International Journal of Smart Grid and Clean Energy

ATHLET simulation code: Model validation of a thermal high-performance storage system

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Abstract

The volatile provision of electricity through renewable energies makes it necessary for thermal power plants, especially in Germany, to operate in a highly flexible manner and thus react to the dynamic requirements of the electricity market. One way of achieving this flexibility is to integrate a high-performance thermal storage system. The function of the thermal high-performance storage system is to store (load) heat in the event of an excess supply of electricity and to release (discharge) heat in the event of a shortage of electricity. In this way, thermal high-performance storage systems contribute to stabilizing the transmission networks and promote the further expansion of renewable energies. The overall goal is to develop a simulation-supported, validated design tool for thermal high-performance storage. This paper presents the current state of development of the dynamic simulation model for a thermal high-performance storage system and the results of the validation. The creation of the dynamic model is realized with the ATHLET simulation code (Analysis of Thermal-hydraulics of LEaks on Transients). The dynamic model of a thermal high-performance storage system corresponds to the displacement storage and other components of the thermal energy storage system (THERESA) in the Zittau power plant laboratory, a test facility at the Zittau/Görlitz University of Applied Sciences. The validation of the generated dynamic simulation model is carried out with the experimental data based on specifically designed testes adapted to thermal power plants and the EBSILON®Professional system. A first validation was successfully completed. In the next step, further experimental tests will be carried out with the THERESA test facility, simulated parallel with EBSILON®Professional, in order to validate the dynamic ATHLET simulation model for a correspondingly large parameter field.

Keywords: Thermal high-performance storage system, dynamic simulation model, ATHLET simulation code, displacement storage, steam storage, high pressure, thermal energy storage

1. Introduction

Due to the highly volatile feed-in of electricity in Germany and throughout Europe, the power plant operators currently facing the challenge of increasing the flexibility of thermal power plants without jeopardizing their efficiency and lifetime. In general, an increase of flexibility for thermal power plants can be achieved by the following measures:

- Improvement of the load change rate;
- Increase of balancing energy for network services;
- Reduction of minimum load; and
- Improvement of black start capability of thermal power plants.

The implementation of these measures requires a maximum utilization of reserves and a consistent further development of existing thermal power plants, along with the development of advanced and innovative power plant concepts.

* Manuscript received March 11, 2018; revised December 20 2018.
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doi: 10.12720/sgce.8.1.1-10

Subject of past work at the Institute of Process Technology, Process Automation and Measuring Technology (IPM) at Zittau/Görlitz University of Applied Sciences (UAS) was the development of an innovative concept to increase the flexibility of thermal power plants [1]. The essential innovation of this concept requires a feasible integration of thermal high-performance storage systems (THPSS) into power plant processes. The overall goal is to develop a simulation-supported, validated design tool for high-performance thermal storage. This paper presents the current state of development of the dynamic simulation model for a THPSS and the results of the validation.

A validated dynamic simulation model is required for simulation-based investigations and for future designs of THPPS for thermal power plants. The present paper deals with the description for development and validation of such a simulation model. The development and validation is based on experimental results, which have been obtained for the THPPS integrated in THERESA. Simulated data from EBSILON®Professional is also used for validation. There are a number of computer programs capable of a dynamic simulation of thermal power plants depending on the application at hand. None of the existing programs [2] has hitherto been used for a dynamic THPSS simulation, thus presenting an entirely new application scenario. We applied the thermo-hydraulic code ATHLET (Analysis of Thermal-hydraulics of LEaks on Transients) for the modeling of a THPSS.

In order to carry out extensive experimental investigations regarding this innovative concept to increase the flexibility of thermal power plants or THPSS, the Zittau/Görlitz UAS has developed and established the THERESA (THERmal Energy StorAge system) large-scale test facility [3]. THERESA simulates nearly all basic components and parameters of a thermal power plant process and includes a THPSS as major object of investigation.

2. Simulation Code for Model Development

2.1. EBSILON®Professional simulation code

EBSILON®Professional is a tool for the energy and process engineering design of individual components and cycle processes (open and closed). In addition to the static design for the consideration of different load cases with full and partial load calculations, in which geometrical properties of the individual components as well as essential thermodynamic data are obtained. It is possible to carry out quasi-unsteady processes in the form of time series simulation. These time series simulations can be used to model and balance different operating modes and connection options of the THERESA test facility (charge, hold, discharge). Basis of the balancing in each time step of the time series simulation is the solution of the issued system of equations according to the Gauss-Seidel method for the mass, pressure and enthalpy balance sheet ([4], [5]).

