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Prediction of the Temperature Field Development in Large Heat Storage Tanks for Integration in Network Simulation

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Abstract. Integrating an increasing amount of renewable energy into district heating systems requires thermal energy storages. For the planning and operation of the whole system valid and powerful storage models are essential for implementation in e. g. thermo-hydraulic network simulations and operational optimisation tools. The modelling of large tank thermal energy storages (TTES) up to 60,000 m³ can be insufficient by using a simple energy balance model as it does not provide information about the temperature profile. The detailed model called FreeTTES is capable of predicting the temperature distribution inside a large atmospheric TTES. This model simplifies fluid dynamic processes by assuming horizontal homogeneity and analyses them only in vertical direction. The analytical fluid mechanics approach is combined with numerical, measurement data-based approaches. The validation of the model is performed using DTS (distributed temperature sensing) data.

Keywords: Thermal Tank Energy Storage, Distributed Temperature Sensing, District Heating, Simulation

1. FreeTTES Model

1.1 Modelled objects

The main goal of FreeTTES is to model the temperature distribution inside large atmospheric Tank Thermal Energy Storages based on the HEDBÄCK principle. Figure 1 gives an overview of three measured TTES and their geometrical properties.

Figure 1. *Overview of measured and simulated atmospheric TTES*

Figure 1 shows a simplified cross section of such cylindrical steel tanks on the left. The charging and discharging take place via specially constructed diffusers at the top and the bottom of the tank. Above the water level in the cylindrical part there is a steam zone that serves to protect against corrosion and is normally kept slightly above atmospheric pressure. The roundabout atmospheric pressure at the top limits the maximum operating water temperature to 98 °C. Unlike pressurized TTES, atmospheric tanks can be built larger and cheaper. The model was developed with the help of the DTS (Distributed Temperature Sensing) measurement data (see Chapter 6.5 in [1]). The DTS system in use enables a temperature resolution of ± 0.24 K and a spatial resolution of 12.6 cm along a vertical fibre optic cable. A special configuration of the fibre optic cable (Figure 2, right), developed for another project, has been installed in multiple large TTES already and enables detailed analysis of the temperature field during phases of static and dynamic operation.

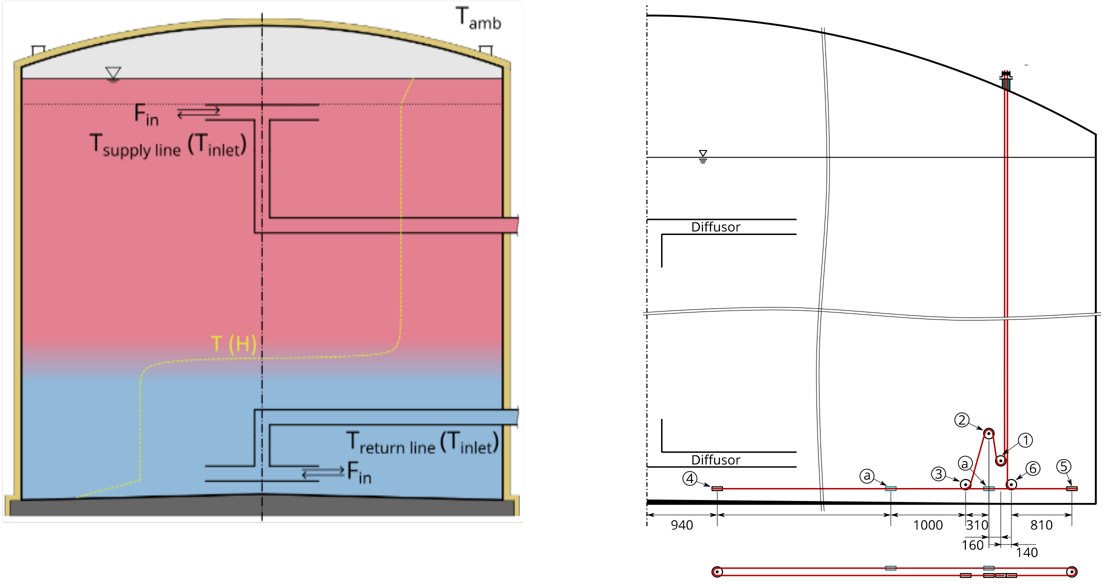

Figure 2. *Simplified cross section of atmospheric TTES based on the* HEDBÄCK *principle. Left:* F_{in} *- volume flow,* $T_{return\ line/supply\ line}$ *(*T_{inlet}*) - inlet water temperature,* T_{amb} *- ambient temperature. T(H) depicts an example of the temperature profile.*
Right: example of DTS fibre cable installation scheme; displayed values are measured in mm.

The DTS measurements from TTES 5 and 8 were used to develop the FreeTTES model. TTES 10 was used to extrapolate the application and validation of the model to larger volumes.

