Stratification in Large Thermal Storage Tanks

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Abstract

Thermal storage tanks are important components in both, solar thermal as well as heat pump systems, because they can bridge the time between production and demand of heat. For low exergy energy sources such as solar thermal collectors, heat pumps, and waste heat recovery, the stratification within the tank is of key importance for the efficiency of the system. In this project, existing recommendations for the design of stratified storages are generalized to any storage size. The deflection relation is identified as a relevant variable. If this deflection relation is less than 0.12 for vertical inlet and less than 0.5 for inlet via an upward or downward elbow pipe pointing towards the top or bottom of the tank, the unintended deflection of the entering fluid stream into local vertical flows is low and an existing storage stratification is effectively maintained.

Keywords: Thermal Storage Tank, Stratification, Computational Fluid Dynamics, Field Study

1. Introduction

Storage stratification has a major influence on the usable storage volume and the efficiency of the connected systems. This is especially the case when storage tanks are combined with so-called low exergy processes like solar thermal systems, heat pumps or heat recovery. The importance of stratification has been demonstrated in particular for solar combi-storage tanks in which sections dedicated to domestic hot and space heating are in contact to each other. It was shown that the stratification efficiency of combi-storage tanks operated in combination with heat pumps has a greater influence on the overall efficiency of the system than the storage heat losses [1].

The temperature stratification in fluids adjusts automatically due to gravity and the temperature-dependent density of water. This natural process can be disturbed or destroyed by various processes [2]:

1. heat conduction in water and in the storage tank internals
2. plume entrainment
3. kinetic energy of direct inlets (inlet jet mixing)

Heat conduction has a significant effect, especially with very long loading and downtimes as well as with low height to horizontal diameter ratios. In short-term storage processes, the kinetic energy and the entraining flow of direct storage tank charging as well as the poor stratification capability of internal heat exchangers are the main causes for destratification.

Plume entrainment occurs when fluid with a certain temperature and density flows into a zone with a different temperature and density. Due to the difference in density, gravitational forces cause the fluid to be deflected or accelerated in a vertical direction. Similar to the steam plume above a chimney, a vertical turbulent flow, driven by the buoyancy force, is created, which, after a more or less pronounced overshoot, stratifies into the temperature layer of equal density. At the border zone of the flow, surrounding fluid is continuously drawn into the motion (see e.g.[3]). In thermal storages, this can be prevented by injecting the fluid at the level at which the temperature is identical to the temperature of the entering fluid. If the vertical position of this layer is not known in advance, an inlet stratifyer unit can be used, which results in a stronger physical separation between ascending or descending fluid and the remaining storage area.

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Loading with high kinetic energy can cause turbulences and flows in the storage tank and thus destroy existing storage stratification. To prevent this, the entry velocity must be kept low. The literature contains a multitude of investigations with mathematical models and experiments, which give threshold values and recommendations for maximum inlet velocities and maximum Reynolds numbers of the entering fluid. A compilation of these results was presented in [4]. In this paper, a work that supplements existing recommendations and develop a standardized criterion that can be applied to different storage sizes is presented. The criterion is validated both with results from fluid dynamics simulations (CFD) and a field data from 7 different storage tanks.

2. Deflection relation as the defining dimensionless quantity

In fluid mechanic problems, it is common to use laws of scaling and dimensionless quantities. This is particularly useful because experiments and simulations are often time-consuming. Large systems in particular are usually difficult or impossible to be tested in the laboratory or simulated with sufficient degree of detail with available computing capacity and time. This problem also arises when considering large thermal storages. Measurements of stratification efficiency with laboratory test methods were performed with tank volumes of approx. 1 m^3 [1]. A measurement of larger storage tanks would be possible in principle, but test stands for sizes up to 100 m^3 are not readily available and testing times and cost would increase substantially. In addition, flow simulations of large storage tanks require a great deal of computing power. A one-hour simulation of a combi-storage with 800 l capacity requires a computing time of 55 h with 12 CPU cores (see [4]). If the storage volume is increased to 100 m^3, simulations can take several weeks, which makes efficient work and the production of results difficult.