2.2. ATHLET simulation code

The ATHLET simulation code is used for modular simulations of arbitrary thermal-hydraulic systems through physical and numerical models. Moreover, ATHLET is a validated simulation code for the modelling of high transient water-steam processes in thermal power plants. The ATHLET simulation code is developed by the company GRS (German: Gesellschaft für Anlagen- und Reaktorsicherheit) in Germany.

The differential equations used in the ATHLET simulation code are based on the numerical solution of the one-dimensional conservation equations for mass, energy and impulse. The phases for liquid and steam are balanced separately in the ATHLET code [6-9]. The multi-dimensional integration of the mass, energy, and momentum balances results in six differential equations of first order; these are referred to as the 6-equation model. The momentum balances for the liquid and steam phase are combined to a total momentum balance for the examination of the liquid-steam mixture. This reduces the 6-equation model to a 5-equation model.

For the temporal integration of the thermo-fluid dynamic models and their differential equations, we use the Forward-Euler-Backward-Euler (FEBE) solver for ordinary differential equations (ODE). The Euler method requires the calculation of Jacobi matrices. ATHLET adopts the sparse matrix package FTRIX for an efficient and fast calculation of Jacobi matrices.

In general, the modelling in ATHLET occurs by physical component models, called objects. Various object types such as TFO (Thermal fluid dynamic object), HCO (Heat conduction object) and TDV (Time dependent volume) are used to model the THPSS.

3. Modelling

The THERESA test facility represents a simplified set-up of a real power plant process (open loop process) with the developed high-performance storage system (THPSS).

The developed EBSILON®Professional model contain all components of the test facility, including the storage system. The simulation software EBSILON®Professional is used for load case analysis (stationary calculations). A dynamic simulation is also possible by means of time series calculation.

The ATHLET model contains the developed and constructed THPSS of the test facility with all its thermohydraulic (two-phase flow in the mixing preheater, valve characteristic during switching processes) and geometric properties (built-in components, measuring technology) which cannot be represented in EBSILON®Professional.

3.1. THERESA large-scale test facility

Fig. 1 shows a 3D model of the THERESA large-scale test facility with its subsystems and components. The subsystems of the test facility are feed water system, preheater system, steam generation system, superheating system, pressure relief as cooling system (corresponds to the turbine in a power plant) and THPSS. Some of the components of the test facility are pumps, valves, electric heaters and pipelines. At the right of Fig. 1 is the displacement storage (DS) a THPSS component with the experimental instrumentation shown. It is shown that the DS has eleven axial measuring planes (MP). Furthermore, each measuring plane of the DS comprises four radially distributed temperature sensors. The experimental instrumentation is applied to acquire measurands for detailed information about the physical processes inside the THPSS or THPSS components. This enables an exact balancing and the creation of databases for the validation of the THPSS simulation model. The operational instrumentation is used to record relevant measurands (pressure, temperature, flow, level) for control and regulation of the system. In addition, an extensive automation ensures a high quality of the test sequences and measurement results. The subsystems and components of the THERESA test facility can almost reproduce the parameters of a thermal power plant process. It is thus possible to investigate i.a. THPSS as well as a variety of other kinds of thermal energy storages.

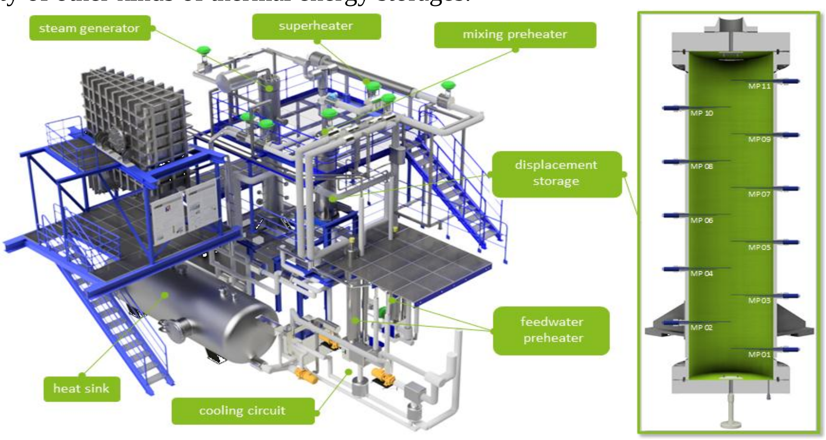


Fig. 1. 3D model of the THERESA test facility with the displacement storage.

