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Evaluation of stratification in thermal energy storages

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Abstract. Thermal stratification in water-based storages can be destroyed by mixing, heat diffusion, and thermal conduction. For this reason, the evaluation of stratification in water-based thermal energy storages is important for assessing their performance. The most promising indicators were identified and assessed based on their suitability for use in practical applications. The selected stratification indicators were calculated for four simulated storage scenarios comprising a fully stratified, a fully mixed, and two realistic storages. It was found that most indicators had severe limitations in their application. For this reason, a new indicator called internal exergy destruction was proposed, which can be used in combination with the overall exergy efficiency for assessing the performance and stratification of thermal energy storages. The main benefit of internal exergy destruction is that it can be used to compare storages with different heat loss coefficients. In addition, it separates the effects of mixing from the heat losses and is easily applied to real-life storages.

Keywords: Thermal stratification, Heat storage, Exergy analysis.

1 Introduction

Thermal energy storages (TES) are often used for bridging the time gap between heat generation and heat demand, especially when using non-dispatchable renewable energy sources [1]. Thermal energy is stored in a TES using heating or cooling in order to be used later. The thermal performance of a heating system utilizing a TES is strongly influenced by stratification. Stratification occurs when a temperature gradient in the TES separates fluid at different temperatures. One study found that by creating stratification in a TES with the use of a diffuser, increased the heating system's coefficient of performance (COP) by 32% compared to having a fully mixed tank [2].

However, achieving a good thermal stratification inside a TES is challenging due to mixing induced by the inlet flow, heat diffusion caused by natural convection in the TES, and downward thermal conduction [3]. The TES geometry, diffuser design, and operation strategy strongly influence the level of stratification. For this reason, it is critical to be able to quantify the degree of stratification inside a TES.

Usually, stratification indicators are used to assess stratification in a TES. Expressions have been developed that can be applied to any water-based heat storage that is directly charged/discharged, i.e., does not use a heat exchanger, e.g., in district heating tanks, domestic hot water tanks, pit thermal energy storages, etc.

Haller et al. summarized most of the available stratification indicators [4]. The same study employed some of these indicators to characterize a theoretical TES case comprised of one charge, standby, and discharge period. The study pointed out that all of the available methods have some drawbacks, e.g., some of them cannot be used for both charge and discharge, whereas others fail to separate the effects of heat losses from mixing. Overall, the study concluded that the available stratification indicators had limitations in their applications. However, the investigated simulation case was very simplified, including only mixing around the inlet and outlet of the storage and did not include heat losses to the ambient and thermal conduction between the water layers.

This study identifies the most promising stratification indicators for assessing the stratification in thermal energy storages for practical applications. The indicators are evaluated on how well they can be used to determine stratification inside a thermal energy storage. Finally, it suggests a new indicator for assessing stratification in TES.

2 Methods

First, the stratification indicators used in this study are presented, namely the MIX number, stratification coefficient, exergy efficiency, and overall exergy efficiency, followed by a description of the investigated scenarios.

2.1 MIX number

The MIX number is a dimensionless indicator that quantifies the degree of mixing inside a TES by comparing it to a fully mixed and a fully stratified reference storage [5]. Its range is between zero and one, corresponding to a perfectly stratified and a fully mixed tank, respectively. The MIX number is defined as the ratio of the difference in the moment of energy between a perfectly stratified storage and actual storage to the difference in the moment of energy between a perfectly stratified storage and a fully mixed one:

$$MIX = \frac{M_E^{stratified} - M_E^{actual}}{M_E^{stratified} - M_E^{fully-mixed}} \tag{1}$$

The moment of energy is calculated for the two theoretical reference cases (stratified and fully mixed) such that they have the same energy content as the actual storage. To calculate the MIX number, the storage is divided into discrete layers (typically corresponding to the number of temperature sensors). The moment of energy for each layer is then calculated by weighing each layer's energy content with the height from the bottom of the storage to the centroid of the layer. The total moment of energy of the storage is then calculated as the sum of all layers, as seen in Equation (2).

$$M_E = \sum_{n=1}^{N} \rho_i \cdot V_i \cdot C_{p,i} \cdot \left(T_i - T_{ref}\right) \cdot z_i \tag{2}$$

Where N is the total number of layers in the storage, ρ_i is the water density, V_i is the water volume of the layer, $C_{p,i}$ is the specific heat, T_i is the water temperature, and z_i is the distance from the center of the layer to the bottom of the storage. T_{ref} is the reference temperature, meaning the temperature at which the storage is considered empty.

