Validation of Thermocline Storage Model with Experimental Data of a Laboratory-Scale Molten Salt Test Facility

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Abstract. The Fraunhofer ISE single-tank simulation model was parameterized and inputs were set according to the Fraunhofer ISE lab-scale storage tank in order to validate the model. The measured stratification during the charging cycle was compared to the temperature distribution of the simulated storage tank. If the effective diffusivity factor was calculated according to literature correlations, it corresponded very well with the measurement data with a mean standard deviation of 1.21%. A parameter identification for the effective diffusivity factor of the storage was performed to reduce these deviations even further. It showed that the ideal effective diffusivity factor is 150. The mean standard deviation was further reduced to 1.14 %.

INTRODUCTION

In course of the project ORC-PLUS, a thermocline single-tank model has been developed at Fraunhofer ISE in the system simulation environment ColSim CSP. Furthermore a laboratory-scale molten salt single tank has been built and operated in several test cycles. System description and first measurement results have been published in previous papers [1,2]. In the present paper the comparison of the measured data with the simulation results is the focus. Especially the impact of consideration of turbulences at the storage inlet on the simulated stratification is assessed.

METHODOLOGY

A stratified storage model developed at Fraunhofer ISE was implemented in the in-house simulation software ColSim CSP. ColSim CSP performs fast dynamic system simulations at an adjustable level of detail. The tool is optimized for solar thermal power plants and solar thermal process heat applications. For a customizable plant layout each component can be connected by inputs and outputs and can be described by parameters in a graphical user interface. An extensive library of detailed models for each component in a solar thermal plant exists at Fraunhofer ISE. As the capacity of each component is included, transient effects are accounted for. The developed storage model can be integrated in more complex system setups.

For the thermocline model special emphasis is put on the heat transfer and discretization of convective fluxes with the spatial derivative. The model tries to fill the gap between complex three dimensional CFD models and simplified one dimensional models that use a first order scheme. While CFD models are very runtime intensive, one dimensional models with a first-order scheme often lead to stratification profiles that highly depend on the number of nodes and are therefore prone to numerical errors. System simulations are usually performed for one full year, so acceptable computing time for all component models involved is a prerequisite. For this reason a one dimensional model is implemented. To reduce the numerical error of a first order scheme, a third order scheme is used in the here described model. The used QUICK scheme is usually applied to all convective fluxes in CFD software [3]. As this scheme may often lead to oscillations, the ULTIMATE scheme was used for limiting the unphysical rise of fluxes [4].

Beside the implementation of the stratification, other destratification effects are taken into account. Firstly the heat conduction in the tank wall is considered, which is particularly relevant for small storages with a rather high wall area to volume ratio, like it is the case for lab-scale storages. Secondly turbulence at the storage inlet is considered as a further contributor to the widening of the thermocline.

The turbulence at the storage inlet and resulting mixing depends on inlet diffuser design and the process parameters such as flow rate and temperature difference. The higher the ratio between buoyant and inertia forces the less mixing occurs. There are several approaches to account for mixing processes. For this model Zurigats approach [5] is chosen which introduces an effective diffusivity factor ε_{eff} which enhances the diffusive fluxes.

$$\varepsilon_{eff} a \frac{\partial^2 T}{\partial x^2} \tag{1}$$

This approach is thus similar to a turbulent thermal diffusivity in CFD software packages. Whereas CFD packages are using the actual flow pattern and the boundary conditions to calculate this parameter, simplified models have to rely on empirical correlations. The factor depends first of all on the position in the storage and decreases from the maximum value at the inlet ε_{in} to 1 at the outlet. The inlet value depends on the inlet type and the ratio between Reynolds and Richardson number. Zurigats introduces equations for three inlet types: side inlet, perforated inlet and impingement inlet.