Fig. 2 shows the THPSS components DS and mixing preheater (MP) as well as a simplified illustration of the THPSS operating modes. With the help of the DS, saturated water is charged and discharged without causing significant temperature losses. The MP is a direct heat exchanger designed specifically to provide high heat capacity during the charging and discharging processes. The heat is transferred by direct condensation of steam. There are three modes of operation: charge (a), hold (b) and discharge (c). The valves and pipelines of the THPSS are used to switch between the operating modes. The red arrows symbolize the flow direction of steam, and the blue arrows show the flow direction of feed water.

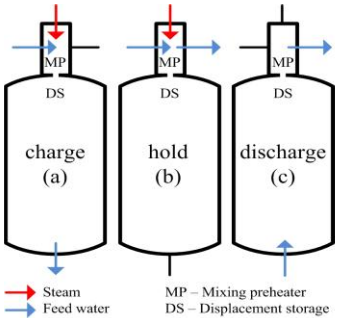


Fig. 2. Operating modes of the THPSS.

Fig. 3 shows the experimental temperature profiles for measuring levels 2, 6 and 10 of the THERESA test facility. The DS is loaded from top to bottom with hot water near saturated water conditions with low impulses. This means that the temperature in measuring level 10 (top) initially increases at the start of loading. The temperature profiles in measuring levels 6 (middle of the DS) and measuring level 2 (bottom of the DS) increase accordingly with a time delay, as the loading of the DS is carried out with low impulse (without mixing of the individual temperature layers) from top to bottom. When the DS is discharged, a flow reversal takes place, the DS is discharged from the bottom to the top, which is also low in impulses. This means that at the beginning of the discharging process, the temperature profile in measuring level 2 decreases at first, and the temperature profiles of measuring levels 6 and 10 follow accordingly with a time delay. As shown in Figure 1, the observed measuring levels 2 and 10 are not located directly on the bottom or top of the DS. The bottom and top of the DS are designed as massive flanges whose influence (heat conduction and convection) on the temperature stratification is not to be considered due to the comparability and transferability of the results to other storage systems.

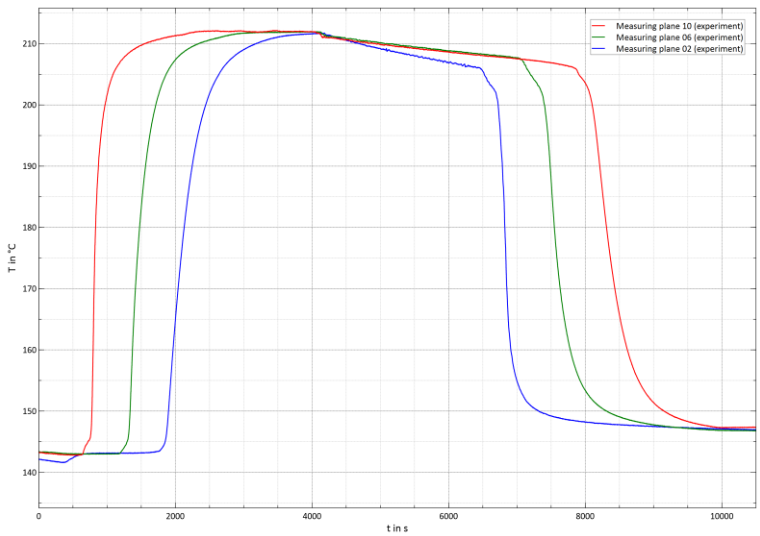


Fig. 3. Experimental data of measuring planes 2, 6 and 10 in the displacement storage.

3.2. Modelling with EBSILON®Professional – THERESA model structure and functionality

Fig. 4 shows the model of THERESA test facility in EBSILON®Professional. It contains all the main components of test facility with their geometric and thermodynamic properties. The most important components are the preheating rail with the preheaters 1W01 and 2W02, the steam generator 1B01, the superheater 1W03, the equal pressure displacement storage 2B01 with the mixed preheater 2W01, which is modelled in the form of component 9 in EBSILON®Professional [10] as a feed water tank. Further peripherals of the system such as the 3B01 and 3B02 heat sink, connecting pipelines and pumps 1P02 and 2P01 were also implemented in the model. Due to the model arrangement, it is possible to simulate and balance all operating modes of the DS (charge, hold, discharge) within a model. By means of switching operations within a time series simulation, it is possible to switch directly between charge, hold and discharge modes.

