Thermal Performance Testing of Outdoor Hot Water Stores for Long-term Thermal Energy Storage

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Abstract

This contribution describes a model-based thermal performance test method for outdoor hot water stores for long-term thermal energy storage. For this purpose an existing TRNSYS model for indoor hot water stores is modified. In particular, local variations of the ambient temperature and the influence of solar irradiation are taken into account. A parameter identification process is proposed, which makes it possible to determine the parameters of the model required for the characterization of the thermal performance of an outdoor installed hot water store. The test method has been developed for an outdoor installed hot water store with a volume of 12 m^3, a vacuum thermal insulation and a transparent thermal insulation as well as for an outdoor installed 100 m^3 hot water store with a conventional thermal insulation. The functionality of the test method is confirmed by measured data, plausibility checks of the model parameters and a comparison to theoretical values determined based on material properties. Furthermore, the influences of the minimization algorithm on the results of the parameter identification process are investigated.

Keywords: Hot water store for outdoor installation, thermal performance test method, parameter identification

1. Introduction

Overground hot water stores with volumes in the range of 10 m^3 to 500 m^3 are an attractive technology for efficient and long-term thermal energy storage due to their relatively low surface to volume ratio compared to stores with smaller volumes. Applications of such stores range from SolarActiveHouses (Gerschitzka et al., 2016) to buffer stores in solar district heating systems (Bauer el al., 2010). In the last decade, several demonstration projects with stores in a volume range of 10 m^3 to 500 m^3 were planned, built and monitored within national and international research projects (Bauer et al., 2010, 2016). These stores are often placed overground and outside due to their large size. The resulting dynamic changes in the ambient conditions and novel effects on the heat losses, such as wind and irradiation, compared to a common indoor installation, require a modification and extension of already existing methods for the performance testing of hot water stores. Hence, in this contribution a model-based thermal performance test method for outdoor hot water stores is developed and validated. An existing TRNSYS model for indoor installed hot water stores (Drück, 2006) is modified. In particular, local variations of the ambient temperature and the influence of solar irradiation are taken into account. A parameter identification process is proposed, which makes it possible to determine the parameters of the model required for the characterization of the thermal performance of an outdoor hot water store for long-term thermal energy storage. The new test method was applied to a 12 m^3 hot water store with a vacuum thermal insulation combined with a transparent thermal insulation (TTI) as well as to a 100 m^3 hot water store with a conventional thermal insulation, see figure 1. Both stores were built for demonstration purposes in the context of two German research projects. The stores are equipped with measuring sensors for the determination of the ambient conditions and the store's thermal behaviour. Especially the temperatures inside the storage medium, outside the stores and on the outer surface of the thermal insulations are measured. Furthermore, the wind speed and the solar irradiation are recorded.

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Fig. 1: Outdoor installed thermal energy stores with a water volume of 12 m^3 (left) and 100 m^3 (right)

The store with a volume of 12 m^3 was developed as part of the German national research project „StoEx“ (Development of a large-volume, low-cost hot water store with high-efficient thermal insulation for outdoor installation; PTJ grant number: 0325992B). The aim of this project was the development of an advanced hot water store for outdoor installation. A significantly reduced heat loss rate compared to conventionally insulated thermal energy stores was achieved by the use of the high-efficient thermal insulation techniques vacuum thermal insulation and transparent thermal insulation (Gerschitzka et al., 2015a). The store was tested at a novel outdoor test facility especially designed for thermal performance testing of large-scale outdoor installed thermal energy stores (Gerschitzka et al., 2016). The project was carried out by the Research and Testing Centre for Thermal Solar Systems (TZS) of the Institute of Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart and the company Sirch Tankbau-Tankservice-Speicherbau GmbH from Germany.

The 100 m^3 store was developed as part of the German national research project “OBSERW” (Overground stores in segmental construction for district heating systems; grant number: 03ET1230C). The partners of the project are the Professorship of Technical Thermodynamics of the Faculty of Mechanical Engineering of the Chemnitz University of Technology (TUC/TT), the Research and Testing Centre for Thermal Solar Systems (TZS) of the Institute of Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart and the company farmatic Anlagenbau GmbH from Germany. Within the project a so-called flat bottom hot water store using a thermal insulation based on polyurethane recycling material is developed (Urbaneck and Platzer, 2015). Regarding the store construction, a novel floating ceiling combined with a CFD-optimized charging device is investigated (Findeisen et al., 2016, 2017). Further topics of the research project OBSERW are the laboratory and application scale tests of the sealing material required for the segmental construction (Gerschitzka et al., 2015b).

