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Modeling a Large Thermal Energy Storage System Using RANS Turbulence Models and High-Resolution Measurement Data

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Abstract – A novel approach to model sensible Thermal Energy Storage (TES) Systems has been developed. Three separate models are used to model the overall system. High-resolution isothermal models are used to simulate the flow around the inlet and outlet diffusers. Velocity data is then used to provide accurate boundary conditions for a simplified non-isothermal model to model the temperature distribution and flow in the main body of the TES. In this short paper, a laminar model is compared with 2 turbulent models and measurement data. Analysis shows the need for further work as the thermocline width increases much faster in all numerical models than seen in the measurement data.

Keywords**:** Numerical Study, Turbulence, Natural Convection, Thermocline, Thermocline Width, Thermal Energy Storage

1. Introduction

The increasing usage of primary energy sources associated with substantial supply volatility requires the use and development of efficient energy storages. Thermal Energy Storage (TES) Systems fill this role in regards to thermal energy used for heating. When used in concert with combined heat and power (CHP) plants, TES systems can help decouple heat and electricity demand and improve efficiency [1]. One common form is the sensible TES system using water. Especially when the water in the storage tank is thermally stratified, this TES system is highly efficient [2]. Mixing of the distinct temperature layers however leads to destratification and a loss of exergy [3]. Four factors are primarily responsible for destratification [4]: Heat losses to the environment, heat conduction between the separate layers, heat conduction in the storage tank walls and other hardware and mixing caused by charge and discharge processes. These factors lead to turbulent natural convection through which the destratification occurs. Additionally, energy losses to the environment directly reduce the energetic efficiency of the system [5].

Not many researchers have looked into numerical modeling of large TES systems. Streckiene et al. [6] presented a two-dimensional numerical model of a TES using a finite volume approach implemented in the commercial software PHOENICS. The model was validated using data from a TES with a gross volume of 1960 m^3 at the CHP plant in Hvide Sande, Denmark. The presented numerical model showed a relative discrepancy from 0.21 % to 3.66 % when compared to the measurement data, which represented an improvement compared to analytical modeling of the TES, whose relative discrepancy varied from 0.22 % to 5.00 %. Further studies of the same authors expanded this work with the implementation of a three-dimensional model and a focus on charge and discharge operation [7]. While no significant differences between the two-dimensional and the three-dimensional model were found, this showed the feasibility of this method.

Kocijel et al. [8] performed further studies using the software package FLUENT. Their work was focused on the influence of various parameters, such as aspect ratio, the inlet position, temperature difference between the warm and cold water and volumetric flow rate, on TES performance and stratification.

Findeisen et al. [9]-[11] studied the influence of diffuser design and operation on the flow and temperature distribution in the direct vicinity of the diffuser using high-resolution RANS turbulence models such as the SST-k-ω-model. They clearly demonstrated the need for turbulence modeling when analyzing TES of this type, most pressingly in the regions in and around the upper and lower radial diffusers.

2. Methods

To facilitate high-resolution modelling of the entire TES system, the computational domain is divided into 3 separate models. Two of these models describe the upper and lower radial diffuser, respectively. The third model covers the entire TES tank and is connected with the other two models via tabulated velocity profiles for charge and discharge flow cases. All models are built using the FEM software package COMSOL Multiphysics 5.6.

2.1. Radial Diffuser Models

The flow inside the upper and lower diffuser is isothermal at all times during normal operation. This allows the usage of an isothermal model for the flow inside these domains, thus reducing computational complexity. Both models are three-dimensional, as an uneven velocity profile around the circumference occurs. The SST-k-ω-model is employed for the turbulence occurring during charging and discharging.

2.2. Tank Model

The entire tank is modelled nonisothermally. As this model covers time periods up to 24 hours, computational efficiency is a major factor. Therefore, the upper and lower diffuser are not modelled in detail and are both represented by a simple inlet/outlet plane in the corresponding position. The velocity profiles generated using the isothermal models are used to apply time-dependent boundary conditions for charging and discharging scenarios. For this work, the performance of a laminar flow model is compared to the k-ε-model and the SST-k-ω-model for a one-hour charging period using the evolution of the thermocline width. The thermocline width is estimated using a SDR-fit as detailed by Mohd et al. [12].