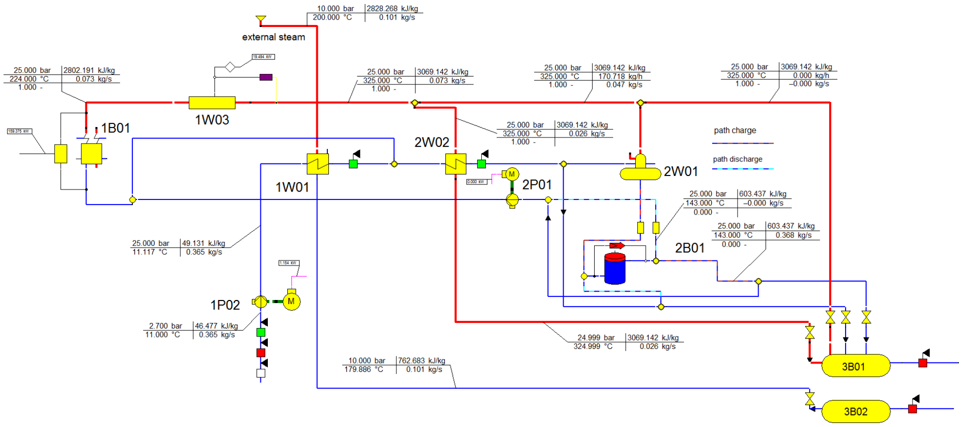


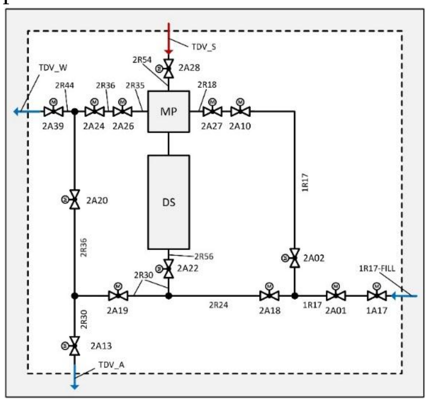
Fig. 4. Model of the THERESA test facility in EBSILON®Professional.

3.3. Modelling with ATHLET – THPSS model structure and functionality

The THPSS model development focuses on simulating thermal-hydraulic properties (e.g. flow paths, pipelines, valves). The operating modes (charge, hold, discharge) are thus optimally represented in the model. Furthermore, the positions of instrumentations were modelled in detail.

Fig. 5 illustrates the developed model structure of the THPSS. The developed model contains the DS with cover and bottom, MP with level control and the adjacent pipelines incl. control and shut-off valves.

The model takes the actual geometrical data of all components (wall thickness, insulation, etc.) into account. Furthermore, the model uses the temperature-dependent material data of the respective components.



Keywords	Labeling	Type	Simulation/Function
2W01 / H2W01	mixing preheater	TFO / HCO	flow path / wall, isolation
2W01a / H2W01a	nozzle pipe	TFO / HCO	flow path / wall, isolation
2B01a / H2B01a	cover	TFO / HCO	flow path / wall, isolation
2B01 / H2B01	storage	TFO / HCO	flow path / wall, isolation
2B01b / H2B01b	bottom	TFO / HCO	flow path / wall, isolation
1R17, 2R18, 2R24, 2R30, 2R35, 2R36, 2R44, 2R54a, 2R54b, 2R56	pipe	TFO	flow path
H1R17, H2R18, H2R24, H2R30, H2R35, H2R36, H2R44, H2R54a, H2R54b, H2R56	pipe	HCO	wall, isolation
1A17, 2A01, 2A02, 2A10, 2A13, 2A18 - 2A20, 2A22, 2A24, 2A26 - 2A28, 2A39	valve	VALVE	cross sectional area, valve position
TDV_S	superheated steam	TDV	steam inlet, system boundary
1R17-FILL	deionized feed	FILL	water inlet, system boundary
TDV_W	water recovery	TDV	water outlet, system boundary
TDV_A	environment	TDV	water outlet, system boundary

Fig. 5. THPSS model structure (left) and summary of model range (right) in ATHLET.

The components DS, MP and pipelines are divided into individual areas (nodes) for simulation in the model. The selected nodalisation for the DS (33 nodes) and MP (3 nodes) is oriented to the measuring points of the test facility [11], [12]. The same applies to the pipelines.

