, but less accurate for BHEs on the outer ring. Since the ratio of BHEs on the outer ring to BHEs on inner rings decreases with the size of a BTES, the MoBTES modelling approach is assumed to be more accurate for large systems. The comparison of the relative difference between FEFLOW and MoBTES for different BTES sizes confirms this hypothesis (see Fig. 4). Especially the amount of thermal energy charged into the storage shows a big deviation for the smallest system, which consists of seven BHEs and decreases with increasing system size. The deviation of discharged thermal energy seems to be less dependent on the storage size. For all observed systems MoBTES overestimates the charging as well as the discharging, whereby the discharging shows larger deviations. This results in a generally higher turnover of thermal energy and an overestimation of the storage efficiency.

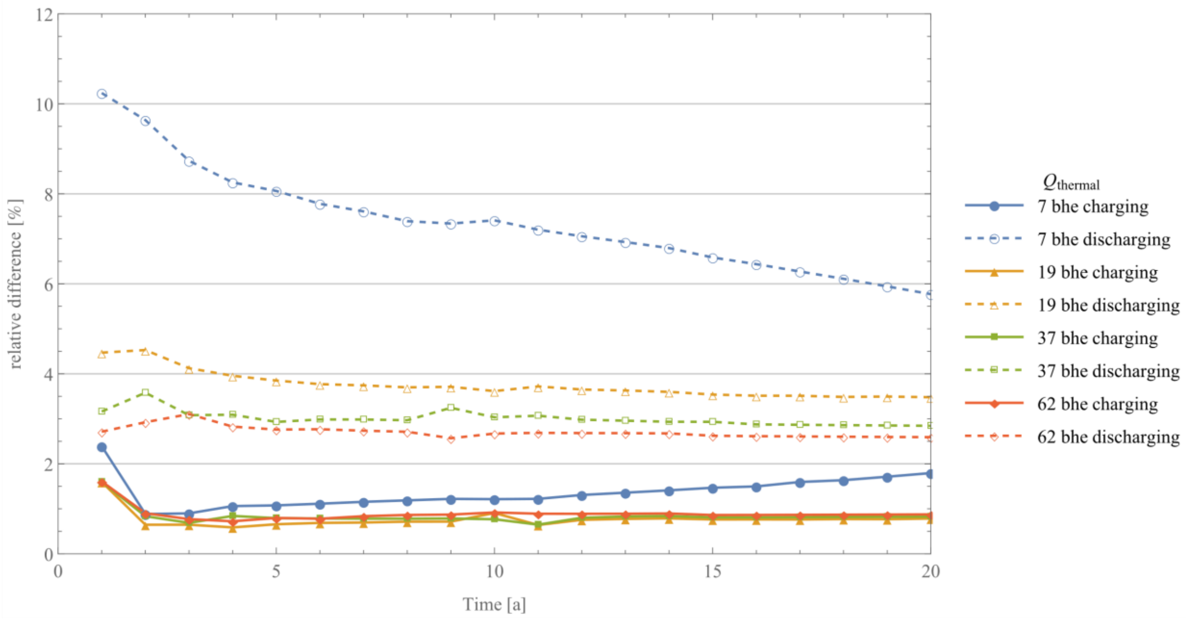

Figure 4: Relative difference between FEFLOW and MoBTES for the charging and discharging of BTES with different sizes (Q_{MoBTES}/Q_{FEFLOW})

Fig. 5 shows the response to the initial step response for different BTES models over the first 10 days. Exemplary the models consisting of 62 BHEs are depicted. The graph shows that the MoBTES model cannot simulate the initial transient behavior of the BTES accurately and shows similar results to the DST model after about five days.

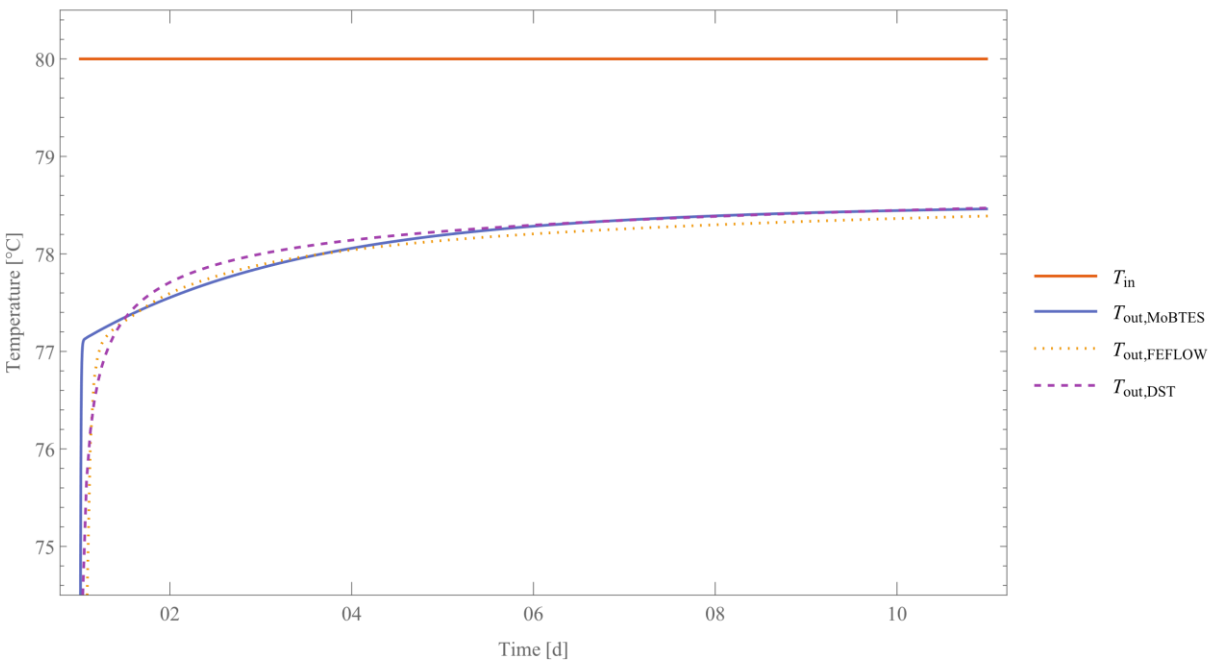

Figure 5: Inlet and outlet temperatures of the BTES models consisting of 62 BHEs over the first 10 days of operation

4. CONCLUSIONS

The presented MoBTES model allows for a computational efficient simulation of BTES systems in Modelica. First results show a good fit of the stored and extracted amount of thermal energy between MoBTES and established BTES simulation tools like FEFLOW and the DST model in TRNSYS. For systems with a larger number of BHEs the deviation could be shown to be below 3 % for discharging and below 1 % for charging. The analysis of the model's response to a step pulse revealed significant differences between the outlet temperatures of MoBTES and FEFLOW. To enhance the accurate simulation of transient system operation, the model should be further improved in this regard. In addition to the presented benchmark study for different storage system sizes, further parameters like BHE length, BHE type or ground parameters should be investigated.

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