1.2 Features of the model

FreeTTES is a 1D analytical-numerical plug-flow model for atmospheric tank thermal energy storages written in Python within the TWINopt project (see 4). It is based on ideas and a Perl-Script of HERWIG – developed during the project SPICE [2] – and works by assuming horizontal homogeneity which was confirmed by DTS measurements. FreeTTES models heat losses, conduction, fluid mixing, fluid inversion and other construction-specific effects. The model uses inlet water flow and temperature as input, and calculates the vertical water temperature distribution inside, as well as the temperature at the outlet side. Figure 2 shows necessary inputs for the model on the left (text in black). To function properly, the model relies on various inputs such as current time, time step length, inlet and outlet water volume (or mass) flows, temperature of the inlet water and the ambient temperature. Additionally, a special configuration file contains information on the storage construction parameters like height and inner radius of the tank, the positions and geometries of the diffusers. In addition to that the file contains specific thermohydraulic parameters – thermal transfer coefficients of the tank walls including insulation and the bottom plate as well as necessary initialization parameters. The model can be initialized either by providing a starting state in form of a vertical temperature profile, or by artificially creating one with given bottom and top temperatures and a charge factor (ratio of “hot” water mass to “cold” water mass).

The model was developed based on several key assumptions and tested on storage tanks larger than 3,500 m³. Its performance on smaller tanks like those for household applications was not evaluated. Another important assumption is the design of the diffusers; they are designed to allow water to enter with very low velocity in a horizontal free jet. Furthermore, the inlet and outlet pipes within the storage tank are assumed to be double-walled as a special kind of insulation; therefore, heat transfer through the pipe walls is neglected.

The 1-D model of FreeTTES depicts an atmospheric TTES as a sequence of fluid cells with the following attributes: vertical position of the cell, its temperature, height, vertical and horizontal impulse. The horizontal impulse is used only for modelling the inflow of the water into the tank and its immediate interaction with the surrounding layers. The number of cells and the degree of discretization is dynamic and depends on the temperature gradient. Usually the number of cells is higher than 1000.

Considering only one dimension causes a loss of information. While the horizontal homogeneity was demonstrated with measurements, slight variations in the temperature and density can cause convection currents that will not be taken into consideration. This can lead to deviations between simulated and measured temperatures. The benefit of the simplification is the runtime performance of FreeTTES in contrast to higher dimensional CFD simulations.

1.3 Modelling of the inversion process

An inversion occurs when colder fluid is injected during the charging process, compared to the fluid at the top of the tank. Conversely, it occurs when warmer fluid is injected during discharging, relative to the fluid at the bottom of the tank. Due to differences in temperature and density, the newly injected fluid plume is moved by the buoyancy force. It is continuously mixing with the surrounding fluid, cooling or warming it during its path. The inversion plume also drags along some of the surrounding fluid and leaves behind some of the newly injected liquid adding to the mixing process. It stops once it reaches the same temperature – and therefore density – level. A typical form of an inversion plume can be seen in Figure 3. The left picture shows a form of the inversion plume in an experiment. The picture on the right shows how warmer medium with a temperature $T_{inversion}$ is entering into a colder medium with a temperature T_{medium} (H_0) and rising due to buoyancy until it reaches temperature $T^*_{inversion}$ similar to T_{medium} (H_1). At that point it stops rising and spreads at that height.

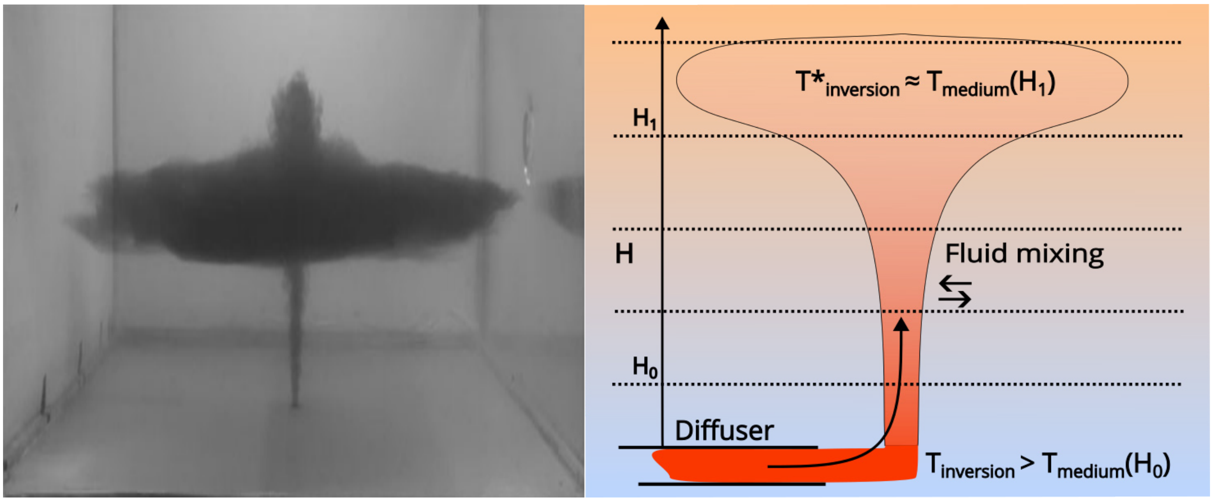

Figure 3. *Single phase inversion plume – Left: example discharging process [3]; Right: simplified sketch with relevant values*