2. Test method for outdoor hot water stores

The application of well-known test methods for indoor installed hot water stores to outdoor installed stores, e. g. of the test methods according to EN 12977-3 (2012) and EN 12977-4 (2012) is not appropriate since these methods are designed for smaller store volumes up to 5 m^3 and for quasi steady state ambient indoor conditions. Additionally, no effects on the heat losses due to the outdoor specific installation are considered such as the decreased heat losses by solar gains. Furthermore, the charging and discharging capacity required to perform the test sequences of these methods is usually not available on-site. Therefore, a modified calculation procedure is developed regarding the determination of heat losses of outdoor installed hot water stores. For this calculation a model based on an extension of the proven TRNSYS Multiport Store-Model by Drück (2006) is used. A novel calculation of the outer surface temperature of the store is considered.

The Multiport Store-Model uses a one dimensional finite difference method to calculate the temperature of the storage medium. The storage medium is discretized along the store height in volume segments characterized by a node representing the temperature of these segments. The temperature of each node is determined by solving the energy balance for all nodes of the store's volume. This is a common approach to model the thermal behaviour of such stores for system simulation studies. A more detailed description of the Multiport Store-Model is given in (Drück, 2006, 2007). The original Multiport Store-Model considers the heat losses of the store medium for each volume segment by a linear approach between the heat flux of the heat losses and the temperature difference between the ambience and the store medium, according to eq. 1. The parameter (UA) represents the heat loss rate. Usually the inner surface temperature of an indoor installed hot water store is assumed to be the storage medium temperature.

$$\dot{Q}_{\mathrm{hl}} = (UA) \cdot (\vartheta_{\mathrm{sto}} - \vartheta_{\mathrm{amb}}) \qquad \text{(eq. 1)}$$

An outdoor installation of a hot water store requires a more detailed approach for the calculation of the heat losses. This is caused by the fact, that the heat flux of the solar irradiation, the convective heat transfer by wind and the heat capacity of the thermal insulation influence the outer surface temperature of the store. Hence, an extension of the Multiport Store-Model is necessary. This extension is done by an afterwards explained novel calculation method using a more detailed calculation of the store's outer surface temperature.

2.1. Calculation of the outer surface temperature

The thermal behaviour of a store's outer surface can be characterized by a multi-node calculation. Each node represents the temperature of a certain area of the outer surface of the store. Eight separate surface temperatures of the store's lateral area in circumferential direction are considered. A vertical temperature distribution within the considered specific surface area is neglected. The outer surface temperatures can be calculated by determining the heat transfer between the outer store surface and the ambience as well as the thermal capacities. The considered heat transport phenomena are the heat transfer by solar and thermal irradiation, a temperature and wind speed dependent convective heat transfer and an internal heat transfer inside the material of the outer surfaces in the circumferential direction.

The model parameters of the surface temperature calculation are the effective heat capacity C_{eff} of the store's thermal insulation, the transmittance-absorptance-product $(\tau_{\mathrm{g}}^{*}\alpha_{\mathrm{a}}^{*})$ and the heat transfer coefficient from the store surface to the ambience h_{ext1} respectively the coefficient of the temperature dependence of heat transfer coefficient h_{ext2}. Furthermore, a wind speed and irradiation dependency of the surface temperature can be included by the parameters h_{w1} and h_{w2}. Concerning the calculation of the incidence angle, depended on solar irradiation, the reflectance of the ambience ρ_{amb}^{*} and the incidence angle modifier K_{b} are of importance. A heat transfer by thermal irradiation between the store's surface and the ambience respectively the sky can be considered by the parameter ϵ^{*}. If there is a transparent thermal insulation on the outer store surface, a heat transfer between different surfaces in circumferential direction can occur. This heat transfer can be considered by the parameter $h_{\mathrm{int,i \to j}}$ between two neighboring segments.

Assuming only a small change of inner energy compared to the incoming solar irradiation and heat losses of the outer store surface, the energy balance of one surface segment can be approximated according to eq. 3. The subscription is exemplary for a north orientated surface segment. The aim of eq. 3 is to calculate the surface temperature ϑ_{sur} of one segment based on the knowledge of the input values and the temperature of the surface $\vartheta_{\mathrm{sur,old}}$ from the time step before. Considering all individual segment equations, an equation system occurs.

