Model Development and Dynamic Simulation of a Thermal High-Performance Storage System with the Simulation Code ATHLET to Increase the Flexibility of Thermal Power Plants

Torsten Klette, Sebastian Braun, Alexander Kratzsch, and Clemens Schneider
Zittau/Görlitz University of Applied Sciences
Institute of Process Technology, Process Automation and Measuring Technology (IPM), Zittau, Germany.
Email: t.klette@hszg.de

***Abstract*—To increase the flexibility of thermal power plants a thermal high-performance storage system has been developed. The THERESA test facility has subsequently been designed and built for experimental investigations. The high-performance storage system consists of a displacement storage and mixing preheater. A dynamic ATHLET model of a high-performance storage system is being developed. Our aim is a simulation-assisted design of thermal high-performance storage systems that will increase the flexibility of thermal power plants. Our focus is, in particular, on the improvement of the load change rate, increase in the balancing energy provision, reduction in the minimum load, decrease in the lifetime consumption, and improvement in the black start capability.**

***Index Terms*—ATHLET, displacement storage, power plant flexibilization, simulation, THERESA, thermal energy storage, thermal power plant.**

I. Introduction

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

- Increase the load rate change.
- Supply a balancing energy for network services.
- Reduction of the minimum load.
- Support for the black start capability of thermal power plants.

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

The subject of past work at the Institute of Process Technology, Process Automation and Measurement 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], [2]. The essential innovation of this concept requires the feasible integration of thermal high-performance storage systems (THPSS) into power plant processes.

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 a large-scale test facility, THERmal Energy StorAge system (THERESA) [3]. THERESA simulates nearly all the basic components and parameters of a thermal power plant process and includes a THPSS as the major object of investigation.

A validated dynamic simulation model is required for simulation-based investigations and the future designs of THPPS for thermal power plants [4]. The present paper deals with the description for the 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. 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 [5] have hitherto been used for a dynamic THPSS simulation, thus presenting an entirely new application scenario. We applied the thermo-hydraulic code analysis of thermal-hydraulics of LEaks on transients (ATHLET) for the modeling the THPSS.

II. ATHLET Simulation Code

The ATHLET simulation code was used for the modular simulations of arbitrary thermal-hydraulic systems through physical and numerical models. Moreover, ATHLET is a validated simulation code for the modeling of high transient water-steam processes in thermal power plants.

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 and are listed in the following conservation equations [6]–[9].

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Equation (1) describes the mass balance for the liquid phase:

$$\frac{\partial((1\text{-}\alpha)\rho_L)}{\partial t}+\nabla*((1-\alpha)\rho_L\vec{w}_L)=-\psi \tag{1}$$

Equation (2) describes the mass balance for the steam phase:

$$\frac{\partial(\alpha\rho_V)}{\partial t}+\nabla*(\alpha\rho_V\vec{w}_V)=\psi \tag{2}$$

Equation (3) describes the balance of energy of the liquid phase:

$$\frac{\partial((1\text{-}\alpha)\rho_L(h_L+0{,}5\vec{w}_L\vec{w}_L-\frac{p}{\rho_L}))}{\partial t}+\nabla* \\ ((1-\alpha)\rho_L\vec{w}_L(h_L+0{,}5\vec{w}_L\vec{w}_L))=-p\frac{\partial(1\text{-}\alpha)}{\partial t} \tag{3}$$

where

$+\vec{\tau}_i\vec{w}_L$	shear work at the phase interface
$+(1-\alpha)\vec{\tau}_i(\vec{w}_V-\vec{w}_L)$	dissipation due to interfacial shear
$+(1-\alpha)\vec{\rho}_L\vec{g}\vec{w}_L$	gravitational work
$+\dot{q}_{wL}$	heat flow through the structures
$+\dot{q}_i$	heat flow at the phase interface
$+\psi(h_{\Psi,L}+0{,}5\vec{w}_\Psi\vec{w}_\Psi)$	energy flow due to phase change
$+S_{E,L}$	external source terms