The development of an algorithm simulating the effect of an inversion, based on observations (real data from Pt100-sensors and DTS measurement systems) and theoretical considerations, was achieved by HERWIG. The modelling of the inversion introduces parameters that are manually chosen in order to adjust the overall performance of the model. One of these parameters introduces a mass exchange between a “moving” cell that is the inversion and the “stationary” cell that represents the surrounding medium. This exchange factor depends on the discretization level, flow rate and time step length. Another parameter, which adjusts the impulse balance slightly, just depends on the time step length. Parameters vary depending on the process – whether the inversion occurs during the charge or discharge. The general validity of these parameters has not yet been determined. New validation results of the FreeTTES model with storage tanks of different geometry and operational parameters are currently underway and first results of TTES 10 are introduced in the next section. With more measurements from large TTES of different sizes and parameters it will be possible to generalize the model to simulate the behaviour of all large atmospheric TTES units.

2. Validation

2.1 Methodology

The model delivers the vertical temperature profile, among other values, as its output. At the moment the main performance (accuracy) evaluation consists of a visual comparison of the simulated temperature profile (FreeTTES) and the measured one (DTS). An absolute deviation of less than1 K at the same height is considered as good performance. Higher deviations need to be investigated in detail in the future. Slightly higher absolute deviations in the high temperature gradient zones (thermoclines) are not viewed as critically, as they are typically caused by discretization and interpolation inaccuracies.

At first the original model written in the Perl programming language by HERWIG was translated to Python in order to make it more flexible for future integrations. The following pre-validation stage consisted of comparing the results of the Perl and Python models which should produce identical outputs. The difficulties at that point were the float number representation and the subsequent precision and rounding errors that can lead to slightly different results. After code refining, the next step was to validate the model's performance by comparing its simulated temperature profile with data from the newly-measured TTES 10. Since this storage tank has different geometrical and operational parameters than those that were used in the initial development of FreeTTES (TTES 5 and 8), the comparison demonstrates the model's general applicability.

The newly built TTES 10 is equipped with various sensor systems provided by the operator. The data includes readings from 53 Pt100 sensors that measure the vertical temperature profile inside the storage tank. The distance between Pt100 sensors is 76.5 cm, with the lowest one positioned 15 cm above the ground. Top sensors are occasionally above the water surface, depending on the current water level. This information is further enhanced by the DTS measurement system, which offers an even finer resolution of the temperature distribution within the tank. The DTS cable is installed as depicted in Figure 1 on the right (red line). The distance to the wall where the Pt100 sensors are installed is around 1 m.

The storage tank is currently in its testing phase, providing an excellent opportunity to evaluate the model under extreme and unlikely conditions. The preferred temperature distribution typically includes two distinct temperature levels and one transition (thermocline) between them. An example of such a distribution T(H) can be seen in Figure 1 on the left (yellow curve) considering the x-axis to be the temperature and the y-axis to be the height. During normal operation the operator will try to maintain this kind of state by controlling the inlet water temperatures. However, when the inlet water temperature varies strongly with time, it creates multiple stratified temperature levels with multiple thermoclines between them like in Figure 8 a). Such a state is sub-optimal and undesired as it decreases the usable energy defined by a certain temperature threshold.

All of the validation examples will be presented with a state before the process and the state after the process, for example Figure 4 a) and b). In addition, a flow and temprature graph will provide information about volume flow, supply and return line water temperatures. A positive volume flow indicates charging, while a negative flow means discharging. During charging the inlet water comes from the supply line and the outlet water goes to the return line. During the discharge the process is reversed – the water from the return line becomes inlet water and the outlet water goes to the supply line.

2.2 Charging process

An example of an unlikely temperature distribution during normal operation is illustrated in Figure 4 a). The temperature profile indicates two distinct water temperatures at 56 °C and 86 °C, but it also shows that there is hotter water than that which cannot be described by a single temperature value. This is undesirable, because of the difficult estimation of usable energy and the varying outlet temperature.

The charging process starts at 08:30 and ends around 16:00. The flow rate during that time reaches values between 1,000 and 2,000 m^3/h. The inlet water temperature entering through the upper diffuser is 98 °C. It can also be observed how the return line water temperature starts rising between 13:00 and 14:00, corresponding to the bottom layers of water with rising temperatures being discharged out of the tank (region between 6 and 8 meters in Figure 4 a).

It can be observed how the injected water creates a new distinct temperature level. The deviation between the measured and simulated temperature profiles does not exceed 1 K, which indicates a good performance of the model. The FreeTTES model predicts the rise of the return line water temperature which is an important aspect for district heating simulations.

