OPTIMIZATION OF A STRATIFICATION DEVICE FOR THERMAL STORAGE TANKS

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ABSTRACT
Different stratification devices are investigated by means of CFD (Computational Fluid Dynamics) calculations. Mixing effects within the charge systems are worked out which lead to a worse thermal stratification in the storage tank and reduce the efficiency of a solar system. The aim of the work is to find good working conditions for stratification devices, which can prevent mixing inside the storage tank. A minimization of these mixing effects was reached by an adaptation of the outlet geometry. Thereby, changes in the outflow behaviour of the stratification pipes were observed. These findings yield to several further optimizations. The design criteria derived from the simulations are discussed.

1. INTRODUCTION
The effective storage of thermal energy requires both a well isolated tank wall and simple charging and discharging systems, which produce and maintain a thermal stratification reliably in the store. The quality of the thermal stratification has a significant influence on the efficiency of the solar system [1, 2]. The main fluid-mechanical requirement for an inlet stratification device can be described as the ability of the device to transport the water into the store without mixing. However, this is not always fulfilled [3, 4], and there are no design criteria for the implementation of inlet stratification devices in large thermal stores. Earlier works [4, 5] contemplate (investigate) the internal flow of inlet stratification pipes intensively. Lohse et al. [5] worked out the two most significant effects contributing to the mixing process within the stratifier (Fig. 1). First, geometrical adoptions are found out by means of CFD calculations. These adoptions decrease the suction effect 2 for the charge of fluid into an existing thermal stratification in the storage tank. However, it was recognized that due to this geometrical changes the suction effect 1 gets stronger and the outflow behaviour of the stratification device changes. This influence is investigated here in greater detail. CFD calculations are carried out using a validated model to quantify the mixing effect 2 as well as the outflow behaviour under several initial and boundary conditions. The aim is to find good working conditions for inlet stratification devices for large thermal energy stores and to develop design criteria for such facilities.

2. NUMERICAL MODEL AND PROCEDURE
The fluid flow in a thermal energy store is investigated by means of CFD calculations using the commercial software package ANSYS CFX 11 [6]. A SST k-ω model extended for free convection is used to simulate the turbulent transport processes in the store. The properties for water are specified temperature-dependent. The cylindrical tank is set to 4 m in height as well
as diameter providing a volume of approximately 50 m³. With a flow rate of 10 m³/h the store represents a short-term store. The computational model was validated against experimental data of a 0.6 m³ thermal energy store in earlier work [4].

![Fig. 1: Suction effects within the stratification device](image1)

Fig. 1: Suction effects within the stratification device

![Fig. 2: Initial temperature distribution](image2)

Fig. 2: Initial temperature distribution

The simulation of the fluid flow and heat transfer in the store is very expensive. Thus short-term tests are performed to reduce the computational time. That means a temperature distribution is predetermined in the tank (Fig. 2) and the store is charged by an inlet flow of a certain temperature and a certain flow rate through the inlet stratification device from above. The charge test is modelled only for few minutes. The developed fluid flow and temperature distribution in the stratification device after that time is approximately steady state and is a result of the initial and boundary (temperature and flow rate) conditions. This is used to estimate the charge behaviour of the device. A suction rate after Eq. (1) is used to quantify the suction effect, which is the ratio between the mass flow rate of the sucked fluid and the charged fluid.

\[ \Phi_{all} = \Phi_1 + \Phi_2 = \frac{m_{suction}}{m_{in}} \]  

(1)

\( \Phi_1 \) and \( \Phi_2 \) describe the suction rate due to the suction effect 1 and 2 from Fig. 1, respectively.

The investigated inlet stratification pipes and their geometrical descriptions are shown in Fig. 3. The inlet of the charged fluid is located at the top of the storage tank.