Equation (4) describes the balance of the energy in the steam phase:

$$\frac{\partial(\alpha\rho_V(h_V+0{,}5\vec{w}_V\vec{w}_V-\frac{p}{\rho_V}))}{\partial t}+ \\ \nabla*(\alpha\rho_V\vec{w}_V(h_V+0{,}5\vec{w}_V\vec{w}_V))=-p\frac{\partial\alpha}{\partial t} \tag{4}$$

where

$-\vec{\tau}_i\vec{w}_V$	shear work at the phase interface
$+\alpha\vec{\tau}_i(\vec{w}_V-\vec{w}_L)$	dissipation due to interfacial shear
$+\alpha\vec{\rho}_V\vec{g}\vec{w}_V$	gravitational work
$+\dot{q}_{wV}$	heat flow through the structures
$+\dot{q}_i$	heat flow at the phase interface
$+\psi(h_{\Psi,V}+0{,}5\vec{w}_\Psi\vec{w}_\Psi)$	energy flow due to phase change
$+S_{E,V}$	external source terms

Equation (3) and (4) for evaporation are also subject to condition (5) and for condensation to condition (6):

$$\vec{w}_\Psi=\vec{w}_L \tag{5}$$

$$\vec{w}_\Psi=\vec{w}_V \tag{6}$$

Equation (7) describes the momentum balance in the liquid phase:

$$\frac{\partial((1-\alpha)\rho_L\vec{w}_L)}{\partial t}+\nabla*((1-\alpha)\rho_L\vec{w}_L\vec{w}_L)+ \\ \nabla((1-\alpha)p)= \tag{7}$$

where

$+\vec{\tau}_i$	interfacial friction
$-(1-\alpha)\vec{f}_w$	wall friction
$-\psi\vec{w}_\Gamma$	momentum flux due to phase change
$-(1-\alpha)\rho_L\vec{g}$	gravitation
$+\alpha(1-\alpha)(\rho_L-\rho_V)\vec{g}D_h\nabla\alpha$	water level force
$+\alpha(1-\alpha)\rho_m(\frac{\partial\vec{w}_R}{\partial t}+\nabla\vec{w}_R)$	virtual mass
$+S_{I,L}$	external source terms

Equation (8) describes the momentum balance in the steam phase:

$$\frac{\partial(\alpha\rho_V\vec{w}_V)}{\partial t}+\nabla*(\alpha\rho_V\vec{w}_V\vec{w}_V)+\nabla(\alpha p)= \tag{8}$$

where

$-\vec{\tau}_i$	interfacial friction
$-\alpha\vec{f}_W$	wall friction
$+\psi\vec{w}_\Gamma$	momentum flux due to phase change
$-\alpha\rho_L\vec{g}$	gravitation
$-\alpha(1-\alpha)(\rho_L-\rho_V)\vec{g}D_h\nabla\alpha$	water level force
$-\alpha(1-\alpha)\rho_m(\frac{\partial\vec{w}_R}{\partial t}+\nabla\vec{w}_R)$	virtual mass
$+S_{I,L}$	external source terms

Equations (7) and (8) are also subject to conditions (9) and (10):

$$\rho_m=\alpha\rho_V+(1-\alpha)\rho_L \tag{9}$$

$$\vec{w}_R=\vec{w}_V-\vec{w}_L \tag{10}$$

The multi-dimensional integration of the mass, energy, and momentum balances result in six differential equations of first order; these are referred to as the 6-equation model. The momentum balances in the liquid and steam phases 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. Equation (11) presents the total momentum balance for the two-phase mixture:

$$\frac{\partial(\rho_m\vec{w}_m)}{\partial t}-\vec{w}_m\frac{\partial\rho_m}{\partial t}+\rho_m\vec{w}_m\nabla\vec{w}_m+ \\ \nabla(\alpha(1-\alpha)\frac{\rho_V\rho_L}{\rho_m}\vec{w}_R\vec{w}_R)+\nabla p= \tag{11}$$

where

$+\vec{f}_W$	wall friction
$+\vec{\rho}_m\vec{g}$	gravitation
$+S_{I,m}$	external momentum source terms

Equation (11) is also subject to condition (12):

$$\vec{w}_m = \frac{1}{\rho_m}(\alpha\rho_V\vec{w}_V + (1-\alpha)\rho_L\vec{w}_L \qquad (12)$$

For the temporal integration of the thermo-fluid-dynamic models and their differential equations, we use the forward-Euler-backward-Euler solver for the ordinary differential equations. The Euler method requires the calculation of Jacobi matrices. ATHLET adopts a sparse matrix package FTRIX for the efficient and fast calculation of the Jacobi matrices.