In the MP model, the water-steam mixing level is calculated in order to take a possible foaming of the filling level into account due to insufficient condensation in the water supply.

A special feature of the THPSS model is that, during a simulation run, the temporal trends of charging, holding, discharging (transients) are simulated. This is achieved by valve positions for changing the operating modes (charge, hold, discharge).

4. Simulation and Results

The aim of the simulation is the recalculation of an experiment investigating the charging, holding and discharging mode of the THPSS. The time sequences of the operational modes (switching of valves) are summarized in Table 1. The switching of operational modes was done by means of ramps. Table 2 shows the initial and boundary conditions for the simulation of the experiment.

Table 1. Time depended operation modes.

Operation mode	Simulation time	Period
overall simulation	0 s – 10500 s	2 h 55 min
hold	0 s – 450 s	0 h 07 min
charge	450 s – 4216 s	1 h 03 min
hold	4216 s – 6488 s	0 h 38 min
discharge	6488 s – 9950 s	0 h 58 min
hold	9950 s – 10500 s	0 h 09 min

Table 2. Initial conditions (IC) and boundary conditions (BC).

Component	Parameter	Unit	Input value ATHLET		Input value EBSILON	
			IC	BC	IC	BC
storage, mixing preheater, pipes	pressure	Pa	25E+05	25E+05[a]	25E+05	25E+05
storage	water temperature	℃	143	-	143	-
mixing preheater	water temperature	℃	219	-	-	-
	steam temperature	℃	224	-	-	-
	level	m	0.55	0.55	-	-
	heat loss	K	-	-	12	12
pipe 1R17	water temperature	℃	147	147[a]	-	-
pipes 2R18, 2R24,	water temperature	℃	145	-	147	147
1R17-FILL	mass flow feed water	kg/s	0.264	0.264[a]	0.264	0.264
pipe 2R30	water temperature	℃	211	-	-	-
pipes 2R35, 2R36	water temperature	℃	218	-	-	-
pipe 2R44	water temperature	℃	171	-	-	-
pipe 2R54	steam temperature	℃	309	-	325	325
TDV_S	steam temperature	℃	325	325[a]		-
pipe 2R56	water temperature	℃	126	-	-	-

[a] Use of the real experimental data

A first validation was carried out for the temperature profile in the displacement storage for measuring plane 2 (bottom of the DS), measuring plane 6 (center of the DS) and measuring plane 10 (top of the DS). These measuring planes are used for validation in order to ignore the influence of the massive lid and bottom of the DS in the THERESA test facility when considering the temperature curves. The validation was carried out on the basis of the experimental data from THERESA test facility and the overall model of test facility in EBSILON®Professional. The EBSILON®Professional model is used as an additional validation option to better evaluate the influence of the selected model properties (i. e. correct model creation) and their influence on the simulation result in ATHLET. A complete load, hold and unload cycle for the DS has been validated. The temperature curves of the simulations in ATHLET and

EBSILON®Professional were compared with the experimental data (verification). Furthermore, the absolute and relative deviations between simulation and experiment were calculated (validation). The absolute deviations of the temperature gradients in Kelvin between the simulations and the experiment were calculated according to equation (1).

$$\Delta T_{abs}(t) = T_{\exp}(t) - T_{sim}(t) \quad for \quad t \in [0s, 1s, 10500s] \tag{1}$$

The relative deviations of the temperature gradients in percent between the simulations and the experiment were calculated according to equation (2).

$$\Delta T_{rel}(t) = \frac{\Delta T_{abs}(t)}{T_{\exp}(t)} \cdot 100\% \quad for \quad t \in [0s, 1s, 10500s] \tag{2}$$

The mean relative deviation over the simulation period is calculated according to equation (3).

$$\overline{\Delta T_{rel}} = \frac{1}{n+1} \sum_{t=0}^{t=n} \sqrt{(\Delta T_{rel}(t))^2} \tag{3}$$

The following fig. (6-8) show the temperature curves and the calculated deviations according to equation (1-3) for the considered measuring plane 2, 6 and 10.