For this reason, it is helpful to develop scaling laws that enable the transferability of results from small storage sizes to any size. Starting from the results that were published for an 800 l combi-storage tank (cf [1,4]), scaling effects were examined with the aid of CFD simulations, with the objective to find appropriate scaling laws. Dimensionless quantities have also been used to characterize mixing in thermal storage tanks in [5] where the Fraud number was used in combination with the Reynolds number to define a correlation between inlet velocities and the amount of mixing caused by the jet.

We hypothesize that in the case of a turbulent jet entering the storage horizontally, the relevant dimensionless quantity is the ratio between the characteristic length l_s in which the jet is deflected and the free distance to the next obstacle d_f. In the present case of an intended downward stratification, only obstacles that permit an upward deflection need to be taken into account. This dimensionless quantity as a deflection relation χ is defined as:

$$\chi = l_s/d_f \tag{1}$$

The length l_s can be formed as a quotient of inflow pulse flow M_0 and buoyancy flow F_0, which in turn is calculated from the volume flow $\dot{V_0}$, the inlet velocity v_0, the gravitational acceleration g, the density of the inflowing fluid ρ, and the density difference $\Delta\rho$ given by the temperature differences (see:[3]):

$$l_s = \frac{(M_0/\rho)^{\frac{3}{4}}}{(F_0/\rho)^{\frac{1}{2}}} = \frac{(\dot{V}_0 v_0)^{\frac{3}{4}}}{\left(\frac{\dot{V}_0 g \Delta\rho}{\rho}\right)^{1/2}} \tag{2}$$

3. CFD settings

The CFD simulations created in the project were carried out with ANSYS CFX 18.2. The models and meshing settings experimentally validated in the StorEx project were adopted, so that a new validation of these settings was not necessary. A detailed description of the validation process can be found in [4]. The scale adaptive shear stress transport model was used as the turbulence model. The meshing was also carried out analogously to the earlier work with an element length of 2 cm. However, for tanks smaller than 800 l the net length has been reduced to 1 cm. A vertical plane of symmetry was inserted in the direction of the inlet pipe. The storage wall was assumed to be a completely adiabatic border.

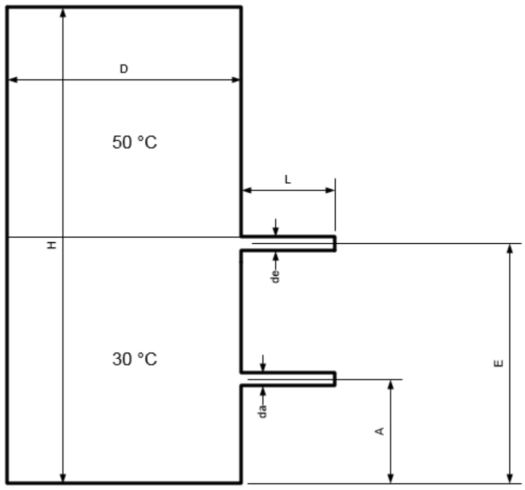


Figure 1 Dimensions of the simulated storage charging.

4. Results for horizontal inlets

To investigate scaling effects more closely, the experiment described in Gwerder et al. (2016) was simulated. In this experiment, the loading of the space heating part of a combi-storage tank was investigated. For this application, it is particularly important that the inflowing fluid does not cause strong circulation flows in the storage tank. If the hot water part is affected by the fluid flowing into the space heating part, this leads to entropy production and to a strong decrease in system efficiency, especially when a heat pump is used for charging [1]. The 800 l combi-storage used as the base case has a height of H=1.84 m and a diameter of D=0.75 m. The inlet is located in the middle of the storage tank at a height of E=0.92 m from the ground. The outlet is located at a height of A=0.387 m. At the beginning of the simulations, the temperature in the lower part of the storage tank was 30 °C, while the upper area had a temperature of 50 °C. A scheme of the used storage tank layout is shown in Figure 1.