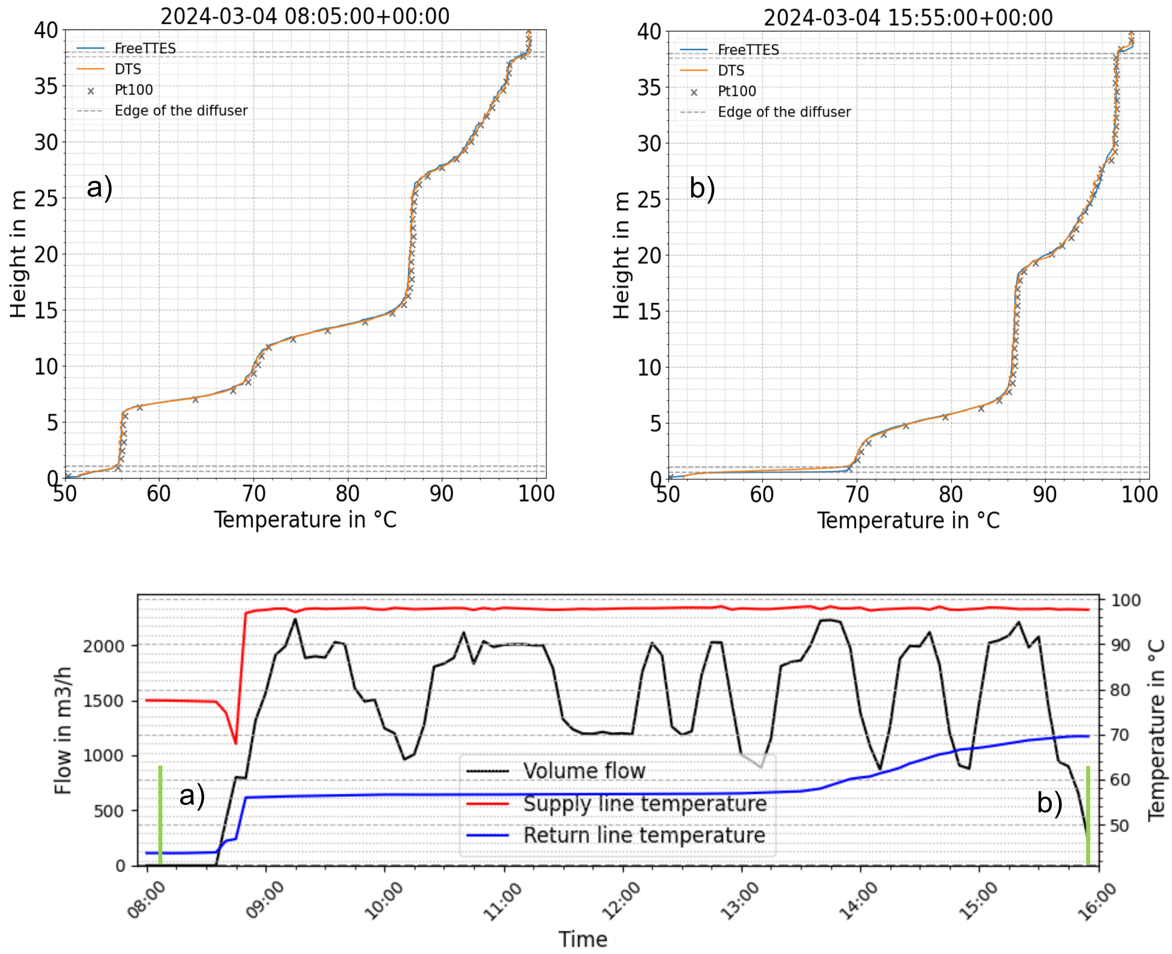

Figure 4. *TTES 10: Charging process – comparison of Pt100 and DTS measurements with FreeTTES-simulation results. a) temperature distribution before the charging process. b) distribution after 7 hrs charging. Below: time course of volume flow, supply line and return line water temperature; green lines show corresponding timestamps a) and b)*

2.3 Discharging process

The comparison of a discharging process is demonstrated in Figure 5. Again, the initial state is an unlikely situation emerged during the testing phase of the storage tank. There are two distinct temperature levels at 56 °C and 87 °C. Around 70 °C there is another temperature level which is characterized by a slight temperature gradient over the height of the tank. Between these water zones there are two thermoclines – the first between 56 °C and 70 °C and the second between 72 °C and 88 °C.

The discharge starts around 09:30 and ends around 13:00 with a total duration of around 3.5 hours. The flow rate during discharging is between 1,200 and 1,500 m^3/h. The inlet water temperature entering the lower diffusor is around 56 °C.

Again, even when the storage tank operates outside standard parameters (multiple temperature levels and thermoclines), the FreeTTES model accurately predicts the temperature distribution during the discharging process. When discharging starts, the supply water temperature rises and remains stable, because of a stable temperature level in the top half of the storage tank.