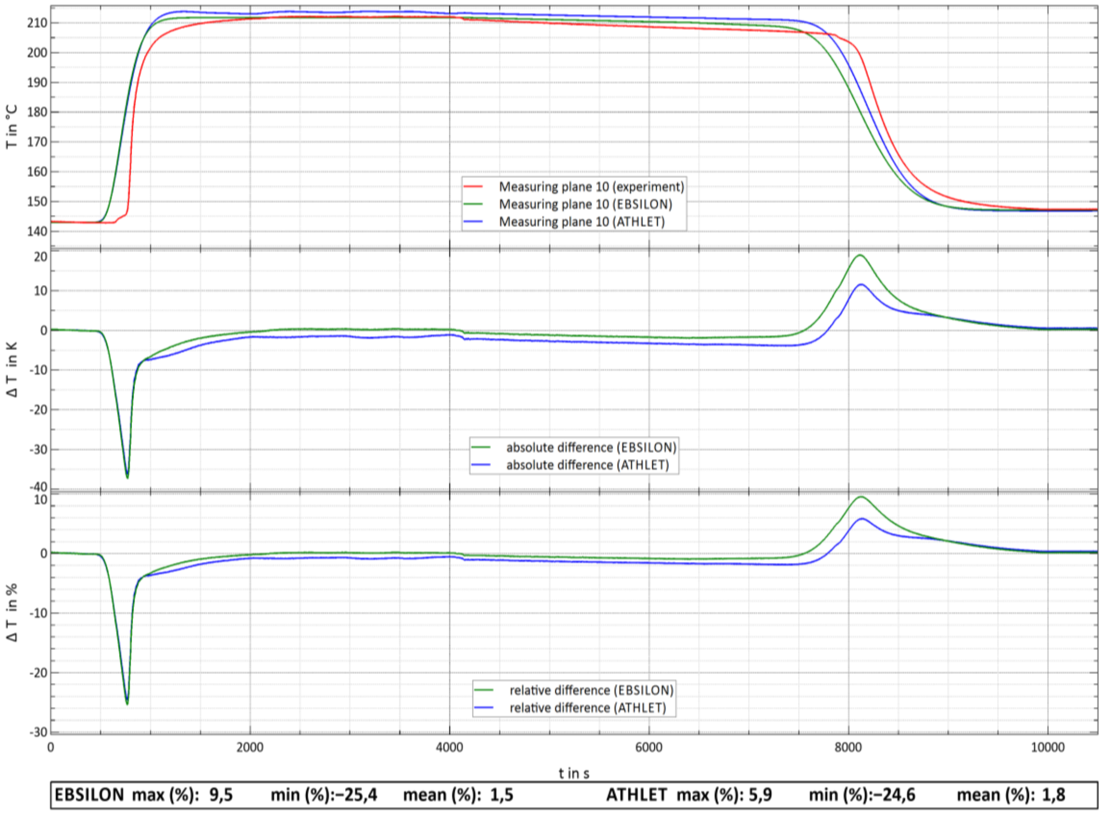


Fig. 6. Temperature on the top in the displacement storage – Measuring plane 10.