III. THERESA Large-Scale Test Facility

An overview to the THERESA large-scale test facility is given in Fig. 1. As mentioned above, THERESA simulates nearly all the basic components and 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 [10], [11].

Figure 1. The THERESA large-scale test facility.

In addition to the THPSS, THERESA is comprised of the following additional subsystems:

- Preheater
- Feed water pump
- Steam generator
- Superheater
- Valves
- Pipelines
- Pressure-relief tank as a heat sink (corresponding to the turbine in a power plant)

Furthermore, the THPSS are comprised of the following components:

- Displacement storage (DS)
- Mixing preheater (MP)
- Valves
- Pipelines
- Operational instrumentation
- Experimental instrumentation

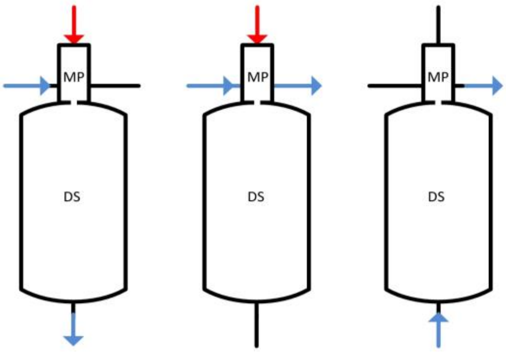
With the help of the DS, saturated water is charged and discharged without causing any significant temperature loss.

The MP is a direct heat exchanger designed specifically to provide a high heat capacity during the charging and discharging processes. The heat is transferred by the direct condensation of steam.

The valves and pipelines in the THPSS are used to switch between the operating modes, as shown in Fig. 2. The red arrows symbolize the flow direction of steam, and the blue arrows show the flow direction of the feed water.

The operational instrumentation is used to record relevant measurands (pressure, temperature, flow, and level) to control and regulate the system. In addition, extensive automation ensures the high quality of the test sequences and measurement results.

The experimental instrumentation is applied to acquire the measurands for detailed information on 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. Fig. 3 exemplifies the experimental instrumentation of the DS. We can see that the DS has eleven axial measuring planes (ME). Furthermore, each measuring plane of the DS is comprised of four radially distributed temperature sensors.



(a) Charge (b) Hold (c) Discharge

Figure 2. The operating modes of the THPSS.

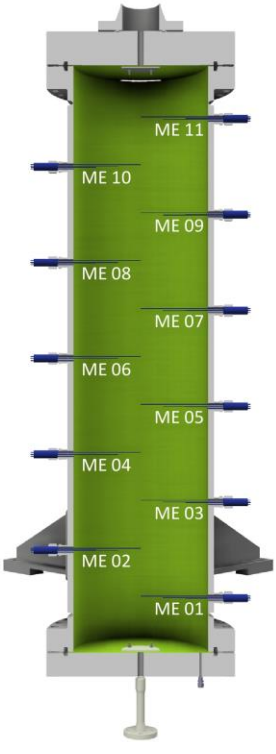


Figure 3. A schematic representation of the DS with the measuring planes (ME).

IV. THPSS MODEL DEVELOPMENT

A. ATHLET Simulation Code

As mentioned above, we applied the thermal-hydraulic code ATHLET from the German company GRS (German: Gesellschaft für Anlagen- und Reaktorsicherheit) to create the model for the THPSS of THERESA [6]–[9]. ATHLET is a 1D/2D thermal-hydraulic code used for the calculation of water and steam flows. ATHLET enables the modeling of the relevant components in a thermal power plant.

In general, the modeling in ATHLET occurs by physical component models called objects. The following types of objects were used for the modeling of the THPSS:

- Thermal fluid dynamic object (TFO)
- Heat conduction object (HCO)
- Time dependent volume (TDV)
- FILL
- VALVE

By means of TFOs, the simulation of flow paths (e.g., pipelines, leaks or more complicated systems) is possible. The geometry and position in the space of the system to be modeled must be defined in order to create a TFO. More complicated systems are often made up of several TFOs.

HCOs were used for the reproduction of heat transfer in up to three different layers (e.g., walls, isolations).