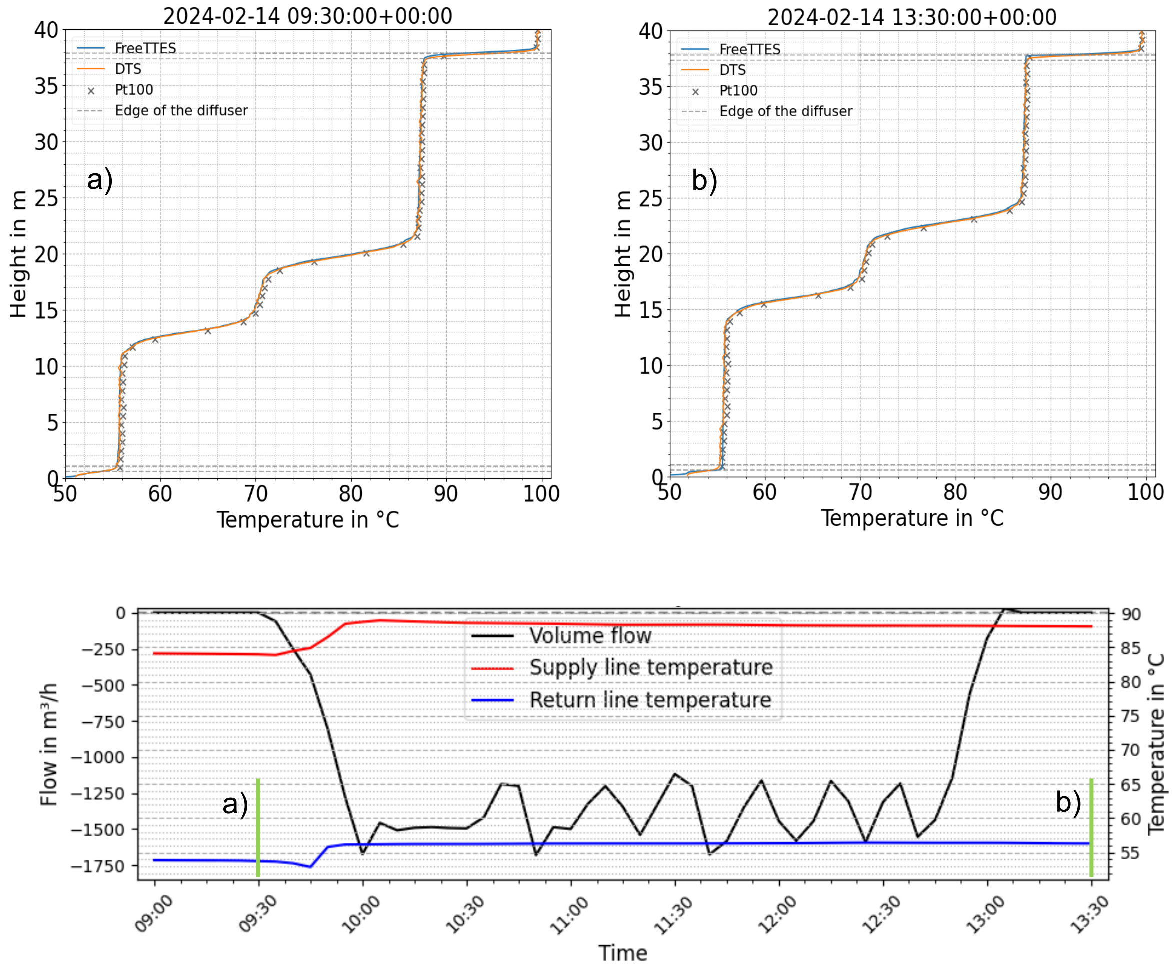

Figure 5. *TTES 10: Discharging process - comparison of Pt100 and DTS measurements with FreeTTES simulation results. a) temperature distribution before the discharge. b) distribution after the discharge. Below: time course of volume flow, supply line and return line water temperature; green lines show corresponding timestamps a) and b)*

2.4 Inversion during charging

One of the main difficulties is the modelling of the inversion process. An inversion during charging occurs when colder fluid enters a hotter environment. As described in section 1.2, the model behaviour was adjusted with the help of measurement data. The adjustment factors are different for charging and discharging processes so both cases will be presented separately in the following.

Figure 6 shows a short-term inversion during charging. The blue curve represents the model result and the orange curve shows the DTS temperature distribution. Within the top 5 m of the tank, the water reaches temperature levels ranging from 92 °C to 98 °C. The water that enters through the top diffuser has a temperature of 60 - 70 °C and a low flow rate of around 300 m^3/h.

Due to the very short duration graphs are zoomed in as the effect is barely visible when displaying the full temperature curve. The reference point helps to observe the dynamics of the process. The charging with inversion lasts for 30 minutes. As can be seen in Figure 6 b) the model predicts the cooling of the water due to the inversion earlier than it occurs in reality (blue curve moves to the left faster than orange). The FreeTTES model overestimates the shift of the temperature profile at this moment. But the deviations between blue and orange curves are still not larger than 1 K, which indicates a good model performance. In c) the model and measured data overlap, indicating that while the model accurately predicts the temperature shift, it overestimates the speed of this shift. The behaviour of the model in this case requires further investigations.