$$\begin{aligned}
\vartheta_{\mathrm{sur,N}} = \; & \vartheta_{\mathrm{sur,old,N}} \\
& + \{ (\tau_{\mathrm{g}}^{*}\alpha_{\mathrm{a}}^{*})_{\mathrm{N}} \cdot A \cdot (K_{\mathrm{b,N}} \cdot G_{\mathrm{hem,dir,N}} + G_{\mathrm{hem,diff,N}} + 0.5 \cdot \rho_{\mathrm{amb}}^{*} \cdot G_{\mathrm{glob}}) \\
& - A' \cdot h_{\mathrm{ext1,N}} \cdot (\vartheta_{\mathrm{sur,old,N}} - \vartheta_{\mathrm{amb}}) - A' \cdot h_{\mathrm{ext2,N}} \cdot (\vartheta_{\mathrm{sur,old,N}} - \vartheta_{\mathrm{amb}})^2 \\
& + A'' \cdot h_{\mathrm{int,N \to NO}} \cdot (\vartheta_{\mathrm{sur,old,NO}} - \vartheta_{\mathrm{sur,old,N}}) \\
& + A'' \cdot h_{\mathrm{int,N \to NW}} \cdot (\vartheta_{\mathrm{sur,old,NW}} - \vartheta_{\mathrm{sur,old,N}}) \\
& - A' \cdot h_{\mathrm{w1,N}} \cdot w \cdot G_{\mathrm{hem,N}} - h_{\mathrm{w2,N}} \cdot A' \cdot w \cdot (\vartheta_{\mathrm{sur,old,N}} - \vartheta_{\mathrm{amb}}) \\
& - 0.5 \cdot \epsilon^{*}{}_{\mathrm{N}} \cdot \sigma \cdot A' \cdot [(T_{\mathrm{sur,old,N}}{}^{4} - T_{\mathrm{amb}}{}^{4}) + (T_{\mathrm{sur,old,N}}{}^{4} - T_{\mathrm{sky}}{}^{4})] \} \cdot \Delta t \,/\, C_{\mathrm{eff,N}}
\end{aligned} \qquad \text{(eq. 3)}$$

The incidence angle modifier K_{b} of the direct irradiation is defined by eq. 4 (Fischer, 2011; Bosanac, 1992). The incident angle Θ between the sun and the normal of the TWD area of each segment is calculated in TRNSYS. The coefficient r_0 is used for the fitting of the incident angle modifier.

$$K_{\mathrm{b}} = 1 - [\tan(\Theta/2)]^{1/r_0} \qquad \text{(eq. 4)}$$

The areas A, A' and A'' are multiplied with the corresponding heat transfer coefficients. The sky temperature T_{sky} is calculated according to Swinbank (Fischer, 2006) for the assumption of clear sky. To get a workable number of model coefficients, only the heat transfer coefficient $h_{\mathrm{int,i\to j}}$ is individually determined for all segments. The remaining parameters are equal for all segments. The input values of the surface temperature calculation are the ambient temperature, the global solar irradiation, the diffuse solar irradiation in the horizontal and the wind speed.

In the novel and extended Multiport Store-Model, the calculated local mean surface temperatures are used for the calculation of the heat losses instead of the ambient temperature, according to eq. 5. The mean surface temperature $\bar{\vartheta}_{\mathrm{suf}}$ is calculated by the average of all eight individual segment temperatures.

$$\dot{Q}_{\mathrm{hl}} = (UA) \cdot (\vartheta_{\mathrm{sto}} - \bar{\vartheta}_{\mathrm{suf}}) \qquad \text{(eq. 5)}$$

In addition to the integration of the surface temperature's calculation into the original Multiport Store-Model (Drück, 2006), two further changes are introduced. On the one hand, the original store model is modified in such a way, that an ambient temperature of the bottom and an ambient temperature of the top can be set as input value. On the other hand, a non-homogeneous temperature distribution in the storage medium is introduced at the initial time step. The possibility of starting the calculation with an inhomogeneous temperature distribution is particularly useful for parameter identification on the basis of in-situ measuring data.

The parameters of the store model, relevant for the thermal behaviour of a long-term thermal energy storage, remain the heat loss rate of the store mantle $(UA)_{\mathrm{man}}$, the heat loss rate of the store bottom $(UA)_{\mathrm{bot}}$, the heat loss rate of the store top $(UA)_{\mathrm{top}}$ and the effective thermal conductivity of the storage medium in a vertical direction k_{eff}. The store model input values are the store's surface temperatures, determined by the novel surface temperature model, and the ambient temperature for the mantle, the bottom and top of the store. It is assumed, that the heat losses of the store don't influence the temperature of the transparent thermal insulation respectively the outer surface temperature of the store.

2.2. Process of parameter identification

The procedure of determining the model parameters of both models, the store and surface temperature model, regarding the thermal behaviour of a long-term thermal energy storage is separated into two individual parameter identification processes. Figure 2 shows the basic approach of such a parameter identification process for a dynamic model (Fischer, 2011). The output values of the model calculation and of the measurement are compared using a target value. Afterwards, an optimization algorithm searches for a minimum of the target value by varying the model parameters.