TDV served to replicate the volume elements with variable volumes. Other parameters such as the data on the chemical media, pressure and temperature must be defined. Therefore, TDV are suitable for reproducing the environment or modeling a system boundary.

FILL objects were used to simulate the fluid flow at the system boundaries. ATHLET distinguishes two types of FILL objects (positive and negative). For example, a positive FILL can be a feed water mass flow. A negative FILL is used for the modeling of leaks.

VALVE objects simulate the valves within the pipelines. For the valves, the cross-sectional areas and dimensionless shape loss coefficients (ZETAVV) must be defined. The definition of the different switching states of a valve during a simulation run is possible.

B. THPSS Model Structure and Functionality

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

Fig. 4 illustrates the developed model structure of the THPSS. We can see that the model includes the following components:

- DS with cover and bottom
- MP incl. level control
- Pipelines incl. control and shut-off valves

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

The model structure of the DS is shown in Fig. 5. It shows the components used short terms of the components, object types, and the degrees of nodalization. The components have the following design and degree of nodalization:

- Cover, consists of TFO (2B01a), HCO (H2B01a), number of nodes: 1
- Storage, consists of TFO (2B01), HCO (H2B01), number of nodes: 11
- Bottom, consists of TFO (2B01b), HCO (H2B01b), number of nodes: 2

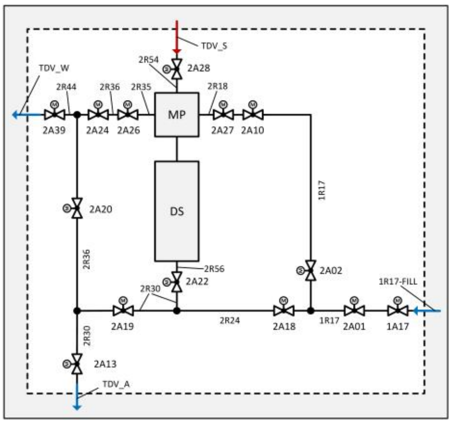


Figure 4. The THPSS model structure.

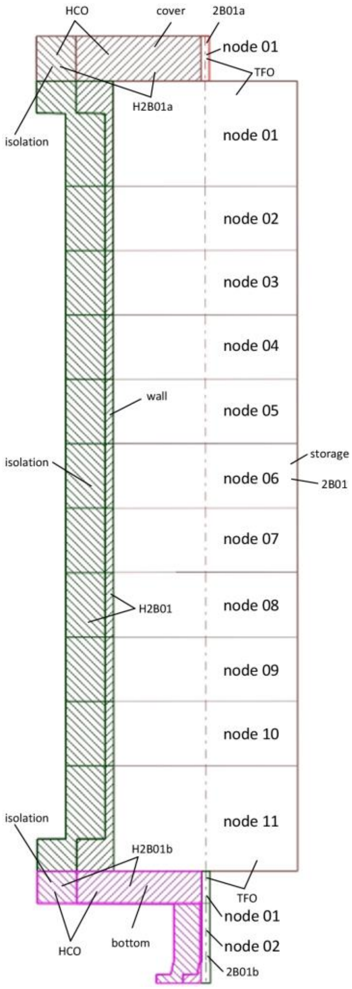


Figure 5. The model structure of the DS.

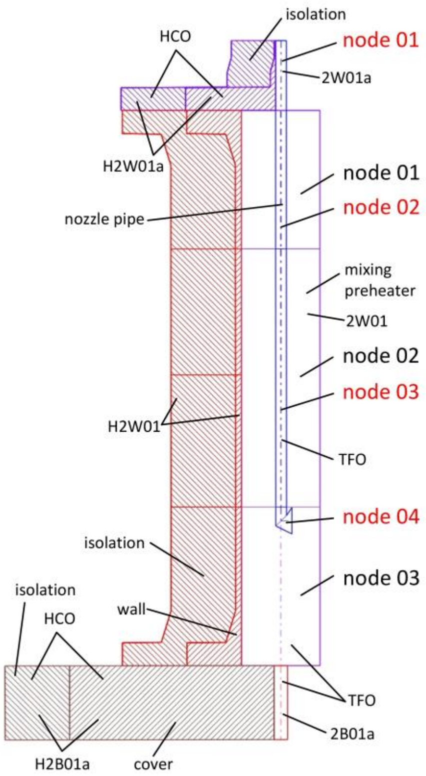


Figure 6. The model structure of the MP.