2.2 Stratification coefficient

The stratification coefficient expresses the degree of stratification based on the mass-weighted square of the difference of the actual storage temperature to the mean storage temperature [6]:

$$St = \sum_{n=1}^{N} \frac{m_i \cdot \left(T_i - T_{avg}\right)^2}{m_{total}} \tag{3}$$

Where T_i is the temperature of each layer, m_i is the mass of each layer, T_{avg} is the average storage temperature, and m_{total} is the total mass of the storage.

2.3 Exergy efficiencies

There are several expressions suggested regarding exergy efficiency. In this study, the two expressions presented by Haller et al. [7] and Rosen et al. [8] are used.

Haller et al. define the exergy efficiency as the internal exergy loss of an experimental TES relatively to the internal exergy destruction of a fully mixed TES:

$$\eta_{st,\xi} = 1 - \frac{\Delta\xi_{destr,exp}}{\Delta\xi_{destr,mix}} \tag{4}$$

Where the internal exergy destruction is found through the exergy balance of the TES, using Equation (5):

$$\Delta\xi_{int,destr} = \Delta\xi_{flow} - \Delta\xi_{store} - \Delta\xi_{heat\ loss} \tag{5}$$

The fully mixed storage is simulated with the same flow rate, inlet temperature, and heat loss coefficient as the experimental storage. For further details, the reader is referred to the paper by Haller et al. [7].

Conversely, Rosen et al. used a general expression for the overall exergy efficiency of a TES, comparing the exergy recovered from the TES to the exergy input of the TES, as defined in Equation (6).

$$\eta_{overall} = \frac{\xi_{output}}{\xi_{input}} \tag{6}$$

It has to be noted that the two expressions are very different in their application, i.e., the former gives information about the precise time when mixing occurs during one storage cycle. In contrast, the latter gives an overall efficiency for one TES cycle.

2.4 Simulated scenarios

In order to demonstrate the performance of the investigated stratification indicators, four idealized storage scenarios were simulated. Mixing was implemented using the methodology recommended by Haller et al. [7].

The investigated scenarios were a fully stratified storage, a fully mixed storage, and two realistic storages. Each case was investigated for two full charge/discharge cycles. The scenarios have been simulated, including and excluding heat losses. The heat loss coefficient used in the simulations was selected such that the "realistic scenario 1" has an energy efficiency of 90%. It has to be noted that the effect of the storage walls was neglected.

Table 1. Simulation parameters.

Parameter	Value	Unit
Storage volume	1	m^3
Water density	980	kg/m^3
Water specific heat capacity	4200	J/(kg K)
Charging temperature	90	°C
Discharging temperature	45	°C
Threshold temperature	10	°C
Number of nodes	60	-
Time step duration	1	min
Flow rate charge/discharge	980	kg/hr
Heat loss coefficient	6	$W/(m^2 K)$
Effective vertical thermal conductivity	2.5	W/(m K)
Storage height	1	m

Each storage was charged using a constant temperature of 90 °C and discharged with a constant inlet temperature of 45 °C. The time step of the simulation was 1 minute, such that the charged/discharged flow was equal to the volume of one node. This ensured that numerical diffusion was avoided. An overview of the simulation parameters is presented in Table 1. Note that constant values for ρ_i and $C_{p,i}$ were used in order to simplify the simulations and focus on mixing effects. In addition, the value of the effective thermal conductivity was set to 2.5 W/(m K) as suggested by Haller et al. [7].

Fully stratified scenario. There is no mixing between the tank nodes and no vertical heat conduction inside the tank in this scenario. Essentially the flow during charge and discharge is simulated as plug flow.

Fully mixed scenario. In the fully mixed scenario, the temperature of the water entering the tank at each time step is instantaneously mixed with the temperature of the rest of the storage.