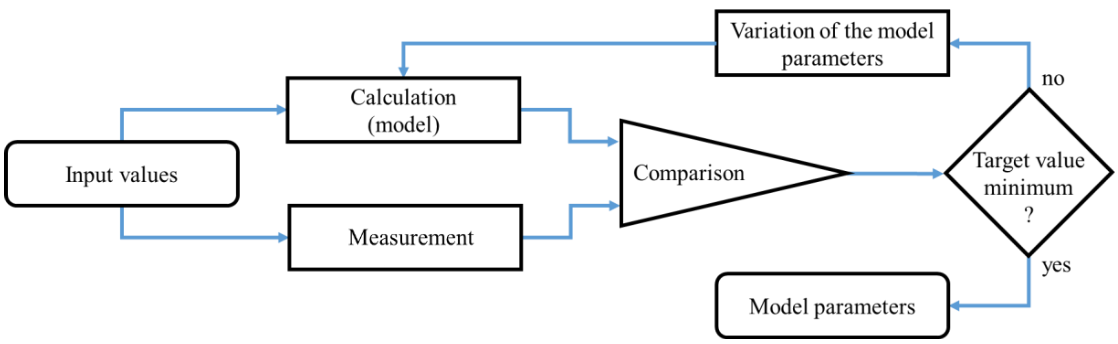

Fig. 2: Schematic process of a parameter identification

In this investigation, several Matlab integrated optimization algorithms are tested. Especially for the dynamic parameter identification of solar collector models in TRNSYS several well working optimization algorithms are known (Bales, 2002; Fischer; 2011, Bosanac, 1992). Because of the similarity to a solar collector, the transparent thermal insulation is also calculated in a time-dependent, dynamic way.

The parameter identification process of the surface temperature model uses the mean quadratic deviation of measured ($\vartheta_{\mathrm{m,j,i}}$) and calculated ($\vartheta_{\mathrm{c,j,i}}$) surface temperatures as target value. The parameter identification process of the store model uses the mean quadratic deviation of measured ($\vartheta_{\mathrm{m,j,i}}$) and calculated ($\vartheta_{\mathrm{c,j,i}}$) store medium temperatures as target value. Equation 6 defines the target value with a constant reference temperature ϑ_{ref} of 10 °C. The reference temperature is used to obtain a dimensionless target value. The value N_{MS} is the amount of considered sensors and the value N_{TS} is the amount of measuring time steps during the considered stand-by test.

$$f' = \sqrt{\sum_{i=1}^{N_{\mathrm{TS}}} \left(\frac{\sum_{j=1}^{N_{\mathrm{MS}}} \left(\vartheta_{\mathrm{m,j,i}} - \vartheta_{\mathrm{c,j,i}}\right)^2}{N_{\mathrm{MS}} \cdot N_{\mathrm{TS}} \cdot {\vartheta_{\mathrm{ref}}}^2} \right)} \qquad \text{(eq. 6)}$$

This approach for the calculation of the target value is similar to the calculation method in (John, 2002), in which the heat loss rates of a store with a volume of 85 m^3 is successfully identified by parameter identification with the Multiport Store-Model.

The charging and discharging characteristics of the Multiport Store-Model with volumes between 5 m^3 and 100 m^3 are assumed to be equal to stores with volumes lower than 5 m^3. This is indicated in (John, 2002), due to a validation of the Multiport Store-Model for a store with a volume of approximately 85 m^3. Hence, no modifications in the Multiport Store Model regarding the charging and discharging characteristics are necessary. Model parameters for the charging and discharging characteristics are for example the height of the input and output flow ports, the number of nodes in the store volume and a local turbulent thermal conductivity (Drück, 2007). However, the currently known test methods according to EN 12977-3 (2012) and EN 12977-4 (2012) for the identification of the charging and discharging parameters are again not applicable to stores with volumes greater than 5 m^3 for the previously mentioned reasons. The following investigations only consider the thermal behaviour of a long-term thermal energy store respectively a stand-by heat loss test of a store, so these charging and discharging model parameters don’t have to be identified.

With the above-described procedure for determining the model parameters three stand-by tests of the store with a volume of 12 m^3 and with a vacuum and transparent thermal insulation are exemplary analyzed. These tests include a stand-by test with an inhomogeneous starting temperature distribution in the vertical direction (test 1), a stand-by test with a homogeneous starting temperature distribution (test 2) and a stand-by test with a homogeneous starting temperature distribution and an additional thermal insulation of the bottom of the store (test 3). The mean daily irradiation sum in the horizontal is 5.59 kWh m^{-2} d^{-1} for the duration of 26 days of test 1, 4.54 kWh m^{-2} d^{-1} for the duration of 18 days of test 2 and 2.72 kWh m^{-2} d^{-1} for the duration of 16 days of test 3. The maximum uncertainty of the eleven Pt100 temperature sensors, used for measuring the vertical temperatures in the store, and the eight Pt100 temperature sensors, used for measuring the horizontal surface temperatures of the TTI, is ± 0.35 K. The maximum uncertainty for the pyranometer is ± 1.5 % of the measured value and 0.2 m s^{-1} for the windspeed sensor. A digital data acquisition system measures the measuring values with a time step of 60 s.