By the use of the dimensionless deflection relation χ, stratification results of one storage size can be scaled to other storage sizes. The validity of the deflection relation as a dimensionless quantity for characterizing stratification quality was tested with a set of CFD simulations. For the case of a horizontal inlet, simulations were done with a direct inlet and with a baffle plate. The velocity of the fluid entering the storage was in the range of approx. 0.1-0.2 m/s. When using a baffle plate, a higher mass flow rate is reached with the same velocity at the outlet of the diffuser due to the higher cross-sectional surface of the flow path. The storage tank was scaled by the factors 0.5, 1.48 and 1.93 in each dimension, starting from the basic case of the 800 l storage tank, whereby for the baffle plate variant only the basic size and the scaling by the factor 1.48 were simulated

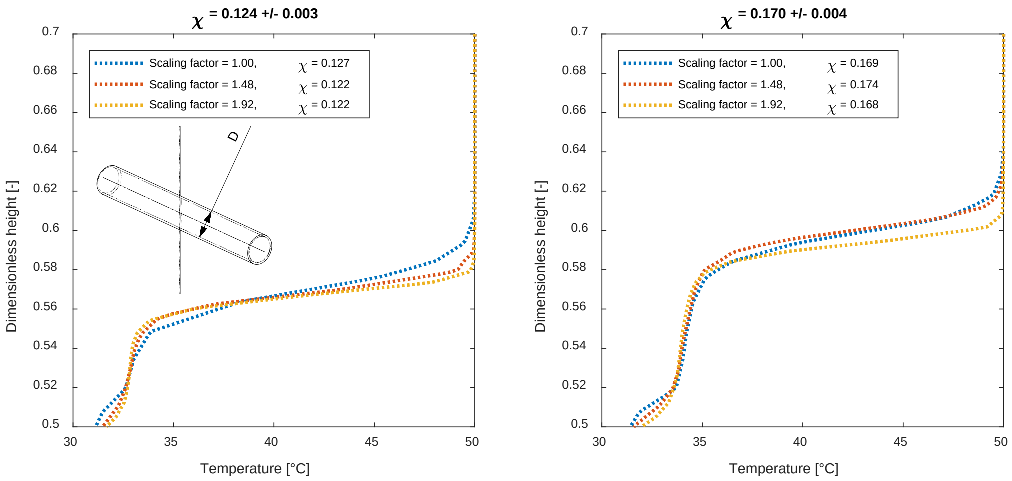
Exemplary scaling results in relation to the vertical temperature curve of the horizontal inlet experiment with direct entry are shown in Figure 2. All results describe the temperature in the storage tank after 50 % of the storage fluid has been replaced by the inlet and outlet flow. It can be seen that for a given deflection relation, the vertical thermocline shift caused by turbulences and motions created by the incoming fluid is relatively independent from the storage size, with a more pronounced displacement of the thermocline for higher deflection relations (Figure 2).

In addition to the shift of the thermocline, the stratification efficiency was evaluated. The storage tanks were simulated without losses to the ambient, and thus the stratification efficiency can be defined as follows [6,7].

$$\Delta \mathrm{S}_{\mathrm{irr,sim}} = -\left(\Delta S_{in\backslash out} + \Delta S_{storage}\right) > 0 \tag{3}$$