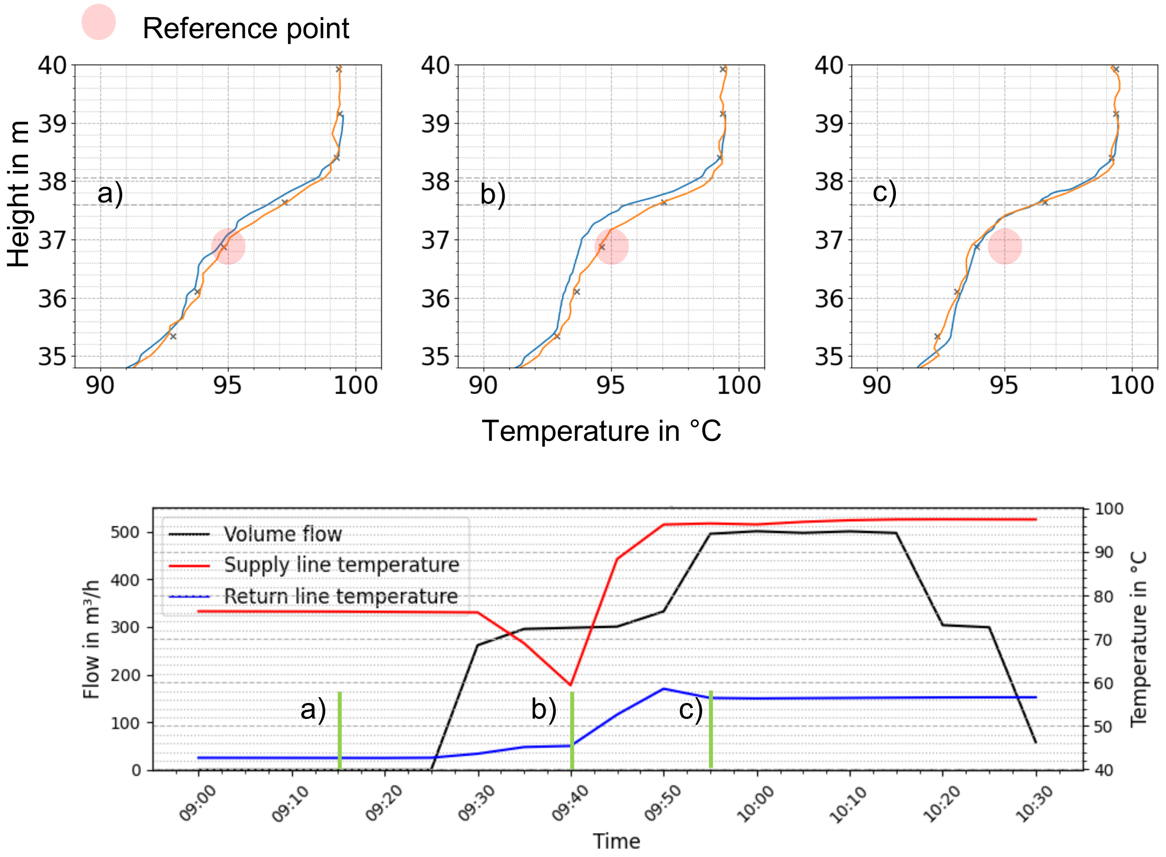

Figure 6. *Inversion during charging process. Blue is the FreeTTES model and orange is the DTS measurement data. Below: time course of volume flow, inlet and outlet water temperature - green lines show the corresponding timestamps of the profiles a), b) and c).*

2.5 Inversion during discharging

An inversion during discharging means that warmer water – compared to the water temperature at the inlet layer of the diffuser – enters the tank through the bottom diffuser and starts rising. Figure 7 a) shows the state before the discharge which is an example of a “good” temperature distribution – two distinct temperature levels and one high temperature gradient thermocline between them. The hot temperature of the tank is between 88 and 90 °C. The cold part of the TTES ranges between 55 and 58 °C. Into that cold part water with a temperature of 90 °C is injected, as can be seen in Figure 7. During the entire operation the storage tank was discharged for a total of 4 hours and charged for 30 minutes (shown by positive volume flow) with water of the same temperature.

The temperature level at the bottom is shifting to the right, and the width of the thermocline is reduced. Considering the deviation between simulated and measured temperatures, it can be seen that it reaches high levels at the thermocline level (around 6 m). This can be explained by the inaccuracies of spatial resolution and interpolation in that region. The model predicts the value of a new cold temperature level (~69 °C) with good accuracy.