3. Results

The following chapter describes a model sensitivity analysis of the surface temperature model and the results of the parameter identification process for measuring data of the three stand-by tests of the thermal energy store with a volume of 12 m^3 and with transparent and vacuum thermal insulation.

3.1. Analysis of the model sensitivity

Due to the dynamic parameter identification of the surface temperature model, typical sensitivity analysis methods for the parameters of the model equation cannot be applied. Therefore, an alternative sensitivity analysis method, called morris method (Morris, 1991), is used to identify the main parameters of the models. A further explanation of the morris method and its extension can be found in (Campolongo et al., 2005; Cropp and Braddock, 2002; Saltelli et al., 2004). The method was successfully implemented in Matlab and tested by means of several test functions compared to literature results. The results of the morris method for the surface temperature model parameter identification show, that the main parameters are $(\tau_g^*\alpha_a^*)$, C_{eff}, h_{ext1}, h_{ext2}, ϵ^*, ρ_{amb}^* and r_0. The parameters h_{w1}, h_{w2} and all individual $h_{\mathrm{int,i\to j}}$ seem to be of small importance. This is indicated in figure 3 (left) by a high value of μ'. A high value of σ' indicates a strong dependency on other parameters or a nonlinear model equation. The range in which the parameters are investigated in the morris method is equal to the range of the parameter identification process.

Further investigations also show, that all eight individual $h_{\mathrm{int,i\to j}}$ cannot not be neglected completely, but can be assumed to be equal for all segments. This finding was confirmed by means of several individual parameter identification processes with a stepwise decrease of the amount of fitting parameters. Exemplary results of the morris method for a decreased amount of parameters are shown in figure 3 on the right side. Only the parameters $(\tau_g^*\alpha_a^*)$, C_{eff}, h_{ext1} and $h_{\mathrm{int,i\to j}}$ are considered. It can be concluded, that due to the parameter reduction the heat losses are characterized completely by h_{ext1}, which is now the most relevant parameter.

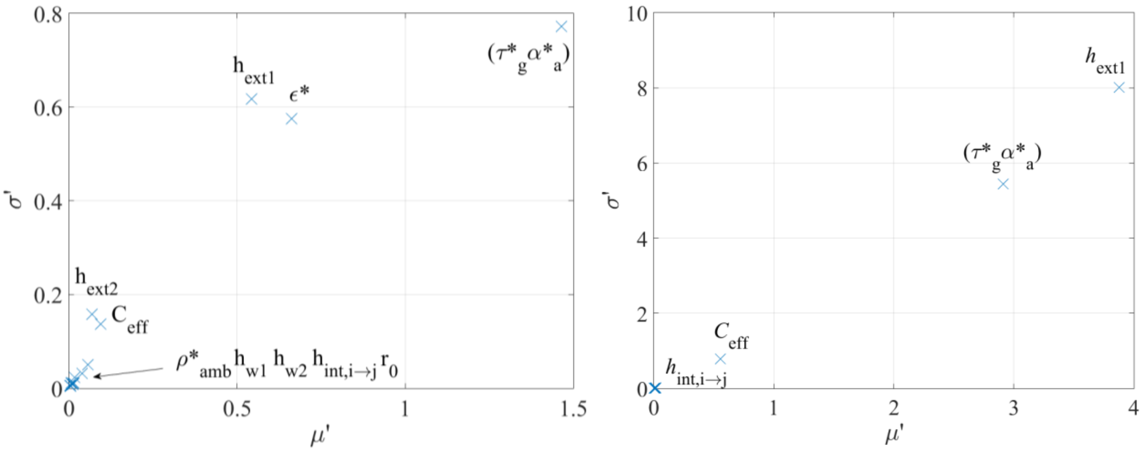

Fig. 3: Results of the morris method ($p' = 50, r' = 2000$, stand-by test 1) for the surface model with all (left) and a reduced amount (right) of parameters

Further investigations concerning the parameter identification process of the surface model show, that there is an influence of the solution algorithm on the target value. A comparison of several Matlab integrated minimization algorithms implemented in the parameter identification process was done. Generic algorithms, especially the particle swarm algorithm, and direct search and simulated annealing methods were investigated. However, these algorithms and methods show no or only slight advantages concerning the target value and the simulation time, compared to the standard interior-point algorithm for the parameter identification of the surface model. Hence, the interior-point algorithm was used for all following parameter identifications.