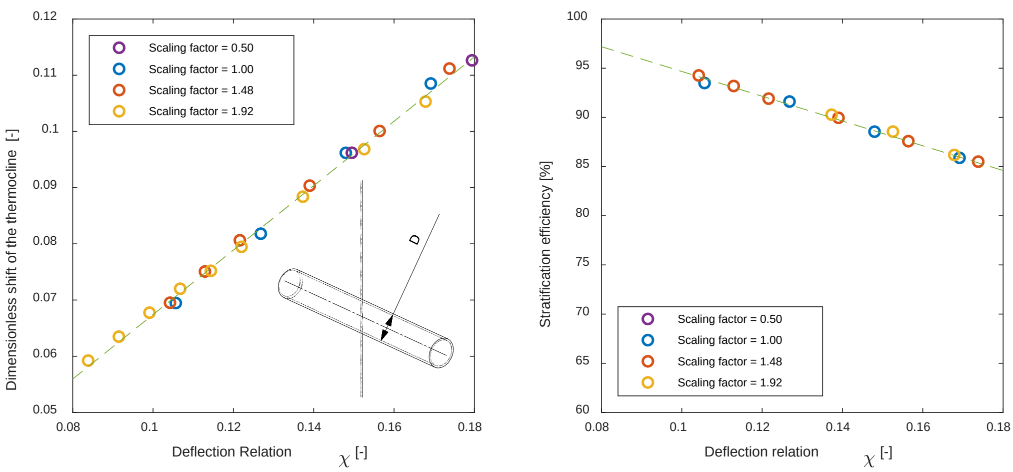
$$\zeta_{str} = 1 - \frac{\Delta \mathrm{S}_{\mathrm{irr,sim}}}{\Delta S_{irr,mix}} \tag{4}$$

In order to evaluate the stratification efficiency of the simulated experiments, it was assumed that the inlet and outlet always take place at a constant temperature level over the simulation period. This condition is almost fulfilled for sufficiently well stratified storage tanks, since in this case the lower storage area is heated only slightly in the defined combi-storage loading experiment. As a result of this simplification, $\Delta S_{in\backslash out} = 0$ applies and thus $\Delta S_{irr,sim}$ can be calculated directly from the temperatures in the storage tank before and after the experiment. As reference value $\Delta S_{irr,mix}$ the entropy production for a storage tank, which is completely mixed after the simulation period, was calculated.



(a) (b)

Figure 2 Vertical temperature line after a replacement of 50 % of the storage volume by incoming fluid at mid-height with constant deflection relations of 0.124 +/-0.03 (a) and 0.170 +/- 0.04 (b).



(a) (b)

Figure 3 Correlation of the shift of the thermocline (a) and the stratification efficiency (b) with the deflection relation in case of a direct inlet.

Figure 3 shows the correlation between deflection relation and thermocline shift (left) and between deflection relation and stratification efficiency (right). The results are based on simulations of storage tanks with different dimensions and different volume flow rates of charging. The scaling factors from 0.5 to approximately 2 for each dimension indicate that the largest storage volume evaluated was 4x4x4 = 64 larger than the smallest one. The simulation results show that both the relative displacement of the thermocline and the stratification efficiency show a linear dependence on the deflection relation in the investigated area. The R^2 value of the linear correlation of the thermocline shift is 0.997 that of the stratification efficiency is 0.994. In Table 1, different quantities that describe the simulation runs are given for a selected number of performed CFD charging experiments with direct horizontal inlets.

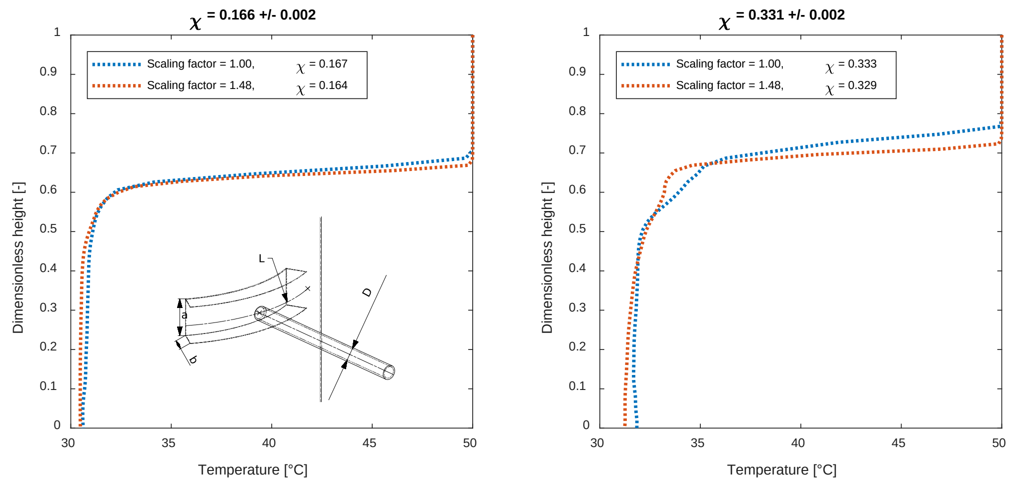
Table 1 Relevant quantities for selected simulation cases with direct horizontal inlet.