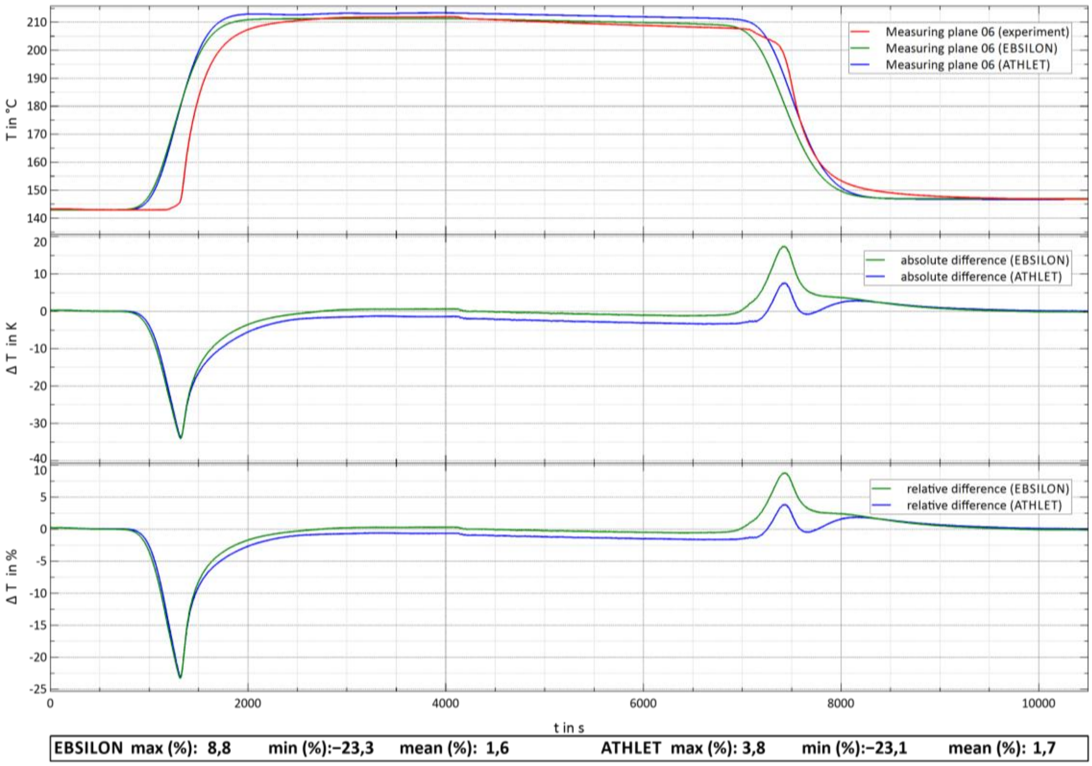


Fig. 7. Temperature in the centre in the displacement storage – Measuring plane 6.

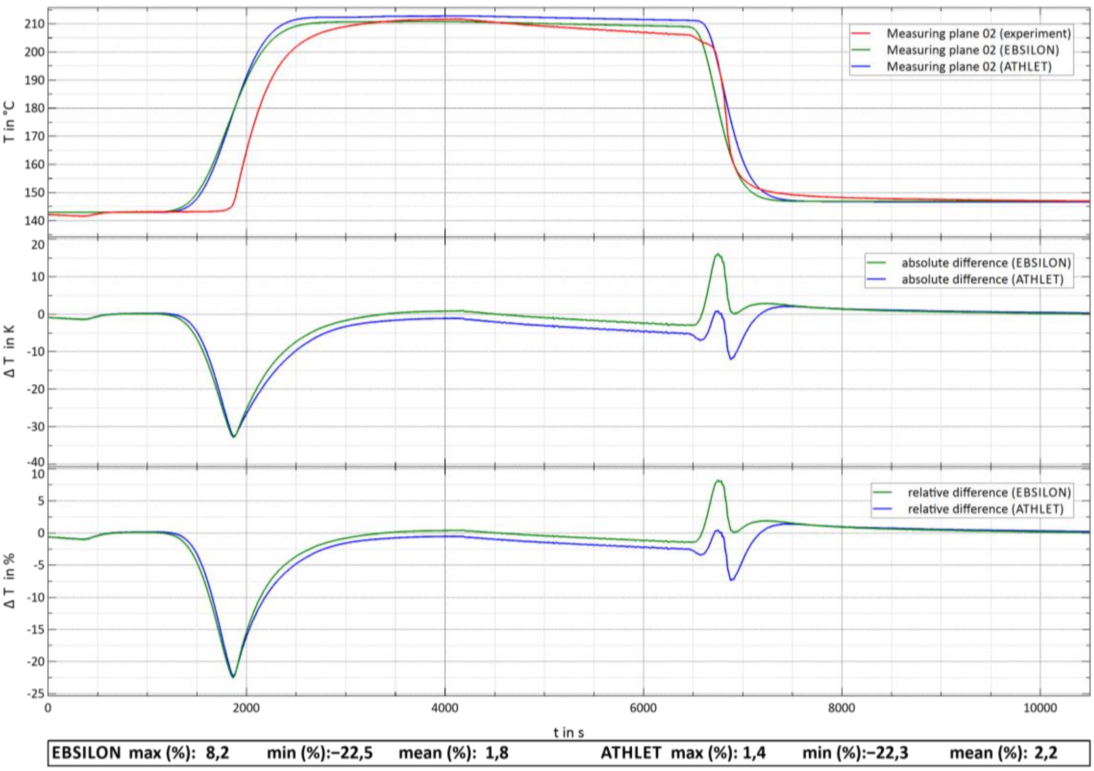


Fig. 8. Temperature on the bottom in the displacement storage – Measuring plane 2.

The model verification was successful because the temperature profiles of the simulations of ATHLET and EBSILON®Professional for all three measuring planes are very well correlated with the experimental temperature profiles. This was confirmed by the successful validation (calculation of absolute and relative deviations). Table 3 summarizes the results of the validation for the considered measurement planes.

Table 3. Validation results of the temperature curves.