Realistic scenarios. The realistic case mimics the actual conditions inside a storage, hence the naming. In this scenario, as water enters the storage, the nodes' temperatures close to the inlet are mixed, simulating the inlet jet-mixing phenomenon. Two variations of the realistic scenario were simulated, corresponding to a better performing and a worse performing diffuser. For the case of the better diffuser, denoted from now on as realistic scenario 1, the total tank volume used for imitating the inlet jet mixing was approximately 10% of the tank's total volume. Similarly, for the case of the worse diffuser, denoted from now on as realistic scenario 2, 20% of the entire tank volume was used. The rest of the simulation conditions were the same for the two realistic scenarios. After mixing, vertical heat conduction was applied between the tank nodes based on the temperature distribution in the storage. Last, heat losses to the ambient were calculated based on the temperature difference between the storage nodes and the ambient temperature (for the cases where heat losses were enabled). An illustration of the investigated storage during charging and discharging is presented in Fig. 1.

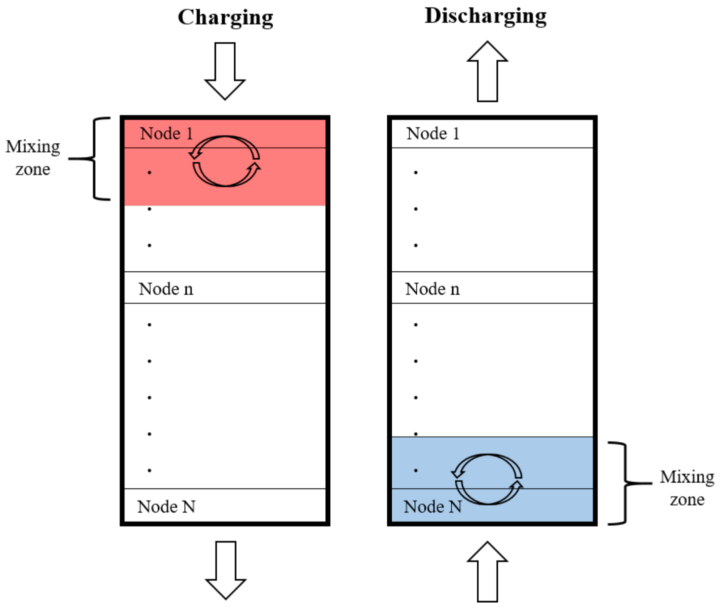

Fig. 1. Illustration of the tank charging and discharging.

2.5 Charging and discharging conditions

The storage in each simulation starts with charging and is initialized as empty, i.e., having a uniform temperature of 45 °C. The storage immediately switches from charging (operation=1) to discharging (operation=0), or vice versa, when the storage is identified as empty or full. The criteria for the storage being full or empty were implemented using a threshold temperature for the top and bottom node, as indicated in Equation (7).

$$operation = \begin{cases} 1, if \;\; T_{bottom} \geq T_{charge} - T_{threshold} \\ 0, if \;\; T_{top} \leq T_{discharge} + T_{threshold} \end{cases} \tag{7}$$

The temperature profile inside the tank during the two storage cycles is presented in Fig. 2. The top figure shows the temperature profile for the realistic scenario 1 without heat losses, while the bottom figure is the same case but includes heat losses. It can be observed that the presence of heat losses lowers the temperature in the tank, predominantly at the top of the storage, and also slightly increases the required time to charge the storage.

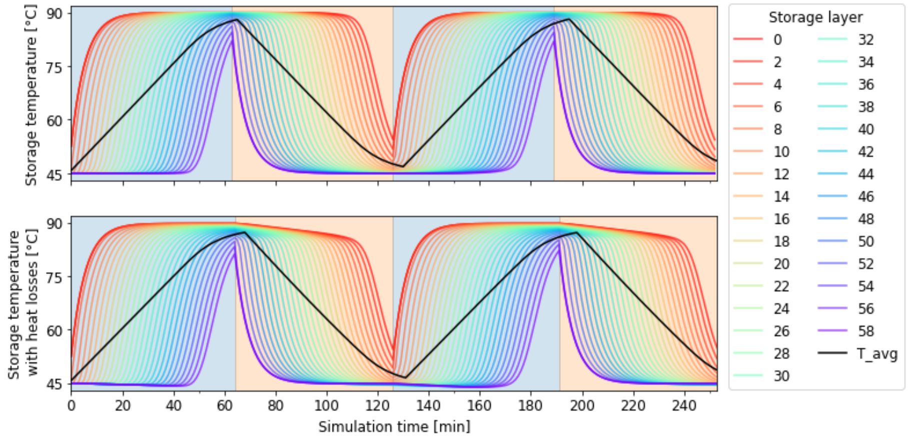

Fig. 2. Temperature profile in the storage for the realistic scenario 1. The top figure does not include heat losses.