2.3. Measurement Data

Measurement data is obtained from the TES system in use at the waste incineration plant operated by ENTEGA AG in Darmstadt, Germany. This TES system operates at temperatures between 65°C and 99°C with a gross volume of 4300 m^3. 144 temperature sensors inside the tank and temperature and flow rate sensors in the lines leading to the upper and lower diffuser provide high-resolution data.

3. Results

Figure 1 shows the width of the thermocline over time for different model setups in relation to the smoothed experimental data. The laminar flow model, k-ε-model and the SST-k-ω-model were modelled using a mesh consisting of 22057 triangular elements. The laminar flow model shows the best performance, staying reasonably close to the experimental data after a higher initial gradient resulting in a significant discrepancy. The k-ε-model does not level off

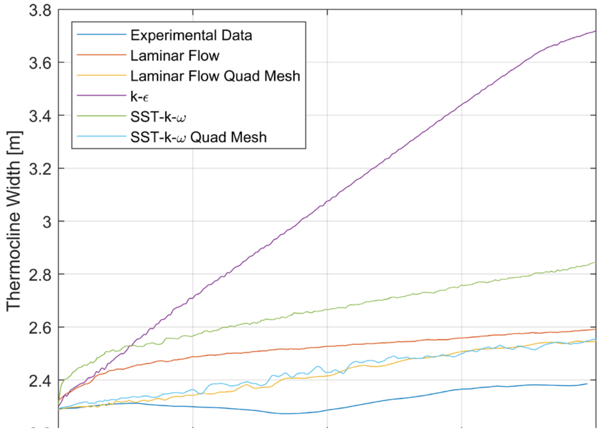

Fig. 1: Numerically calculated Thermocline Width over time compared to experimental data.

resulting in the worst performance out of all models. The SST-k-ω-model performs similar to the laminar flow model but shows a steeper initial gradient and a slightly steeper gradient after 10 minutes. Additionally, the laminar flow model and SST-k-ω-model were modelled using a mesh consisting out of 43693 quad elements. Overall, they perform very similar to each other. These models show a better initial phase and seem to match the overall gradient after 10 minutes of the other SST-k-ω-model quite well. Figure 2 shows the vertical position of the Thermocline in the TES over time for both experimental data and the numerical models. All models seem to track the Thermocline position rather well, but it can be seen that both the laminar model and especially the SST-k-ω-model with the quad element mesh shows higher fluctuations than the rest, while the k-ε-model shows smaller high-frequency fluctuations.

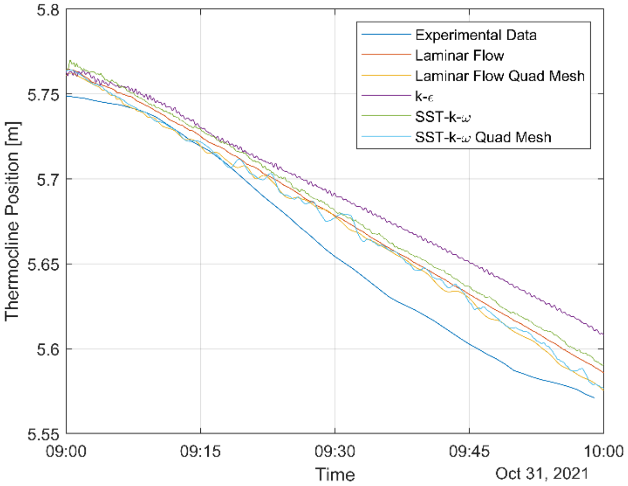

Fig. 2: Numerically calculated Thermocline Position over time compared to experimental data.

4. Conclusion

While the vertical position of the Thermocline is represented well in all numerical models, none of the models represent the measured thermocline width evolution adequately, especially when the shown performance is extrapolated to a longer timeframe such as 24 hours. Therefore, more work is needed to find the reason for the observed discrepancies. After these have been identified and addressed, further optimization of the model is needed to reduce computation time to allow the examination of longer time periods.

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