A second sensitivity analysis, based on the fit results of the parameter identification process for each month of one year of measuring data, is determined. Table 1 summarizes the mean parameter values for all fits for one year and the corresponding standard deviations. The parameter $\bar{h}_{\mathrm{int,i\to j}}$ represents the average of all individual parameters $h_{\mathrm{int,i\to j}}$.

Tab. 1: Selected deviations derived from the cross correlation matrix and mean parameter values of the store model for a monthly parameter identification of one year

	$(\tau^*_g\alpha^*_a)$ in [-]	C_{eff} in kJ K^{-1}	h_{ext1} in W m^{-2} K^{-1}	h_{ext2} in W m^{-2} K^{-2}	$\bar{h}_{\mathrm{int,i\to j}}$ in W m^{-2} K^{-1}	ϵ^* in [-]	ρ^*_{amb} in [-]	r_0 in [-]
mean value	0.60	119.44	3.51	$2.1\cdot10^{-2}$	183.37	$4.70\cdot10^{-3}$	$2.4\cdot10^{-1}$	$3.4\cdot10^{-2}$
standard deviation	0.14	25.47	0.54	$1.2\cdot10^{-4}$	45.15	$7.79\cdot10^{-5}$	$2.4\cdot10^{-2}$	$3.0\cdot10^{-2}$

It can be concluded, that the standard deviation of most of the parameters is in an acceptable range for the interpretation of the results, expect the parameter r_0. The results of parameter r_0 indicate, that the modelling of the incidence angle modifier strongly depends on the season of the year.

3.2. Results of the parameter identification process

Table 2, table 3 and table 4 show a summary of the parameters determined for the surface temperature model and the store model for all stand-by tests mentioned above by means of parameter identification. The determined overall heat loss rate $(UA)_{\mathrm{ov}}$, which is summed up by $(UA)_{\mathrm{man}}$, $(UA)_{\mathrm{top}}$ and $(UA)_{\mathrm{bot}}$, is 6.410 W K^{-1} for the stand-by test 1, 6.618 W K^{-1} for the stand-by test 2 and 5.038 W K^{-1} for the stand-by test 3. The lower overall heat loss rate of the stand-by test 3 results from the additional thermal insulation at the bottom of the store. The higher value of the effective thermal conductivity k_{eff} compared to the material value of water can be explained due to several stratification devices integrated in the store and the store's lateral walls made of steel, which increase the thermal conductivity in the vertical direction. The quite similar results of the overall heat loss rate and of the store's effective thermal conductivity for all three experiments indicate, that the procedure for modeling dynamic ambient conditions respectively for identifying the model parameters provides reasonable and reproducible results.

Tab. 2: Summary of store model parameters and target values

Test	$(UA)_{\mathrm{man}}$ in W K^{-1}	$(UA)_{\mathrm{top}}$ in W K^{-1}	$(UA)_{\mathrm{bot}}$ in W K^{-1}	$(UA)_{\mathrm{ov}}$ in W K^{-1}	k_{eff} in W m^{-1} K^{-1}	f in [-]
1	2.412	0.122	3.874	6.410	1.553	0.087
2	1.876	0.142	4.599	6.618	1.595	0.009
3	2.404	0.053	2.582	5.038	1.611	0.022

Tab. 3: Summary of surface model parameters and target values (part 1)

Test	$(\tau^*{}_{\mathrm{g}}\alpha^*{}_{\mathrm{a}})$ in [-]	C_{eff} in kJ K^{-1}	h_{ext1} in W m^{-2} K^{-1}	h_{ext2} in W m^{-2} K^{-2}	$\bar{h}_{\mathrm{int,i\to j}}$ in W m^{-2} K^{-1}
1	0.670	136.093	3,928	0.011	199.488
2	0.695	135.876	4.657	0.010	171.235
3	0.574	110.780	3.561	0.026	164.316

Tab. 4: Summary of surface model parameters and target values (part 2)

Test	ϵ^* in [-]	ρ^*_{amb} in [-]	h_{w1} in s m^{-1}	h_{w2} in J m^{-3} K^{-1}	r_0 in [-]	f in [-]
1	0.010	0.231	0.019	1.172	0.028	0.427
2	0.006	0.239	0.018	0.939	0.016	0.369
3	0.004	0.230	0.005	0.492	0.023	0.312

If the averaged sum of the heat loss rate of the mantle and the top for all three experiments is converted to an effective thermal conductivity with the assumption of an one-dimensional heat transfer, a calculated effective thermal conductivity for the vacuum thermal insulation of $13.3\cdot10^{-3}$ W m^{-1} K^{-1} is obtained. This value is 11 % higher than the value expected from laboratory measurements of $12.0\cdot10^{-3}$ W m^{-1} K^{-1} (Gerschitzka et al., 2016).