Side inlet: $$\varepsilon_{eff}^{in} = 0.344 \left(\frac{Re}{Ri}\right)^{0.894} \tag{2}$$

Perforated inlet: $$\varepsilon_{eff}^{in} = 3.540 \left(\frac{Re}{Ri}\right)^{0.586} \tag{3}$$

Impingement inlet: $$\varepsilon_{eff}^{in} = 4.750 \left(\frac{Re}{Ri}\right)^{0.522} \tag{4}$$

The quality of stratification is shown by plotting the temperature measurement next to the simulation results along the height of the storage tank for different time steps. For each time step the standard deviation in temperature is calculated. In this paper the influence of consideration of wall effects and effective diffusivity factor is assessed. Parameter identification was performed to identify the effective diffusivity factor that leads to the lowest standard deviation. The parameter was then compared to Zurigats equation for impingement inlet.

RESULTS AND DISCUSSION

The simulation model is parametrized according to the design of the test facility. Mass flow, inlet temperature and initial storage fluid temperature of the charging cycle are used as model inputs. The inlet temperature is controlled to be around 395 °C, the initial storage temperature is approx. 295 °C. The mass flow ranges from 936 to 1296 kg/h, so from 0.26 to 0.36 kg/ s respectively. The inlet temperature and mass flow of the evaluated charging cycle are shown below.

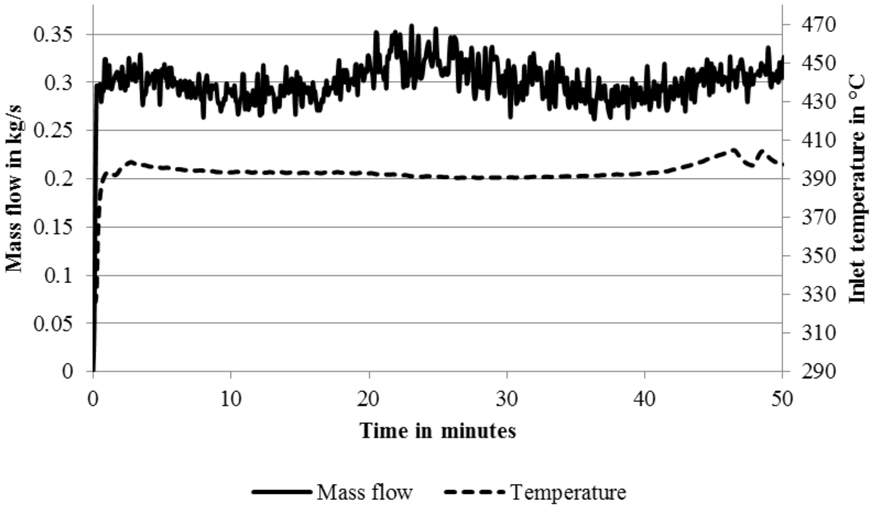

FIGURE 1: Mass flow and inlet temperature into lab-scale stratified one-tank storage

With the parameters and inputs mentioned above one charging cycle is simulated. The resulting temperature distribution over time is now compared to the measurement results of the thermocouples located in the center of the lab-scale storage vessel. First, no wall effects and turbulences at storage inlet are considered. The comparison of simulation and measurement results is shown in FIGURE 2. Especially the thickness of the thermocline is very different for all time steps. The standard deviation for all measurement points is 6.34 K. The model gives rather poor results.