TABLE I: A SUMMARY OF THE MODEL RANGE.

Keyword	Labeling	Type	Simulation/ function
2W01	Mixing preheater	TFO	Flow path
H2W01	Mixing preheater	HCO	Wall, isolation
2W01a	Nozzle pipe	TFO	Flow path
H2W01a	Nozzle pipe	HCO	wall, isolation
2B01a	Cover	TFO	Flow path
H2B01a	Cover	HCO	Wall, isolation
2B01	Storage	TFO	Flow path
H2B01	Storage	HCO	Wall, isolation
2B01b	Bottom	TFO	Flow path
H2B01b	Bottom	HCO	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

The model structure of the MP is shown in Fig. 6. The MP was installed on the lid of the DS. We used the following subdivision for modeling:

- MP, which consists of TFO (2W01) and HCO (H2W01); number of nodes: 3
- Nozzle pipe, which consists of TFO (2W01a) and HCO (H2W01a); number of nodes: 4

In the MP model, the water-steam mixing level was calculated in order to take any 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 and discharging (transients) are simulated. As mentioned above, this is achieved by valve positions that are used to change the operating modes (charge, hold, and discharge).

Table I summarizes the components and system boundaries of the THPSS model.

C. 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 II. The switching of the operational modes was carried out by means of ramps.

Table III shows the initial and boundary conditions for the simulation of the experiment.

TABLE II: THE TIME DEPENDENT OPERATION MODES.

Operation mode	Simulation time	Period
Overall simulation	0–10500 s	2 h 55 min
Hold	0–500 s	0 h 8 min
Charge	500–4216 s	1 h 2 min
Hold	4216–6488 s	0 h 38 min
Discharge	6488–9950 s	0 h 58 min
Hold	9950–0500 s	0 h 9 min

TABLE III: THE INITIAL AND BOUNDARY CONDITIONS.

Component	Parameter	Unit	Input value
-	Simulation time	s	10500.0
Storage, MP, pipes	Pressure	Pa	25.0E + 05
Storage	Water temperature	℃	143
MP	Water temperature	℃	219
	Steam temperature	℃	224
	Start level	m	0.55
	Desired level	m	0.55
Pipe 1R17	Water temperature	℃	147
Pipes 2R18, 2R24,	Water temperature	℃	145
Pipe 2R30	Water temperature	℃	211
Pipes 2R35, 2R36	Water temperature	℃	218
Pipe 2R44	Water temperature	℃	171
Pipe 2R54	Steam temperature	℃	309
Pipe 2R56	Water temperature	℃	126
TDV_S	Steam temperature	℃	309
1R17-FILL	Water temperature	℃	147
	Volume flow	l/min	17.1
TDV_A	Air pressure	Pa	1.01325
	Air temperature	℃	29

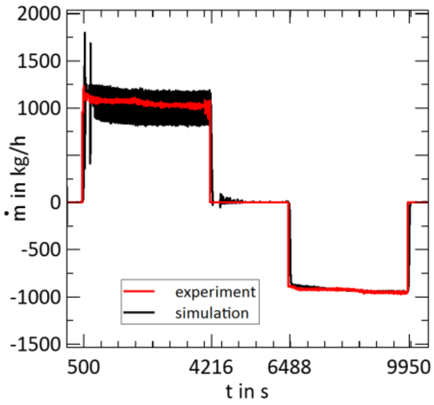


Figure 7. The mass flow in the DS.

In Fig. 7, the curves of the mass flow in the DS of the experiment and simulation are comparatively illustrated. The experiment and simulation start in the holding mode, which means that no mass flow occurs inside the DS.

The charging mode starts after 500 s. We can see in Fig. 7 that the simulation model correctly reproduced the mass flow curve of the experiment. Furthermore, an initial peak is present in the simulated mass flow. The reasons for this fact are the pressure compensation processes between MP and DS. The mass flow through the DS is composed of the feed water and steam mass flow. The condensed steam mass flow occurs due to the thermodynamic state of equilibrium. The impulse-shaped steam condensation in the MP causes high fluctuations in the simulation, which are significantly lower in the experiment.