3 Results

The results of the calculated stratification indicators are presented in Fig. 3 - Fig. 6. Each indicator is applied to all the possible storage scenarios, i.e., fully mixed (with and without heat losses), realistic 1 and 2 (with and without heat losses), and fully stratified. The fully stratified scenario is only simulated without heat losses since if heat losses did occur, it would no longer be a fully stratified case.

3.1 MIX number

As expected, the MIX number for the fully mixed storage is constantly equal to one, regardless of heat losses. Similarly, the MIX number is always equal to zero for the fully stratified storage. For the realistic storages, the MIX number varies throughout the storage cycles. This is partly because the MIX number is strongly affected by the energy content of the storage. Large spikes can be noticed at high (fully charged) and low (fully discharged) energy contents in the MIX number because a fully charged and discharged storage is considered not stratified.

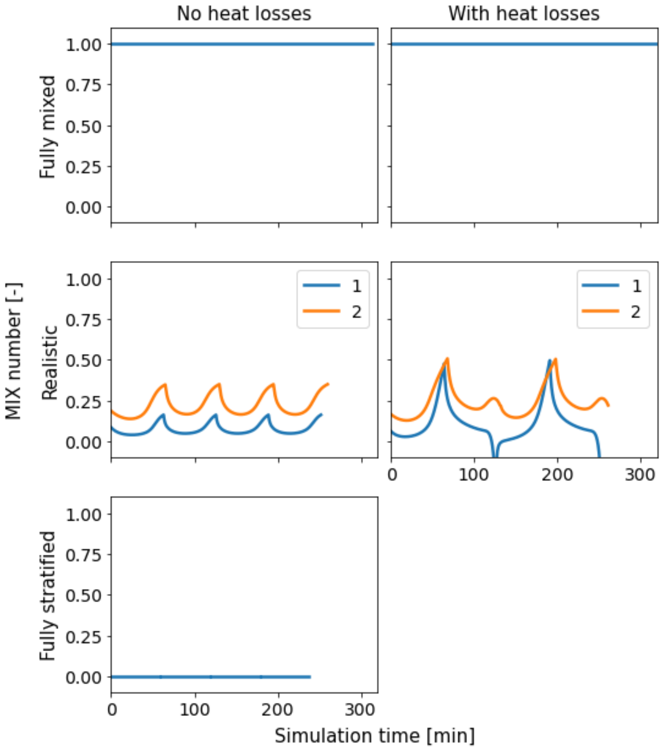

Fig. 3. MIX number for the investigated storages.

By comparing the two realistic storages, it is clear that a worse performing diffuser (case 2) creates more mixing in the TES; thus, it has a higher MIX number. By adding heat losses to the simulation, the MIX number shows the storage to be more stratified during discharging than charging. In fact, the MIX number becomes negative for a few time steps for Case 1, as the heat losses bring the average storage temperature below the reference temperature. While the MIX number does provide some use in comparing similar storages, it is difficult to draw a conclusion regarding stratification. In addition, it is highly influenced by the heat losses and the choice of the reference temperature.

3.2 Stratification coefficient

For the fully mixed storage, the stratification coefficient was zero since there was a uniform temperature in the storage at all times. The stratification coefficient was proportional to the energy content for the fully stratified storage and ranged from 0 to approximately 500 K^2. The values were between the two ideal cases for the realistic cases, with a maximum of approximately 400 K^2 and 300 K^2 for cases 1 and 2, respectively. The results of this indicator are much easier to interpret than the MIX number and were more useful in comparing the two storages. Similar to the MIX number, the stratification coefficient shows a low level of stratification when the storage is almost full or empty. However, this indicator has the benefit of not depending on a reference temperature and, therefore, never becomes negative.