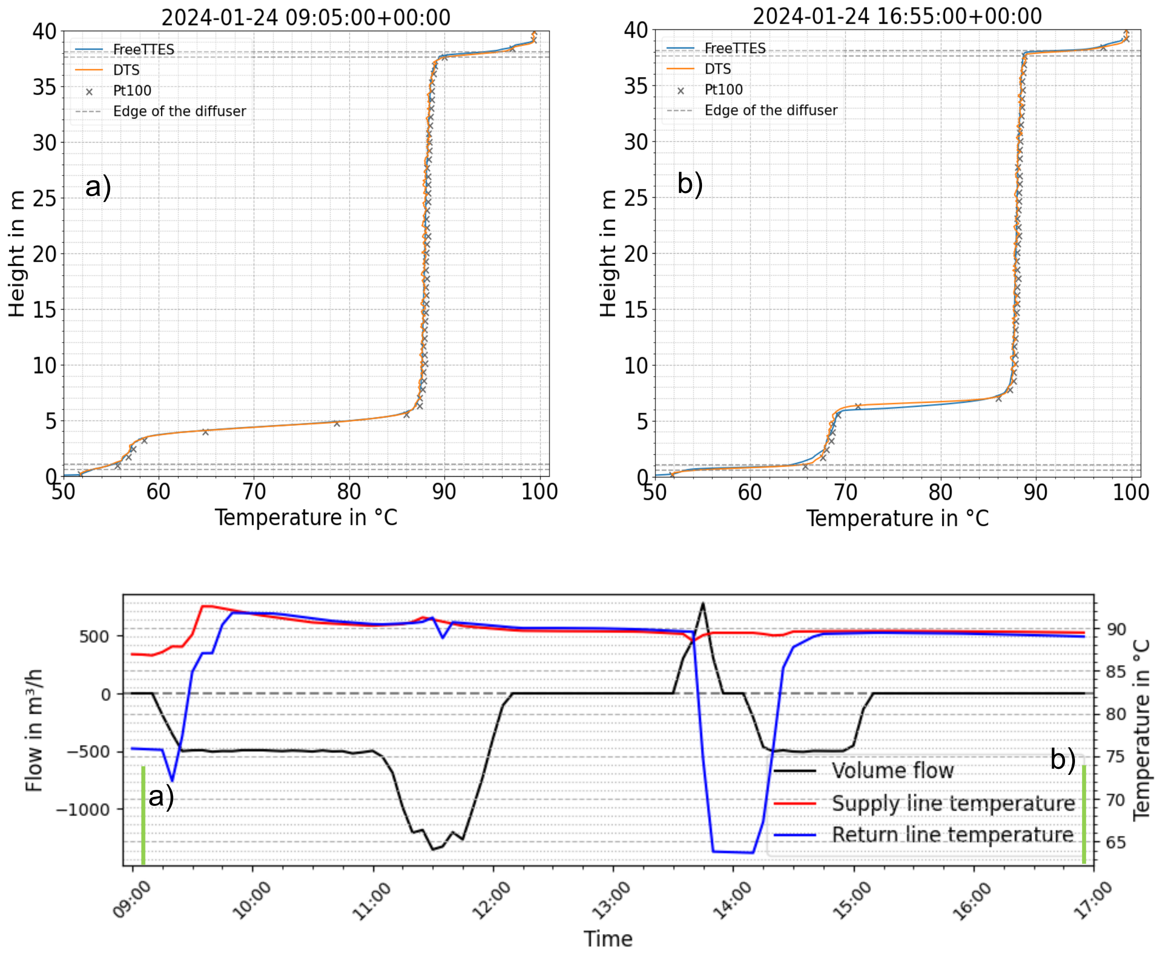

Figure 7. *Inversion during discharge process – comparison of Pt100 and DTS measurements with FreeTTES simulation results. a) temperature profiles before discharge. b) temperature distribution after discharge. Below: time course of volume flow, inlet and outlet water temperature; green lines show corresponding timestamps of the profiles a) and b).*

2.6 Limitations of inversion modelling

The FreeTTES model accurately predicts the temperature distribution during inversions in most scenarios. However, a specific case during the testing phase of the storage tank was identified where the model's limitations are evident. Figure 8 illustrates another inversion during charging where a) shows a state at the beginning of the process. Looking at the next time step in b) it can be seen that FreeTTES slightly overestimates the temperature reduction caused by the inversion (top of the tank like in chapter 2.4). In the next time step c) the DTS curve suddenly shifts in a manner that has not been observed before. A slight deviation of Pt100 and DTS measurement data in that region can also be seen. At the moment the reason for this deviation between the measuring systems is unknown. A possible explanation could be the fact that the DTS cable is closer to the centre of the tank, and the capacitive qualities of the Pt100 sensors play a delaying role. In d) the deviation between measured temperatures and the simulated ones becomes even larger, while the deviation between DTS and Pt100 subsides. It is possible that FreeTTES underestimates the mixing caused by the inversion during charging. However, at the moment the reason remains unclear and requires further investigation.