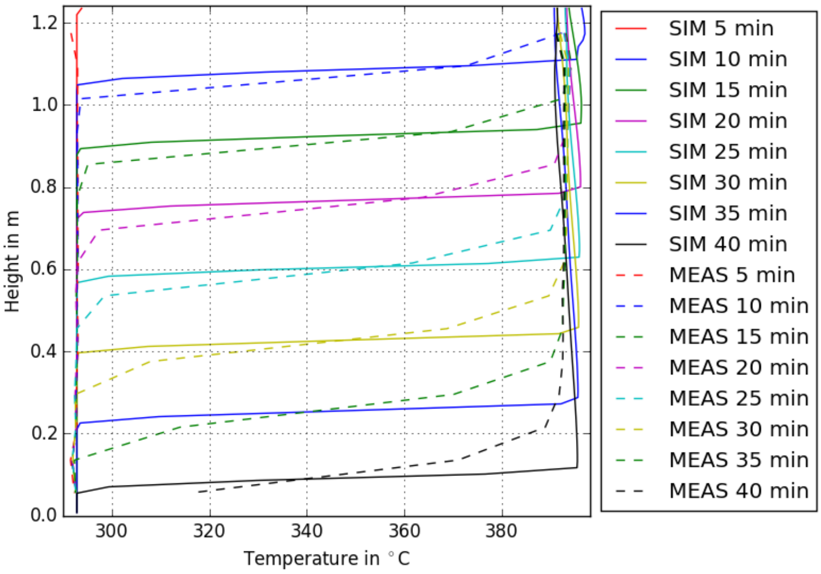

FIGURE 2: Measured temperature distribution of charging cycle compared to simulation results, if no turbulences and wall effects are considered

Destratification effects as thermal conduction in tank wall as well as turbulences that occur at the storage inlet have a big impact on the thickness of the thermocline. To consider turbulences at the storage inlet, however, the effective diffusivity factor has to be known. Based on the equation for impingement inlets given the methodology chapter the effective diffusivity factor was calculated. As shown in FIGURE 3 the inlet diameter is 34 mm.

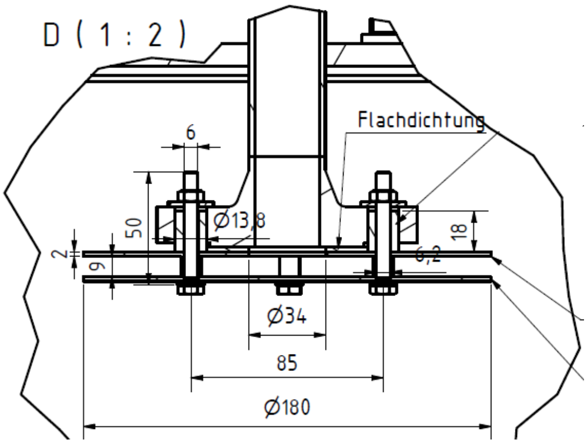

FIGURE 3: Double-plate radial diffuser of the storage tank.

The Reynolds number Re can be calculated from the mean velocity at the storage inlet and kinematic viscosity. The Richardson number Ri can be calculated from the mean velocity at the storage inlet, storage height and other fluid properties. The resulting Reynolds number of 6167 and the resulting Richardson number of 14.53 lead to an effective diffusivity factor of 112.

$$\varepsilon_{eff}^{in} = 4.750\left(\frac{6167}{14.53}\right)^{0.522} = 112 \tag{5}$$

If this effective diffusivity factor is applied, the simulation results are much closer to the measured values. This is shown in FIGURE 4. The comparison already shows that the selection of the effective diffusivity factor has big impact on the stratification profile. The standard deviation for this validation is only 4.31 K.