![Fig. 3: Investigated stratification devices with different outlet types and their geometrical description, type A: Initial stratification pipe, type B and B2: ConSens charge system, type C, D and D2: Advanced stratification devices [5]](image3)

Fig. 3: Investigated stratification devices with different outlet types and their geometrical description, type A: Initial stratification pipe, type B and B2: ConSens charge system, type C, D and D2: Advanced stratification devices [5]

3. CHARGE BEHAVIOUR

The investigations presented here concentrate on the mixing effects within the inlet stratifier during the charging process of an initially cold store. Under these conditions the suction effect...
1 occurs primarily. From [4, 5] it is well-known that larger values for $h_R$ and smaller values for $d_R$ can reduce the suction effect 2 during the charge of fluid into an existing thermal stratification. It is examined, which consequence this geometrical adoption has on the suction effect 1.

For the investigation of the suction effect 1, the initially cold ($T_{min}$) storage tank is charged through the stratification pipe by fluid with a higher temperature ($T_{in} > T_{min}$). The charged flow enters the tank through the top inlet opening. If the opening is not filled completely with hot charge fluid, cold fluid is sucked in from above through the stratification device. The charged fluid cools down due to the mixing with the colder tank fluid in the outlet nozzle. First of all this is observed at the outlet geometry type B and B2 (Fig. 4a).

Fig. 4: Temperature distribution in the inlet stratification device for different outlet designs, $\Delta T = 15$ K, $V_{in} = 10$ m$^3$/h

It is examined whether it’s possible to reduce the suction effect 1 with a skilful geometrical design of the outlet. Thus vertical redirections were inserted in the outlet geometries type C, D and D2. The idea was to build a range inside the outlet where warm charged fluid gathers due to lift forces and fills out the pipe completely. Thus, no colder fluid can be sucked in from below. Fig. 4 shows the temperature distributions during the charging process with three different outlets under the same boundary conditions. It can be seen that the siphon-like organization of the outlet (type C and D) does not prevent the suction effect under these conditions.

Fig. 5 shows the suction rate $\Phi_1$ depending on $h_R$, $d_R$ and type of the outlet. It can be seen a direct relation between the geometry parameter $h_R$, $d_R$ and the suction rate. At $h_R = 0$ the suction does not take place in principle. With rising $h_R$ the suction rate increases as well. Smaller values of $d_R$ lead to an approximately linear reduction of the suction mass flow. Depending on outlet the representation shows that for each value $h_R$ a value for $d_R$ exists, where suction does not take place. As a result of the horizontal adjustment of the outlet a kind of a stack effect is developed. The longer the outlet nozzle is the greater the pressure-difference between charging device and storage tank becomes. This pressure difference can be calculated with Eq. (2):

$$\Delta p_{buoyancy} = \Delta \rho \cdot g \cdot h_R$$

where $\Delta \rho$ is the density difference between the charge fluid and the tank fluid. Under the described boundary conditions we can define following requirements for the charge behaviour of inlet stratification device:

- No suction effects at all.
- The hot fluid enters the tank only through the top outlet.

In order to prevent the suction effects, the cross section of the outlet must be filled out fully with charge fluid. This is reached, if the pressure loss over the outlet is slightly larger than the pressure difference after Eq. (2). The necessary pressure loss of the outlet results thereby to
\[ \Delta p_{v,R} \geq p_{v,C1} = \Delta \rho \cdot g \cdot h_R \quad (\text{Criterion 1}) \]  

If the pressure loss over the outlet is larger than \( \Delta p_{v,C1} \) in Eq. (3), the charge fluid is pressed further downward in the main pipe toward the second outlet level of the stratification pipe. This can lead to the fact that the charged fluid also enters the tank over the underlying outlet level. To prevent this, the pressure loss of the outlet should remain below \( \Delta p_{v,C2} \) after Eq. (4):

\[ \Delta p_{v,R} \leq p_{v,C2} = \Delta \rho \cdot g \cdot (h_R + \Delta h_c) \quad (\text{Criterion 2}) \]  

with the demand that the values for \( h_R \) in the second outlet level is identical to the value of the top outlet level.