After 4216 s, the changeover to another holding mode was carried out. Again, no mass flow occurs inside the DS. A constant feed water mass flow is further conveyed through the MP.

At 6488 s, a switching to the discharging mode was performed. This results in a reversal of the flow direction or in a negative mass flow (cf. Fig. 7).

Cold fluid flows into the DS from below. At the same time, hot fluid is discharged at the outlet of the DS. Because of the feeding of cold fluid into the DS, the mass flow increases due to density changes. At 9950 s, the discharging process is terminated and the experiment stops with another holding mode.

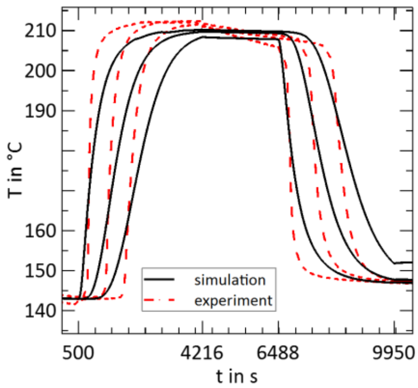


Figure 8. The fluid temperature in the DS.

Fig. 8 shows the simulated and experimentally determined curves of the temperature within the DS. The temperature curves of the upper, middle, and lower layers for charging, holding, and discharging of the DS are shown.

The simulation model reproduces the temperature layers inside the DS in a physically plausible manner. The temperature profiles of the simulation do not show any mixing of the individual layers. However, the time behavior of the simulation model differs from the experiment. The reasons for this are the different boundary conditions of the heat transfer processes into the storage wall. During the experiment, the maximum charging temperature was 212 ℃. On the other hand, for the simulation we reached a maximum charging temperature of 210 ℃.

The temperature drop during the holding mode is smaller in the simulation. The reason for this is the ideal insulation of the DS in the simulation model. The DS of THERESA is insulated with insulating mats. At the contact points of the two insulating mats and the ducts for the temperature measuring devices detected increased heat losses. This causes a higher temperature decrease during the experiment.

The temperature level (approx. 147 ℃) for the lower and middle storage layers at the end of the discharge process (9950 s) is correctly simulated. The simulated temperature of the upper storage layer reaches only about 157 ℃.

The reason for the deviation in the temperature profiles between experiment and simulation are the simplifications used in the simulation model. The simplifications are particularly present in the region of the cover or base of the DS. The simulation model considers the radial and axial heat conduction within a component. The axial heat conduction between:

- DS wall (H2B01) and DS cover (H2B01a)
- DS wall (H2B01) and DS bottom (H2B01b)
- DS cover (H2B01a) and MP wall (H2W01)
- MP wall (H2W01) and MP nozzle pipe (H2W01a)

are not currently taken into account during the simulation model. Further investigations are necessary to assess the influence of the model's simplifications.

Fig. 9 shows the surface temperature of the insulation in the center (node 6) of the DS. The simulation model represents the temperature profile very well. There is only a slight temperature difference of approx. 2 K between experiment and simulation.

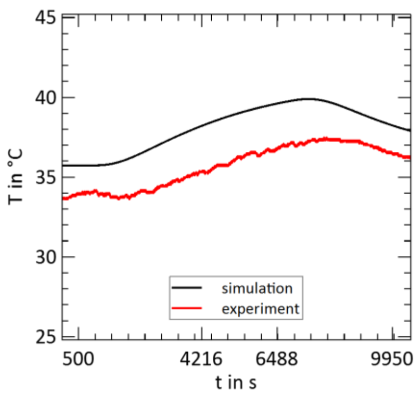


Figure 9. The insulation surface temperature in the DS.

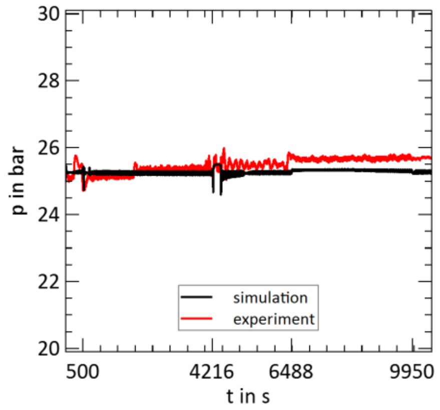


Figure 10. The pressure in the DS.