Measuring plane	EBSILON			ATHLET		
	max (%)	min (%)	mean (%)	max (%)	min (%)	mean (%)
02	8,2	-22,5	1,8	1,4	-22,3	2,2
06	8,8	-23,3	1,6	3,8	-23,1	1,7
10	9,5	-25,4	1,5	5,9	-24,6	1,8

Taking into account the existing measurement deviations of the experimental data (Pt100 to 400 °C: ±0.95 K according to IEC 751), the calculated mean relative deviations in the EBSILON®Professional and ATHLET model are to be classified as small. The greatest deviations between the experiment and the simulations result during the charging process of the displacement storage. The reason for this is the insufficient consideration of the storage capacity of the cover during simulation in the ATHLET model. Fig. 9 shows the upper section of the displacement storage with cover and isolation.

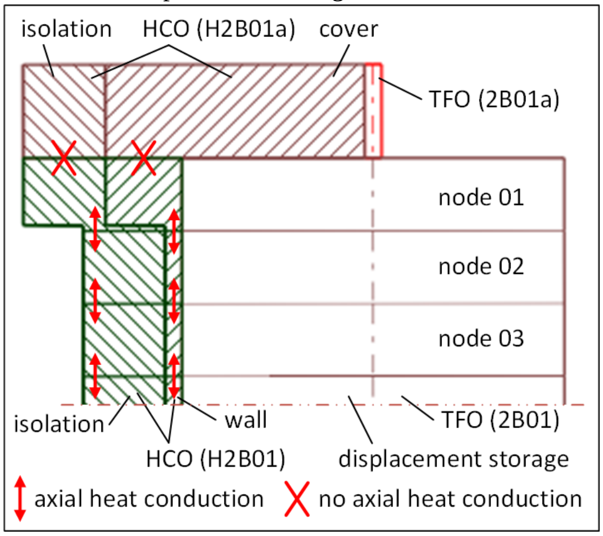


Fig. 9. Displacement storage with cover in ATHLET model.

The ATHLET model takes into account the radial heat transfer (fluid - wall - isolation - environment) as well as the axial heat conduction within the wall and isolation. The model does not take into account any heat conduction between the wall and the cover (Fig. 9). This means that the available storage capacity of the cover is used insufficiently during simulation. In the EBSILON®Professional model, the cover is not included in the model.

There is a need for further optimization in terms of model development and validation. For the underlying experiment, the quality of the ATHLET model can be assessed as sufficiently accurate. Further experiments and simulations are necessary to expand the feature space of the ATHLET model.

5. Summary and Outlook

The Zittau/Görlitz Universität of Applied Science Institute for Process Technology, Process Automation and Measuring Technology has developed and established the THERESA large-scale test facility. THERESA contains a THPSS, which is designed for the flexibilization of thermal power plants. Due to its high operating parameters, the THPSS mainly has thick-walled components and thus high storage capacities. The high storage capacities significantly influence the temporal behavior of the THPSS. A dynamic simulation model with the validated ATHLET code has been developed for the simulation-based design of the THPSS. The simulation model in EBSILON®Professional is used to validate the ATHLET model in addition to the experimental data. This paper describes the structure of the simulation models in ATHLET and EBSILON®Professional and compare them with experimental data from THERESA test facility.

For a first validation, an experiment of the THPSS of the THERESA test facility was used. The experimental database formed a complete charging and discharging cycle, with interim hold. For the validation of the ATHLET model, the temperature curves in the displacement storage of the THPSS were used. The calculated mean deviation (relative) between the ATHLET model and the experiment is, for the measuring planes 2, 6 and 10, a maximum of 2.2 %. The EBSILON®Professional model used for the comparison shows an average deviation (relative) of maximum 1.8 % to the experiment. This showed that the dynamic behavior of the ATHLET model correlates very well with the results of the experiment and the EBSILON®Professional simulation. The developed ATHLET model thus forms the basis for further validation. This includes the creation of a feature space, whose main influencing variables are the charge and discharge mass flow, the system pressure as well as the loading and unloading temperature of the displacement storage.

Subsequently, the model can be made useful for real applications, e.g. in future storage developments in centralized and decentralized storage systems. In the future, the model should also allow the representation of process variables, which cannot or only difficultly detected by measurement technology. These process variables are e.g. steam content, density of the storage medium or the temperature course inside the container wall. This allows more complex charging and discharging simulation scenarios (e.g. multiple charging and discharging, partial charging).

Acknowledgment

This work is co-funded by the European Regional Development Fund (ERDF) and the Saxon State Ministry for Economic Affairs, Labour and Transport.

Gefördert aus Mitteln der Europäischen Union

Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

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