The pressure loss of the outlet is, however, in most cases unknown. Several CFD computations are performed to determine the pressure loss of outlet type D. The results depend on the mean velocity in the outlet and can be approximated over a polynomial of 3rd order after Eq. (5):

\[ \Delta p_{v,R,\text{type D}} = -251.5523 \cdot v_R^3 + 1413.415 \cdot v_R^2 + 10.1054 \cdot v_R + 0.03785 \quad [\text{Pa}] \]  

The mass flow in the 2nd outlet is shown in Fig. 6 as a function of the charge flow rate. A negative mass flow rate means an inflow (suction) and a positive value means an outflow out of the stratification device. Both criteria from Eq. (3) and (4) converted to mean velocities over Eq. (5) are also illustrated. It is shown that with a flow rate lower than the associated value of criterion 1 after Eq. (3), fluid from the tank is sucked in the inlet stratifier. The higher charge flow reduces the suction flow rate. If the volume flow rate (or pressure loss) within a single outlet nozzle is too high, the flow enters the tank over the 2nd outlet level as well. This leads to a stronger mixing outside the charging device. In first approximation the two criteria from Eq. (3) and (4) describe the flow behaviour inside the stratification device well, although the value for the 2nd criterion is slightly too high. In comparison to Fig. 6, three different temperature distributions in the inlet stratification device are shown in Fig. 7.
4. OUTFLOW BEHAVIOUR

Past work’s focus was mainly limited to the detailed quantification of the suction effect within the inlet stratification pipe. However, it was observed that both geometrical parameters and boundary conditions have an influence on the outlet level, where the fluid enters the storage tank. The outflow of the fluid at an unfavourable outlet leads to stronger mixing of hot and cold fluid in the tank. In order to evaluate this in further work, the outflow behaviour is investigated here.

The ideal case of the outflow behaviour is that the charged fluid enters the tank next to that fluid layer in the store, which has the same temperature as the charged fluid. The used temperature distributions in the tank are always in such a way that the fluid layer with the same temperature as the charge fluid is next to the 4th outlet level (see Fig. 2, $y_s = 2.7$ m). Consequently, the ideal case is that the complete fluid flows out at the 4th outlet level.

The mass flow rates at the outlets at several charge flow rates, outlet nozzle diameters $d_R$ and heights $h_R$ are shown in Fig. 8. It can be seen that this ideal case occurs rarely. Often the charge fluid enters the tank over several outlet levels at the same time. This occurs especially for small values of $h_R$ and higher charge flow rates.
One reason for that is the suction of hot fluid from the tank. The fluid in the main pipe heats up and is therefore warmer as the fluid next to the outlet level 4 in the tank. Therefore, the fluid flows out of the stratifier at outlet level 3 partly. Another reason for that is that the pressure loss of the outlet particularly at diameters of $d_R = 0.1\,\text{m}$ is too high. It is recognized that the outflow behaviour with $V > 6\,\text{m}^3/\text{h}$ is better if the suction is prevented. Especially at a flow rate of $6\,\text{m}^3/\text{h}$ and large values for $h_R$, the charge fluid enters the tank already completely over the 3rd outlet level. Under these conditions the pressure loss over the outlet is too low and thus the pressure in the stratification pipe is not sufficient to press the fluid up to the 4th outlet level. This is shown also in Fig 11 a).

In order to improve the outflow behaviour with large value for $h_R$, the heights of the outlet nozzle are reduced stepwise in each outlet level. That means that the outlet nozzle height in the upper outlet level is 0.9 m, in the 2nd level only 0.6 m, in the 3rd level 0.3 and in the lower outlet level 0.1 m. The comparison of the outflow behaviour of the adapted stratification device and the type D with $h_R = 0.9\,\text{m}$ is shown in Fig. 9. With the adapted geometry the charged fluid enters the tank over the 4th opening almost exclusively. Especially in the range of small flow rates the outflow behaviour can be improved. However, the suction is increased a little bit over the 1st outlet level at the same time. Two cases of the temperature distribution during the charge process are shown in Fig. 11.