Fig. 10 shows the time courses of the absolute pressure observed for the experiment and simulation. It shows that in both cases the absolute pressure was approximately constant. Furthermore, no significant deviations in the absolute pressure occur between the experiment and simulation. In the area of the switching processes between the operating modes, there is a short-term pressure drop, which is correctly represented by the simulation model. The pressure course of the experiment is profoundly influenced by the steam generator in THERESA. Therefore, there are deviations between the ideal course of the simulation model and the realistic course of the experiment. The switching to the discharging mode at 6488 s leads to a reversal of the flow direction. This causes a slight increase in the pressure due to the charging pressure losses.

The MP is a central element of the THPSS. It enables the steam condensation and subsequent charging of saturated water into the DS. With the help of the filling level control, the filling level in the MP is kept constant at 55 cm.

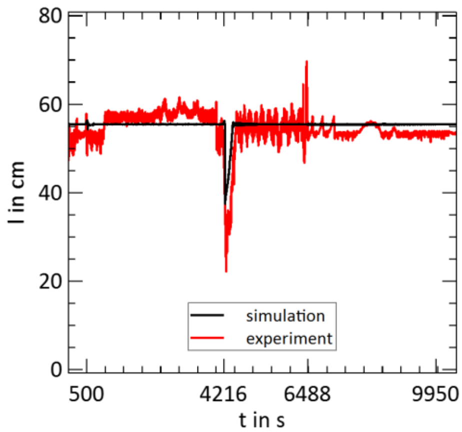


Figure 11. The fill level of the MP.

Fig. 11 shows the experimentally determined and simulated courses of the fill level in the MP. We can see that the simulation model correctly reproduces the course of the filling level. During switching from the charging to holding mode, a large drop in the filling level was obvious in the experiment. The simulation model simulates this behavior correctly.

V. Summary and Outlook

The Zittau/Görlitz UAS Institute for Process Technology, Process Automation and Measurement Technology (IPM) has developed and established the THERESA large-scale test facility. THERESA contains a THPSS, which was designed for the flexibilization of thermal power plants. Due to its high operating parameters, the THPSS has mainly 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. This paper describes the structure of the simulation model. A basic distinction has been made between the following components:

- DS
- MP
- Pipelines and valves

The simulation model takes the real flow paths, geometries, and properties of the components into account. It simulates the axial and radial heat transfer processes between the fluid and the components as well as their charging, holding, and discharging characteristics. Furthermore, it reproduces the operating modes and time-variable ambient conditions within the scope of a simulation calculation.

The results of the simulation calculations have been compared with the experimental data. It was shown that the results from the simulation and the experiments qualitatively match. The mass flow measured during the experiment corresponds to the simulation. The temperature courses inside the DS determined during the experiment qualitatively match with the simulated temperature courses. However, deviations in the temporal behavior have been found. The temperature stratification could be proved by the simulation model. The experimentally determined surface temperature of the insulation, the pressure course, and the filling level in the MP are correctly reproduced by the simulation model.

Future work needs to include further model adjustments and subsequent experimental validation of the simulation model.

The essential optimization measures relate to the MP, since the simulated condensation behavior shows a significant deviation from the experiment. For this, the MP's degree of detailing must be further increased. Due to the deviating temporal behavior, the heat transfer between the components must be further investigated and optimized in the THPSS.

Furthermore, it is planned to finally validate the present model. Subsequently, the model can be made useful for specific applications. In the future, the model should also allow the representation of the process variables, which cannot or only difficultly detected by measurement technology. These process variables are, for example, the 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, and partial charging).

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Torsten Klette, Dipl.-Ing. (FH) (male): Mr. Klette was born on 3 October, 1980. In 2001, he finished his vocational training as a technician for central heating and ventilation at GESU Haustechnik GmbH. After his alternative civilian service, he obtained his general university entrance qualification in 2004. He graduated in 2008 with an engineering degree in the field of Energy and Environmental Engineering. He then started working as a research assistant at the Institute of Process Technology, Process Automation and Measurement Technology at the Zittau/Görlitz University of Applied Sciences, where he became leader of the laboratory in 2015. Moreover, since 2016 he is a specialist boiler attendant at the THERESA testing facility in the Zittau Power Plant Laboratory. Mr. Klette is a member of the Association of German Engineers (VDI). He has experience in dynamic modeling in the area of thermodynamics and process modeling using the ATHLET thermo-hydraulic code and DynStar simulation software. Furthermore, he is skilled in uncertainty analyses using the ATHLET program extension SUSA and constructions using Inventor Professional (3D-CAD software).