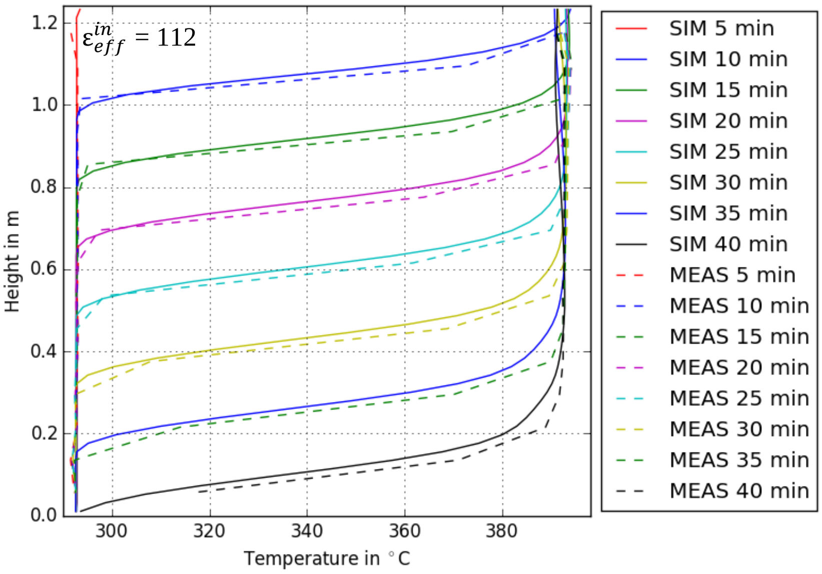

FIGURE 4: Measured temperature distribution of charging cycle compared to simulation results for effective diffusivity factor of 112.

To determine the ideal effective diffusivity factor a parameter variation is performed. Simulations are run for effective diffusivity factors from 100 to 200 to see the impact on the standard deviation of measurement and simulation results. The results are shown in table TABLE 1. The minimum standard deviation of 4.139 was obtained for a thermal diffusivity factor of 150.

TABLE 1: Standard deviation in K of simulation and measurement results for several effective diffusivity factors

Effective diffusivity factor ε_{eff}^{in}	Standard deviation in K	Percentage
100	4.312	1.230
130	4.145	1.157
150 (Minimum)	4.139	1.139
170	4.176	1.139
200	4.286	1.159

However, the deviation is very close to the one obtained for effective diffusivity factor of 112. As shown in FIGURE 5 the improvement is almost not visible to the naked eye.

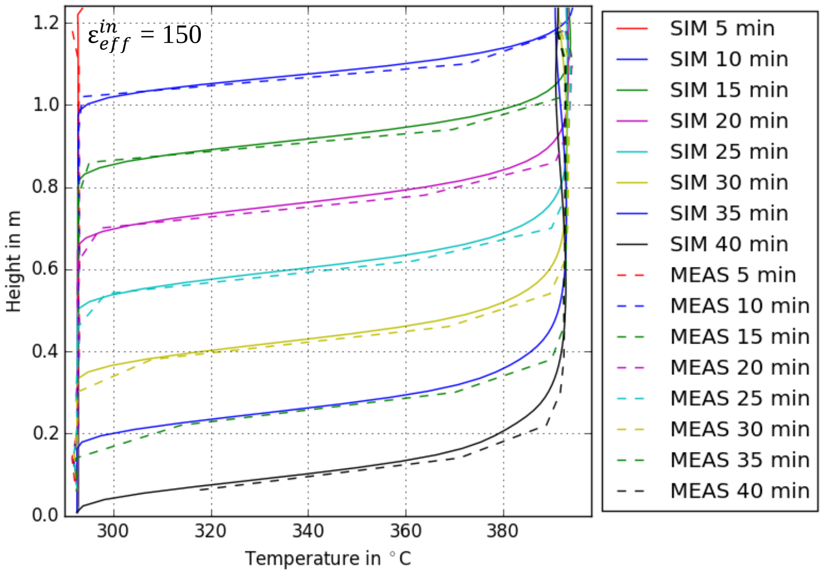

FIGURE 5: Measured temperature distribution of charging cycle compared to simulation results for effective diffusivity factor of 150.

The standard percentage deviation of each measurement point for the case with diffusivity factor of 150 is 1.39 %, while the actual percentage deviation is only 0.51 %. The validation with literature equations shows that the effective diffusivity factor of 112 is a good estimate. The validation shows that stratification can be modelled very accurately with the described model.

CONCLUSION

The Fraunhofer ISE single-tank simulation model was parameterized and inputs were set according to the Fraunhofer ISE lab-scale storage tank. The measured stratification during the charging cycle was compared to the temperature distribution of the simulated storage tank. If the effective diffusivity factor was calculated according to literature correlations, it corresponded very well with the measurement data with a mean standard deviation of 4.31 K.

Parameter identification for the effective diffusivity factor of the storage was performed to reduce these deviations even further. It showed that the ideal effective diffusivity factor for the lab-scale storage tank is 150. The standard deviation in this case was 4.13 K.

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