The value of the effective heat capacity used in the surface temperature model exceeds the theoretically expected value of a cylindrical metal sheet with same dimension as the store's outer surface steel sheet by 10 %. This indicates, that a part of the pourable filling material of the vacuum thermal insulation also acts as a thermal capacity.

The values of the heat transfer coefficient from the surface to the ambience are within the expected range of free convection at a vertical cylinder. The transmittance-absorptance-product for all stand-by tests falls below the theoretical value of an incidence angle of 90° by 18 %. This can be explained due to the simplified calculation of the incidence angle modifier by only one parameter for all segments. The remaining coefficients of the surface model are within the expected range.

The target value according to eq. 6 multiplied by ϑ_{ref} can be interpreted as mean deviation between the calculated and the measured temperatures of the store and surface temperature model. According to this interpretation, the mean deviation of 0.39 K from the calculated and measured temperatures of the store parameter identification shows very good results and the mean deviation of 3.70 K from the calculated and measured temperatures of the surface parameter identification shows acceptable results.

For an exemplary presentation figure 4 shows the measured and calculated temperatures of the south-orientated surface of the transparent thermal insulation and the hemispherical respectively diffuse solar irradiation for the first three days of the stand-by test 1. Despite some deviation during the time of maximum temperatures, the results of the calculation of the southward-orientated surface temperature fit quite well. It has to be considered, that only the hemispherical und diffuse solar irradiation, the wind speed and the ambient temperature are available as input values. Furthermore, the surface temperature model does not take shadings into account. These occur in the morning and evening of the considered days and are caused by the horizon and neighboring buildings.

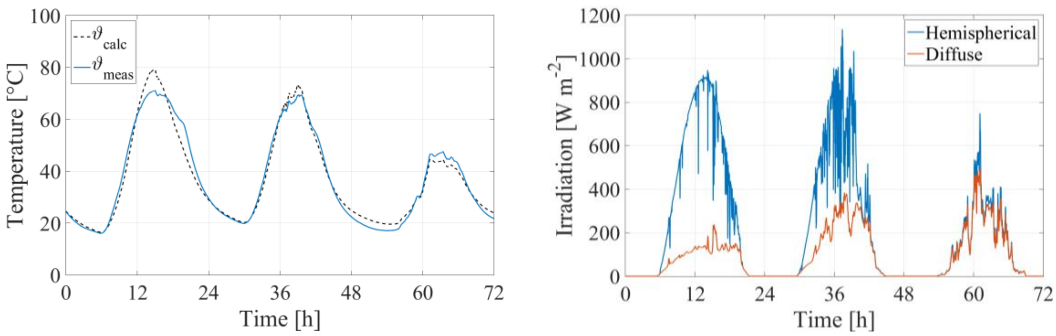

Fig. 4: Measured and calculated temperature of the south orientated surface of the transparent thermal insulation (left) and the south orientated hemispherical respectively diffuse solar irradiation (right)

If the previous calculation method for the heat losses of the store according to equation 1 is used, the determined heat loss rate of the store mantel $(UA)_{\text{man}}$ is on average 30 % lower than the heat loss rate of the store mantle for all three stand-by tests calculated according to equation 5. The reduction of $(UA)_{\text{man}}$ is 38 % for the stand-by test 1, 33 % for the stand-by test 2 and 19 % for the stand-by test 3. These results correspond with the mean daily radiation sum for the three stand-by tests. The heat loss rate decreases, because the positive effect of a lower temperature difference over the vacuum thermal insulation is taken into account for the parameter identification of the heat loss rate. Derived from these results, the importance of the consideration of the surface temperature calculation for the heat loss rate determination can be seen.

4. Conclusions

It can be summarized, that additional effects for the characterization of the heat losses of an outdoor installed hot water store have to be taken into account compared to an indoor installed one. These effects can be described by means of the developed combination of the surface temperature model and the store model. The novel calculation of the outer store surface temperature is applied to separate surface segments of the store's lateral area in circumferential direction. These surface temperatures are used for the calculation of the heat losses of the modified store model derived from the well-known Multiport-Store Model from TRNSYS. An evaluation of both model parameter identification processes using three stand-by tests show reasonable and reproducible results, compared to theoretical, material based values. Based on the identified model parameters of both models, the detailed characterization of the heat losses of outdoor installed hot water stores for long-term thermal energy storage is possible. A comparison of the identified model parameters using the previous and the novel surface temperature calculation method shows, that the dynamic ambient conditions can have a significant influence on the heat loss rate of a hot water store. A mean change of the mantel heat loss rate of 30 % in the parameter identification process due to the surface temperature calculation cannot be neglected.