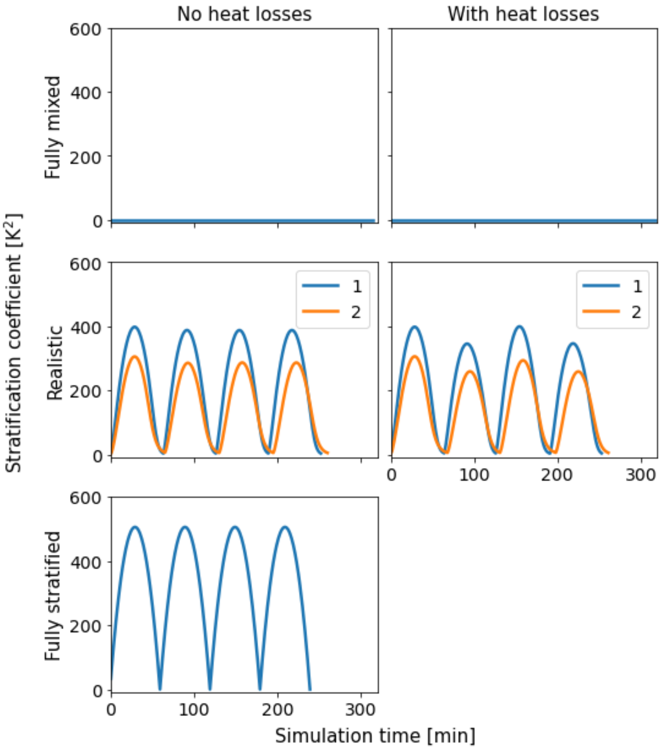

Fig. 4. Stratification coefficient for the investigated storages.

Nonetheless, the absolute value of the stratification coefficient has no physical meaning and, like the MIX number, is affected by heat losses. When applying heat losses to the realistic cases, the stratification coefficient shows a smaller degree of stratification during discharging compared to charging. This is because, when charging, the temperature at the top of the storage is constantly 90 °C, while during discharge, the top temperature decreases due to heat losses, as can be seen in Fig. 2. This leads to a lower stratification coefficient during discharge. Overall, this indicator can be used to compare the stratification degree in two storages, but one needs to be cautious when the two storages have different heat loss coefficients.

3.3 Exergy efficiencies

In Fig. 5, the exergy efficiency of the investigated storages is presented. As expected, the fully mixed storage had an exergy efficiency of 0%, while the fully stratified had an efficiency of 100%. Again, the realistic storages had an efficiency between the other two, and applying heat losses reduced the exergy efficiency. The method of Haller et al. [7] gives significantly different results compared to the MIX number and the stratification coefficient.

However, it is difficult to apply Haller's exergy efficiency method to real-life scenarios. This method can only be applied for specific, well-defined time periods in the storage operation. For example, it requires a clear distinction between the charge and discharge periods, which in some cases is not possible, e.g., for storages that are used both for short and long-term storage. In addition, it can only be used if the charging and discharging mass flow and inlet temperature are constant during the storage operation.

In general, the methods that compare a real-life storage with reference fully mixed or fully stratified cases, i.e., the MIX number and exergy efficiency, are difficult to use in practice.

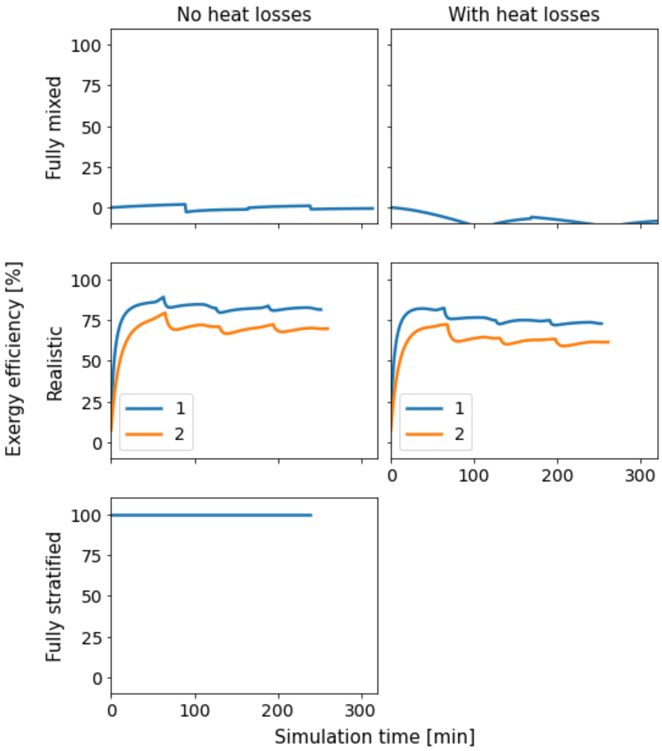

Fig. 5. Exergy efficiency for the investigated storages.