Volume (l)	Scaling factor s (-)	Pipe diameter (inch)	Volume flow rate (l/h)	Deflection relation χ (−)	Inlet velocity (m/s)	Reynold number (-)	Stratification efficiency (%)
800	1	2”	953	0.127	0.12	7507	91.5
2593	1.48	3”	2434	0.122	0.14	13574	91.8
5751	1.93	4”	4682	0.122	0.16	20165	90.2
800	1	2”	1279	0.169	0.16	15015	85.8
2593	1.48	3”	3477	0.174	0.20	27148	85.4
5751	1.93	4”	6438	0.168	0.22	40330	86.1

The same method was used to examine the storage tank inlet via a baffle plate. The shape of the baffle plate is shown in Figure 4. The initial conditions, the height of the inlet and the outlet as well as the simulation time are identical to the case with direct inlet. As a base case, a mass flow rate that only slightly exceeds the recommended inlet velocity of 0.1 m/s when leaving the baffle plate was used. To check the limits of the proposed deflection relation the entry velocity was doubled for another simulation. In Table 2 the used inlet velocities for the scaled storage as well as other relevant quantities are shown. The two resulting temperature curves are shown in Figure 4. The thermocline shift and stratification efficiency are shown in Figure 5. It becomes evident that the same inlet velocity leads to a higher impulse flux due to the higher inlet cross section area and consequently to an increased deflection relation compared to the direct inlet with a smaller cross section. While a deflection relation of $\chi = 0.166$ still leads to a similar temperature distribution in both simulated cases, a larger difference of the two temperature curves is present when the entry velocity is doubled and the corresponding deflection relation increases to $\chi = 0.331$. For the simulation experiments with baffles, the correlation values of 0.904 for the thermocline shift and 0.955 for stratification efficiency are significantly lower than in the case of the direct inlet.

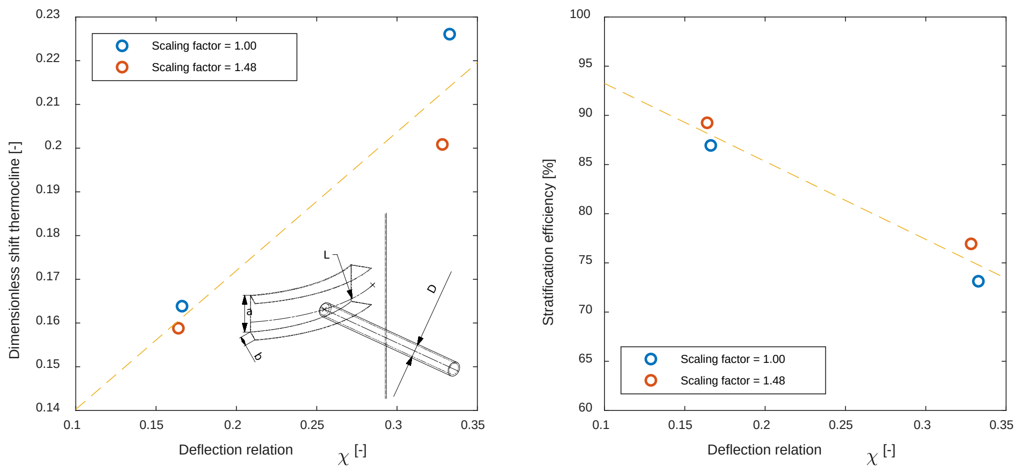
Table 2 Relevant quantities for selected simulation cases with baffle plate horizontal inlet.