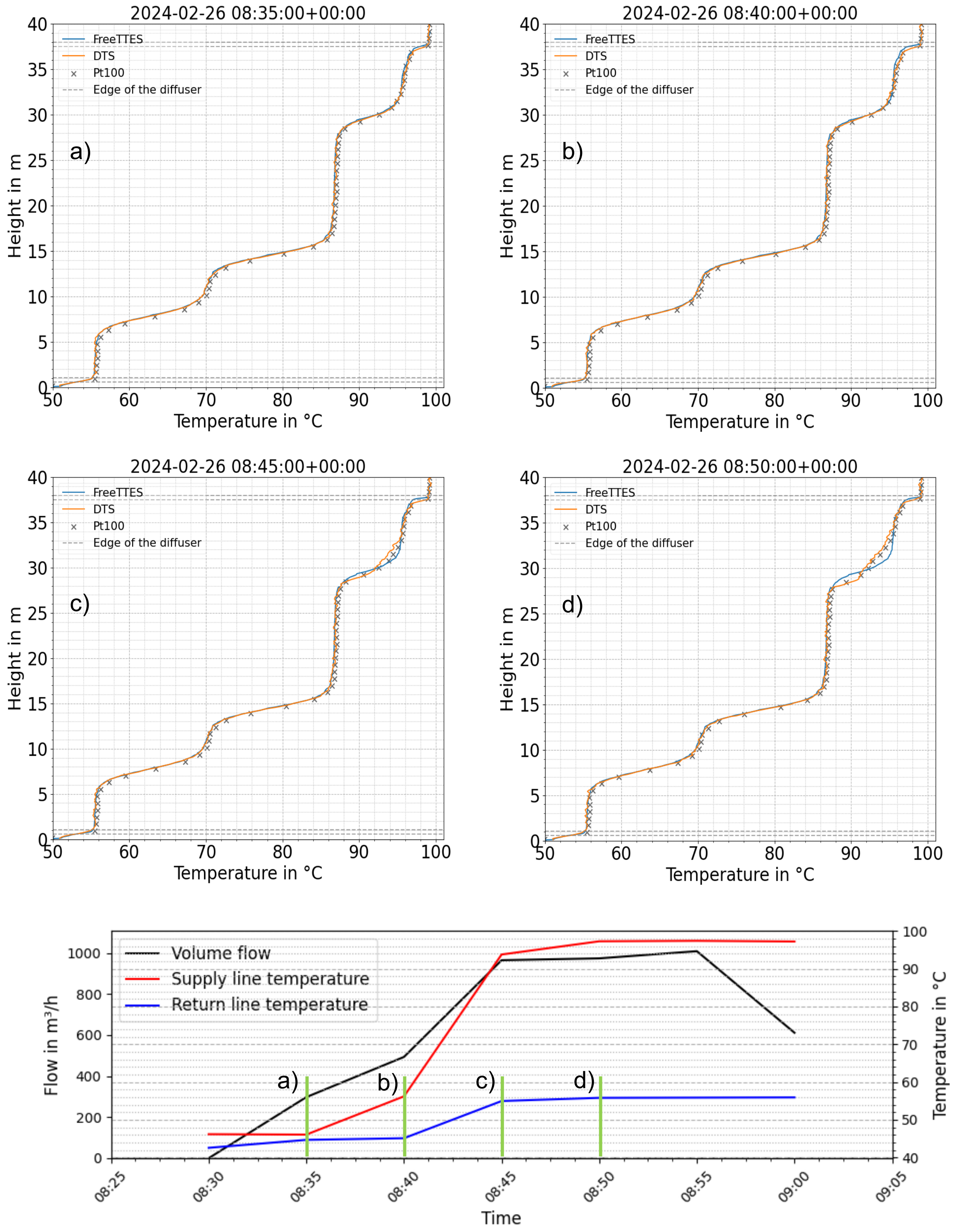

Figure 8. *Short inversion during charging - comparison of Pt100 and DTS measurements with FreeTTES simulation results. Below: time course of volume flow, inlet and outlet water temperature; green lines show the corresponding timestamps of the profiles a), b), c) and d).*

3. Conclusion and outlook

The FreeTTES model, designed to predict the water temperature distribution inside large atmospheric storage tanks, has been introduced. Implemented in Python, this model allows for easy integration into various simulation systems. Its advantage is that it simplifies the process enough to be significantly faster than a CFD simulation, while maintaining sufficient accuracy for thermohydraulic district heating simulation purposes. FreeTTES is capable of simulating inversions even during non-standard operational events. The performance of the model was demonstrated by comparing the simulation results with sensor data during different operation processes. The comparison shows a good match between model and data. The limitation of the model was also introduced, although further research is necessary in order to identify the root cause. Further work in the project is going to focus on validating the model further, integrating it into other simulations and evaluating DTS measurement data from various storage tanks.

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Competing interests

The authors declare that they have no competing interest.

Data availability statement

The data that support the findings are not provided by the operators of the TTES and are not openly available due to security reasons.

Author contributions

Bogdan Narusavicius: Data Analysis, Code Development, Writing Draft; **Franziska Koch:** Code Development, Review and Edit; **Anja Matthees:** Data Analysis and Investigation; **Peter Stange:** Data Analysis, Visualization, Review and Edit; **Karin Rühling:** Project Administration and Supervision, Review and Edit.

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