Future work will deal with the development of a more detailed node model for the surface temperature calculation, especially to account for a vertical temperature gradient. It is also planned to optimize the surface temperature model for thermal energy stores in outdoor installation with no transparent thermal insulation, especially for the 100 m^3 store of the project OBSERW. For stores of this kind, the influence of the wind speed could be more relevant for the surface temperature calculation than for stores with transparent thermal insulation.

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Nomenclature

A	Projected area of the TTI [m^2]	A'	Area of the TTI [m^2]
A''	Cross section area of the TTI [m^2]	C_{eff}	Effective thermal capacity of one TTI segment [kJ K^{-1}]
f'	Target value [-]	$G_{\mathrm{hem,dir}}$	Direct hemispherical solar irradiance [W m^{-2}]
$G_{\mathrm{hem,diff}}$	Diffuse hemispherical solar irradiance [W m^{-2}]	G_{glob}	Global solar irradiance [W m^{-2}]
h_{ext1}	Heat transfer coefficient from store to the ambience [W m^{-2} K^{-1}]	h_{ext2}	Temperature dependent heat transfer coefficient from store to ambience [W m^{-2} K^{-2}]
$h_{\mathrm{int,i\rightarrow j}}$	Heat transfer coefficient within the TTI [W m^{-2} K^{-1}]	$\bar{h}_{\mathrm{int,i\rightarrow j}}$	Mean heat transfer coefficient within the TTI [W m^{-2} K^{-1}]
h_{w1}	Parameter of the wind speed dependency of the TTI heat losses [s m^{-1}]	h_{w2}	Parameter for the wind speed and irradiation dependency of the TTI heat losses [J m^{-3} K^{-1}]
K_{b}	Incidence angle modifier [-]	k_{eff}	Effective thermal conductivity of the storage medium water [W m^{-1} K^{-1}]
p'	Discretization parameter of the morris method [-]	N_{TS}, N_{MS}	Number of time steps, number of measuring sensors [-]
$\dot{Q}_{\mathrm{hl}}$	Heat flux caused by the heat losses of the store [W]	r'	Number of runs of the morris method [-]
r_0	Fitting parameter for the incidence angle modifier [-]	T_{amb}	Ambient temperature [K]

T_{sky}	Sky temperature [K]	$T_{\mathrm{suf,old}}$	Surface temperature of the TTI at the previous time step [K]
(UA)	Heat loss rate [W K^{-1}]	$(UA)_{\mathrm{bot}}$	Heat loss rate of the bottom of the store [W K^{-1}]
$(UA)_{\mathrm{man}}$	Heat loss rate of the mantle of the store [W K^{-1}]	$(UA)_{\mathrm{top}}$	Heat loss rate of the top of the store [W K^{-1}]
$(UA)_{\mathrm{ov}}$	Overall heat loss rate of the store [W K^{-1}]	w	Wind speed [m s^{-1}]
ϑ_{amb}	Ambient temperature [°C]	$\vartheta_{\mathrm{calc}}$	Calculated temperature [°C]
$\vartheta_{\mathrm{c,j,i}}$	Calculated temperature of the sensor j at the time step i [°C]	$\vartheta_{\mathrm{m,j,i}}$	Measured temperature of the sensor j at the time step i [°C]
ϑ_{ref}	Reference temperature for the target value calculation [°C]	ϑ_{sto}	Store temperature of the storage medium water [°C]
ϑ_{suf}	Surface temperature of the TTI [°C]	$\bar{\vartheta}_{\mathrm{suf}}$	Mean surface temperature of the TTI [°C]
$\vartheta_{\mathrm{suf,old}}$	Surface temperature of the TTI at the previous time step [°C]	$\vartheta_{\mathrm{meas}}$	Measured temperature [°C]
ϵ^*	Parameter of the emittance of the TTI [-]	${\rho^*}_{\mathrm{amb}}$	Ground reflectance of the ambience [-]
$({\tau^*}_{\mathrm{g}}{\alpha^*}_{\mathrm{a}})$	Transmittance-absorptance-product of the TTI [-]	μ'	Evaluation parameter of the parameter relevance [-]
σ'	Evaluation parameter of the parameter correlation to other parameters [-]	σ	Stefan-Boltzmann constant [W m^{-2} K^{-4})]
Δt	Time step [h]	Θ	Incidence angle [°]

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