Volume (l)	Scaling factor s (-)	Baffle plate area $a \cdot b$ (cm²)	Baffle plate length L (one side) (cm)	Volume flow rate (l/h)	Deflection relation χ (-)	Inlet velocity (m/s)	Reynold number (-)	Stratification efficiency (%)
800	1	90	26.7	3104	0.167	0.10	8137	86.9
2593	1.48	197	39.5	3104	0.164	0.13	13574	89.2
800	1	90	26.7	4682	0.333	0.2	15656	73.1
2593	1.48	197	39.5	1279	0.329	0.26	31312	76.9



(a) (b)

Figure 4 Vertical temperature profile after a replacement of 50 % of the storage volume with constant deflection relations of 0.166 +/-0.002 (a) and 0.331 +/- 0.02 (b) through an inlet with a baffle plate.



(a) (b)

Figure 5 Correlation of the shift of the thermocline (a) and the stratification efficiency (b) with the deflection relation in case of an inlet with a baffle plate.

5. Results for inlets bent towards the top or bottom of the tank

Besides solar combi-storages, also storage tanks used as buffers that even out the mismatch between the production of a single heat source and a single heat sink are common, especially in larger installations. A field study that was carried out within this project showed that a common form of integrating a storage tank with more than 5 m^3 volume is to place it as a hydraulic separator between two T-pieces. Frequently, these tanks have an elbow pipe that directs the fluid motion towards the top (hot) or the bottom (cold) of the tank. Consequentially, investigations were carried out on the scaling effects during a charging process with this storage type. An example storage tank configured in ANSYS 18.2 CFX and initialized to 45 °C. In the simulated experiment, fluid is entering the upper inlet until 30 % of the tank volume is replaced. A sketch of the simulated tank as well as the used dimensions for the base case (scaling factor 1) are shown in Table 2 and in Figure 6.

To check the usability of the deflection relation for the charging experiment 2 with curved pipe, the scaling factors 0.5 and 0.25 were tested, starting from the basic storage tank with 6400 l volume. The tested inlet velocity range was 0.12-0.44 m/s. Two different temperature difference between initial storage temperature and the entering fluid are used (5K and 20K). When calculating the deflection relation, the storage diameter was again used as the characteristic length. The choice of the characteristic length is heuristic and other definitions may be used instead by other authors, e.g. the height of the storage. Which size results in more robust correlations under varying proportions between height and width has yet to be clarified in future studies. The storage tank temperature at the start of the simulation was 45 °C, and two different charging temperatures of 65 °C and 50 °C were analyzed.

Table 3 Dimensions of the simulated storage with inlets bent towards the top and bottom.

Quantity	Value
Volume (m^3)	6.4
Diameter (m)	1.7
Height (m)	3.15
Inlet diameter (m)	0.105
Distance inlet to tank top/bottom (m)	0.225

The temperature curves in Figure 7 show simulations with a charging temperature of 65 °C. In this case, the displacement of the thermocline is not a suitable indicator for the mixture in the storage, as it results from the plug flow of the fluid in the storage. For this reason, only the stratification efficiency was considered for the evaluation. The results show a clear extension of the boundary layer between warm and cold area, and accordingly also a lower stratification efficiency for higher values of the deflection relation. The quality of the correlation decreases for increasing values of χ. The resulting R^2 value of the linear correlation of stratification efficiency with the deflection relation is 0.963.

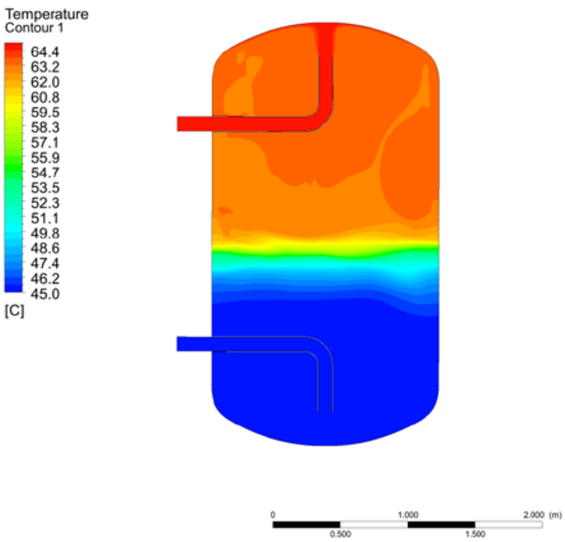


Figure 6 Cross section of the simulated tank with inlet bent towards the top.