The overall exergy efficiency, presented in Table 2, is considered the most reliable indicator of stratification performance. This table gives information about the percentage of exergy lost due to mixing and heat losses. For example, the realistic storage 1 has a 10% lower efficiency due to mixing compared to the fully stratified storage, but 18% lower exergy efficiency, including mixing and heat losses.

Table 2. Overall exergy efficiency for investigated storages.

Overall exergy efficiency	**Value [%]**
Fully mixed storage	54
Fully mixed with heat losses	51
Realistic storage 1	90
Realistic storage 1 with heat losses	82
Realistic storage 2	85
Realistic storage 2 with heat losses	77
Fully stratified storage	100

In order to get information about the precise time when mixing occurred in the storage, it is suggested to use the internal exergy destruction as given in Equation (5). Exergy destruction gives the amount of exergy lost in the storage due to mixing caused by inlet jet mixing and vertical thermal conduction. Since the exergy loss due to heat losses is subtracted from the expression, the internal exergy destruction can be used for comparing the amount of mixing in two or more storages, even if they do not have the same heat loss coefficient.

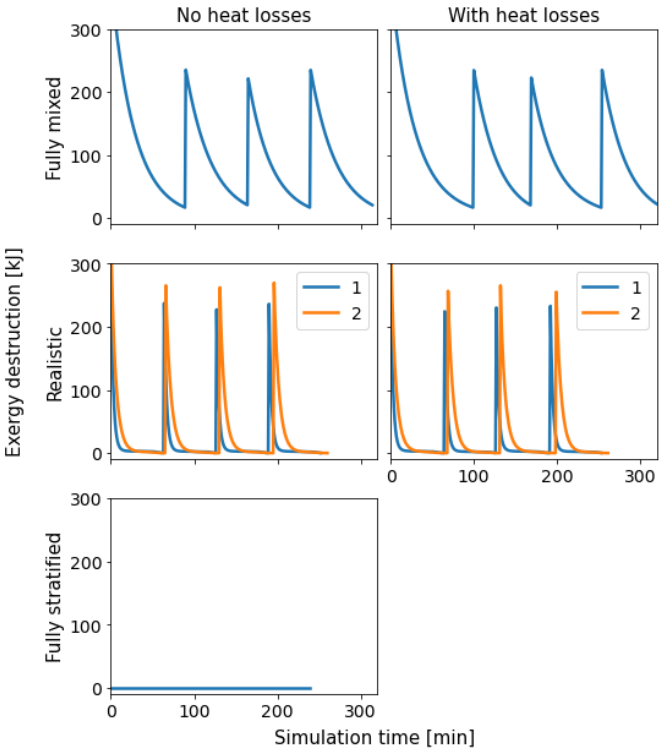

Fig. 6. Internal exergy destruction for the investigated storages.

Fig. 6 presents the internal exergy destruction for the investigated storages. It can be observed that, apart from the fully stratified storage, the exergy destruction mainly occurs at the start of the charge and discharge period, as this is when the thermocline develops. In the case of the realistic storage 1, which is well stratified, the exergy destruction only occurs at the beginning of charge and discharge and is close to zero during most of the storage operation. However, for a less stratified tank (e.g., for the realistic storage 2), the internal exergy destruction occurs over a longer period, as it takes longer to build up the thermocline. In addition, the internal exergy destruction remains essentially the same regardless of heat losses, allowing the comparison of the level of stratification independent from the heat losses.

4 Conclusions

This paper investigated stratification for four different storage scenarios: a fully mixed, a fully stratified, and two realistic scenarios. Four stratification indicators were assessed from the literature: the MIX number, stratification coefficient, exergy efficiency, and overall exergy efficiency.

Apart from the overall exergy efficiency, all the other investigated indicators had significant drawbacks leading to either results that were difficult to interpret or results applicable to specific, well-defined periods in the storage operation. It is suggested to use the overall exergy efficiency and supplement it with the internal exergy destruction for assessing stratification in a storage. The overall exergy efficiency gives a thermodynamically based quantification of the stratification performance of a TES. The internal exergy destruction can then be used to illustrate the specific times at which mixing occurs in the storage. The main benefit of these two methods is that they do not rely on a fully mixed or fully stratified reference storage simulation, which can be difficult or impossible to implement in real-life cases.

Applying the recommended methods to real-life storages is a topic of future work. It is believed that they have a great potential for comparing the stratification among storages since they can be applied to all storages regardless of their use, e.g., short term, long term, or combination of the two.

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