Beside the outflow level the velocity and temperature of the out flowing fluid are very important. To estimate the mixing effects outside the stratification device a theoretical and a real Richardson number after Eq. (6) and (7) are calculated. The theoretical number is based on the fact that the fluid enters the tank only through one outlet level and no suction effect occurs.

$$Ri_{R,\text{theo}} = \frac{g \Delta \rho d_R}{V^2 \rho} \quad \text{mit} \quad \Delta \rho = \rho_{sp, \text{min}} - \rho_{\text{fin}}$$

(6)

The real Richardson number is solved with the velocities and temperature or densities at the outlets from the CFD calculations:

$$Ri_{R,\text{real}} = \frac{g \Delta \rho d_R}{V_{i,\text{max}}^2 \rho} \quad \text{mit} \quad \Delta \rho = \rho_{sp, \text{min}} - \bar{\rho}_R$$

(7)
Fig. 10 shows the real Richardson number in relation to the theoretical Richardson number for a charging experiment with different boundary conditions and outlet geometries. It can be recognized that the real Richardson numbers are clearly smaller than the theoretical values. The small Richardson numbers point to stronger mixing outside the charge system. It can be seen that the real Richardson numbers are higher if the suction rate $\Phi_{all}$ is less than 0.25. We can deduce, therefore, that if the suction is prevented the outflow behaviour will be better and less mixing will occur in the tank.

![Graph showing real and theoretical Richardson numbers](image)

**Fig. 10: Real Richardson number in relation to the theoretical Richardson number ($\Delta T = 10$ K)**

![Temperature distribution in the storage tank](image)

**Fig. 11: Temperature distribution in the storage tank during the charge process, $\Delta T = 10$ K, $y_s = 2.7$ m, a) $V_{in} = 6$ m³/h, b) $V_{in} = 14$ m³/h**

### 5. CONCLUSIONS

Different stratification devices were investigated using CFD calculations. The main interest was both the quantification of the suction effects and the description of the outflow behaviour of the inlet stratification devices. The results show clearly that the minimization of mixing effects as well as the optimization of the outflow behaviour is possible due to geometrical adoptions of the outlet. To prevent the suction effects the outlet nozzle must have a certain height value for $h_R$ and the pressure loss must be between the values of Eq. (2) and (3). A bet-
ter outflow behaviour can be reached when the outlet nozzle heights $h_R$ are reduced stepwise in each outlet in downward direction (charging from above). If the suction effects are prevented the outflow behaviour will be better. The velocities and Richardson numbers at the outlets have to be in moderate ranges to prevent mixing outside of the stratification device.

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Nomenclature

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<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Subscripts</th>
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<tr>
<td>$d$</td>
<td>diameter [m]</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>height [m]</td>
<td></td>
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<tr>
<td>$m$</td>
<td>mass flow rate [kg/s]</td>
<td></td>
</tr>
<tr>
<td>$Ri$</td>
<td>Richardson number [-]</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>time [s]</td>
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</tr>
<tr>
<td>$T$</td>
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</tr>
<tr>
<td>$\Delta T$</td>
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<tr>
<td>$\nu$</td>
<td>velocity [m/s]</td>
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<tr>
<td>$\dot{V}$</td>
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</tr>
<tr>
<td>$y_s$</td>
<td>distance between fluid surface and thermocline [m]</td>
<td></td>
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<tr>
<td>$\Delta p_{v,R}$</td>
<td>pressure loss [Pa]</td>
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| $\Phi_{all}$ | suction rate [-] |
| $\Phi_{1}$   | suction rate [-] |
| $\Phi_{2}$   | suction rate [-] |
| $\rho$       | density [kg/m³]  |

Subscripts

- $A$ main pipe
- $i$ outlet level
- $in$ inlet
- $max$ maximal value
- $min$ minimal value
- $R$ opening, outlet nozzle
- $real$ real value
- $St$ storage tank
- $theo$ theoretical value

References