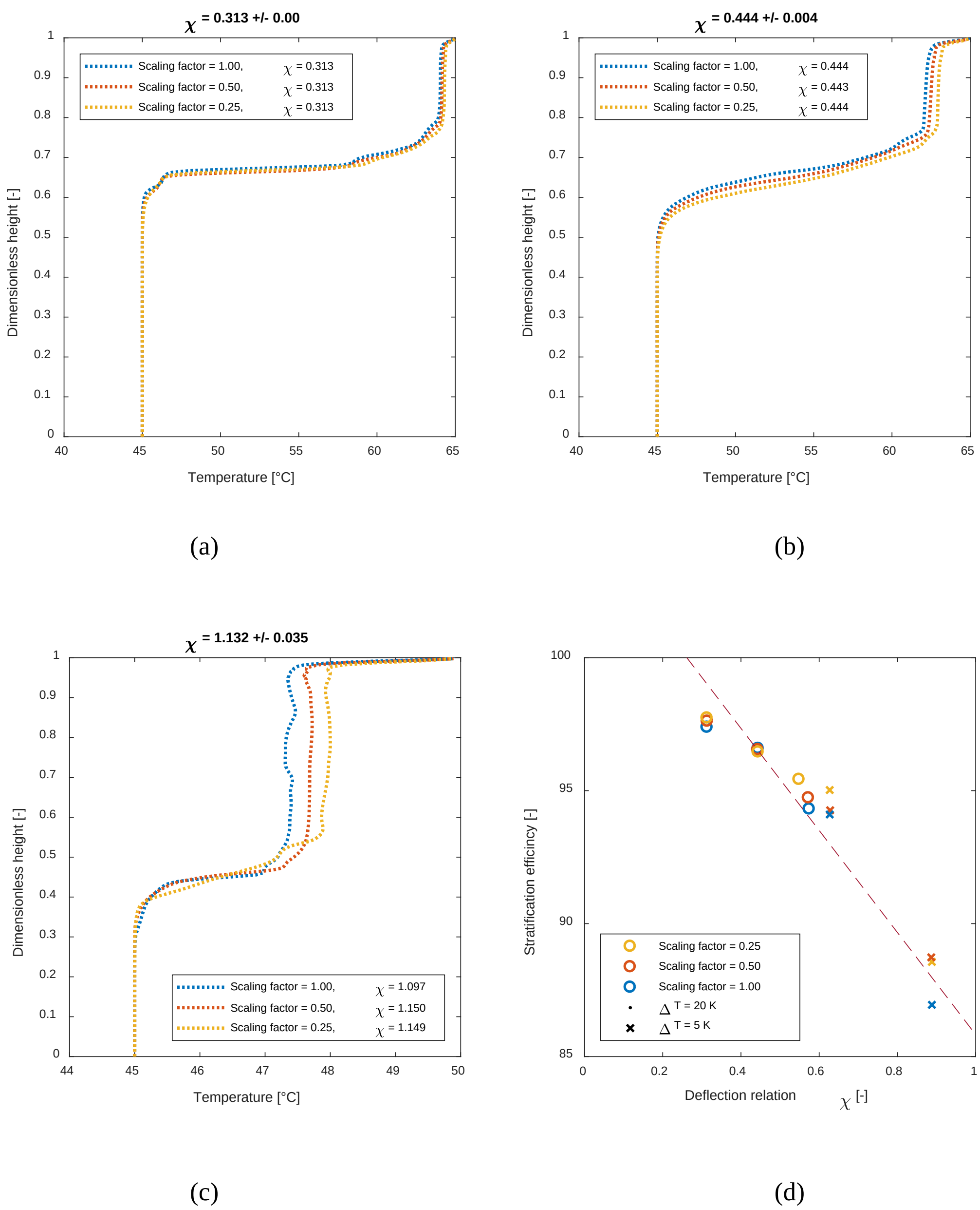


Figure 7 Vertical temperature profile after 30 % of the tank volume was replaced with fluid from a topward bent inlet and deflections relations 0.313 +/- 0.00 (a), 0.444 +/- 0.004 (b) and 1.132 +/- 0.035 (c). Correlation of the deflection relation with the stratification efficiency (dt).