Sebastian Braun, Dipl.-Ing. (FH) (male): Mr. Braun was born on 8 January 1982. After obtaining his general university entrance qualification he graduated with a degree in Technical Building Management at the Hochschule für Technik und Wirtschaft (HTW), Berlin in 2008. Among others, his studies emphasized on electrical energy supply and distribution in buildings and on real estate, moreover on heating, ventilation, and sanitary engineering and also on instrumentation and control technology in buildings and energy management. He started his career at the Techno-Innovation Zittau GmbH, where he worked as a project leader in research and development in the area of solar power energy, energy management and controlling, process measuring, and control technology and microelectronics. Since 2012, he has been working at the Institute of Process Technology, Process Automation and Mesurement Technology (IPM) at the Zittau/Görlitz University. He specializes in the conception and design of installation engineering, particularly in thermal energy storage systems, power plant technology, error proof control and sensor systems and measuring, and control technology. In recent years, he has been involved in various research projects on hightransient thermal energy storage systems, increasing the energy efficiency of thermal energy systems and flexibilization analysis of lignite-fired power plants by means of thermal energy storage systems.

Alexander Kratzsch, Prof.-Dr.-Ing. (male): Mr. Kratzsch was born on 28 August, 1979. After obtaining his general university entrance qualification, he graduated in 2003 at the Zittau/Görlitz University in degree program Electrical Engineering and Automation Technology. He then worked as a research assistant at the Zittau/Görlitz University of Applied Sciences and completed his doctorate in the field of Automation Engineering in 2009, funded by the Vattenfall Europe Nuclear Energy GmbH. Since 2009, he has been working as project manager at the Institute of Process Technology, Process Automation and Measurement Technology (IPM) and holds a professorship in the field of Measurement Technology and Process Automation. He is the chair of the IPM department Measurement Technology/Process Automation. Prof. Kratzsch is actively involved in the GMA-expert committee and works as a reviewer for the International Conference on Nuclear Engineering, AiF. Additionally, he is the chair of the Automation and Mechatronics academic planning committee at the Faculty of Electrical Engineering and Computer Science at the Zittau/Görlitz University.

Clemens Schneider, Dr.-Ing. (male): Mr. Schneider was born on 25 November, 1983. After completing his training as a car mechanic in a dual education system at the Berufliches Schulzentrum für Technik in Zittau in 2004, he gained his university entrance qualification (Fachhochschulreife) at the same institution one year later. In 2005, he was admitted on a course of study at the Zittau/Görlitz University of Applied Sciences in the field of Energy and Environmental Engineering. He graduated in 2009 and began working at the Institute of Process Technology, Process Automation and Measurement Technology at the Zittau/Görlitz University of Applied Sciences in Zittau. In 2015, he finished his doctorate on experimental investigations on nucleate boiling in sub-cooled flows. In recent years, he has been involved in multiple research projects. In 2009, he started experimental investigations on boiling processes using optical methods and parameter determination for CFD-calculations at small-scale test facilities, which formed the basis for his doctoral degree in 2015 (Dr.-Ing.). In 2013, he began to work in the research project Increase of Energy Efficiency in Thermal Energy Plants. Later, in 2015, he was committed to the start of operation of the THERESA testing facility. Currently, he is participating in the development of a design method for dimensioning and integration of thermal energy storages into a power plant process. Mr. Schneider authored various papers, e.g., on experimental investigations of nucleate boiling on optically transparent heated surfaces with optical coherence tomography and infrared thermography. Moreover, since 2012 Mr. Schneider has been a member of the German Nuclear Society (Kerntechnische Gesellschaft KTG) and the American Society of Mechanical Engineering (ASME). Mr. Schneider has experience in image processing programs and computer programs such as LABVIEW, EBSILON; MATHSOFT MATHCAD, DYNSTAR and AUTODESK INVENTOR.