The results for the three investigated inlet geometries show that the deflection relation is a suitable dimensionless quantity for characterizing the expected reduction in stratification efficiency that results from the kinetic energy of the inlet jet into the storage and the circulation flows caused thereby. The results in Table 4 show that the Reynolds number of well stratified cases is between 7'500 and 20'500, whereas Reynolds numbers between 15’000 and 41’000 are observed for cases with low stratification efficiency. Inlet velocities for well stratified results are between 0.11-0.16 m/s and for less stratified results between 0.16-0.22 m/s. However, neither Reynolds numbers nor the inlet velocity take into account the presence of an obstacle in the path of the entering fluid. Thus, the deflection relation is a more suitable and stable criteria for the design of a well stratified storage tank than the inlet velocity or the Reynolds number.

According to Gwerder et al. (2016), 0.1 m/s is a suitable limit value for the 800 l storage that was considered by the authors. An entry velocity of 0.1 m/s leads to a deflection relation of 0.127 in the defined 800 l storage with 2" connection. From this it can be estimated that the deflection relation of $\chi < 0.12$ can be regarded as the first reference value for the still permissible relationship between free distance to the next vertical obstacle and the kinetic energy of the inflowing fluid. A comparison with the values of the other inlet geometries shows that a deflection relation of $\chi < 0.12$ in the horizontal inlet case and a deflection relation of approx. $\chi < 0.5$ in the vertical inlet case leads to only a minor impairment of the stratification efficiency. All linear regression curves show a stratification efficiency of more than 90 % for these values. For this reason, it can be concluded that the deflection relation is a good guideline for the design, assessment and dimensioning of storage facilities.

6. Comparison with monitoring data and conclusion

Seven field systems with large storage tanks of at least 2 m^3 were evaluated in different system variants. It was shown that especially storages positioned as hydraulic separators between the source and sink with large temperature differences between the supply and return are well stratified. It is more difficult to ensure stratification in systems with smaller temperature differences. The two systems with temperature difference of less than 10 K showed no clear stratification in the evaluation. With the method developed for assessing the expected stratification efficiency for large tanks, field systems can be dimensioned and evaluated without the need for complex and time-consuming CFD simulations. Table 7 lists the relevant variables and the resulting deflection relation for the investigated field systems, together with the quality of stratification that was observed from the temperature curves.

Systems 2, 4 and 5 do not fulfil the condition of $\chi < 0.12$ for storage tanks with horizontal inlet and $\chi < 0.5$ for storage tanks with top/bottom bent pipe inlets set out in chapter 4. Conversely, all storages that were judged to be well-stratified meet the condition of the distraction relation. Although this confirms the applicability of the deflection relation, it is desirable to add further field system results in order to broaden the data basis for the validity for a larger range of systems and conditions.

Table 4 Results of field systems

Number	**Diameter Inlet (m)**	**Maximal volume flow (m^3/h)**	**Distance d_f (m)**	**Geometry**	**ΔT storage (K)**	**Deflection relation χ (-)**	**Stratification quality (-)**
1	0.114	10	1.7	bent	20	0.370	good
2	0.114	30	1.7	bent	20	1.109	average
3	0.114	10	1.5	bent	15	0.392	good
4	0.273	3	1.11	horizontal	4.3	0.434	mixed
5	0.036	52	3.8	bent	30	0.484	good
6	0.115	72	3.5	bent	28	0.304	good
7	0.114	37	1.9	bent	5	1.108	mixed

7. Acknowledgement

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8. References

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