

RADIAL DIFFUSERS IN STRATIFIED HOT WATER STORES: GEOMETRY OPTIMIZATION WITH CFD

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Abstract

This abstract deals with thermal energy stores for solar and district heat supply systems and presents numerical results for the performance of radial diffusers in a new type of overground storage tank which has a floating ceiling. The influence of the position of the radial diffuser in the thermal store was investigated revealing significant potentials regarding thermal stratification and storage efficiency. The optimization of the diffuser geometry led to a new free-form radial diffuser, which allows charging temperatures up to 98 °C. A Large Eddy Simulation (LES) illustrated the development of the stratification.

Keywords: CFD, district heating, floating ceiling, geometry optimization, heat supply, hot water, LES; charging device, radial diffuser, solar heating, thermal energy storage, thermal stratification

1. Introduction

Sensible thermal energy stores can make heat surpluses available to the consumer if necessary. A thermal stratification inside the storage tank is achieved by separating water with different temperatures through buoyancy. In a store operating according to the displacement principle, a water exchange takes place by direct charging and discharging. Radial diffusers can serve as charging devices. They consist of radial plates guiding the flow through a narrow gap horizontally into the cylindrical storage tank. For use in solar thermal systems an operation via matched flow is recommended to realize constant loading temperatures.

Numerical results will be presented for a new storage design proposed by Urbaneck et al. (2016) offering numerous benefits compared to other storage types. Here especially the effect on the temperature distribution inside this storage tank will be discussed using Computational Fluid Dynamics (CFD). The main novelty of the construction is an indoor protected floating ceiling, with the upper charging device directly attached to it. A flexible connection allows the free movement of the floating ceiling between a top and bottom dead center. During charging of the tank a gravity current occurs directly at the ceiling, which is an essential prerequisite for a good thermal stratification as will be shown later in this paper. The design is illustrated in fig. 1c. In comparison, fig 1a and 1b show examples of conventional storage types where the radial diffuser is mounted in a fixed position resp. floating (e.g. Hedbäck, 1993).

A demonstrator of the new storage design was already built in cooperation with industrial partners. By now, experiments are in progress to prove the high stratification quality and the very low heat losses. The investigations are part of the OBSERW project (Urbaneck et al., 2017).

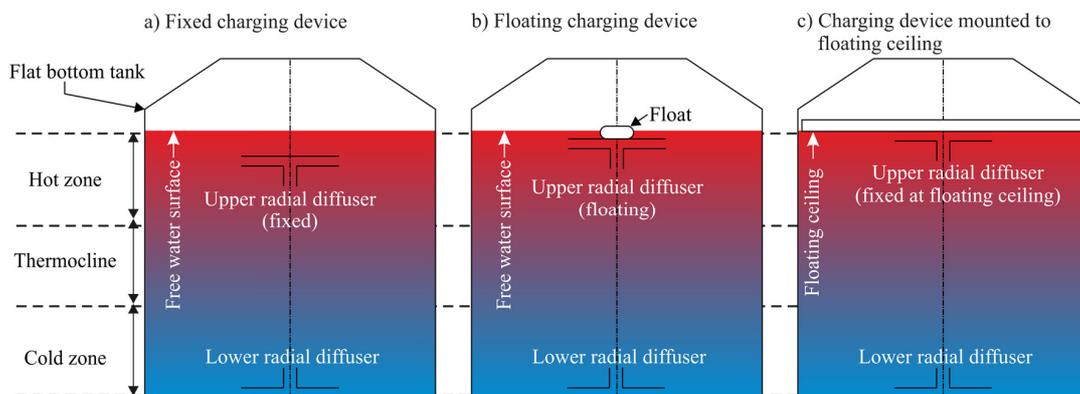


Fig. 1: Thermal energy storage with different possibilities of mounting the charging device in the store

2. CFD model and boundary conditions

A two-dimensional axisymmetric model was used to perform the simulations with Ansys CFX. The CFD model takes buoyancy into account. The $k-\omega$ -SST model serves as a turbulence model. Additional production and dissipation terms capture the effects of density gradients on the turbulent flow. Fig. 2 presents the simulation model. Findeisen et al. (2016) describes the modeling in detail. The boundary conditions at the inlet as well as the initial condition in the tank are determined by the operating conditions in tab. 1 (assumption: constant volume flow and constant charging temperature).

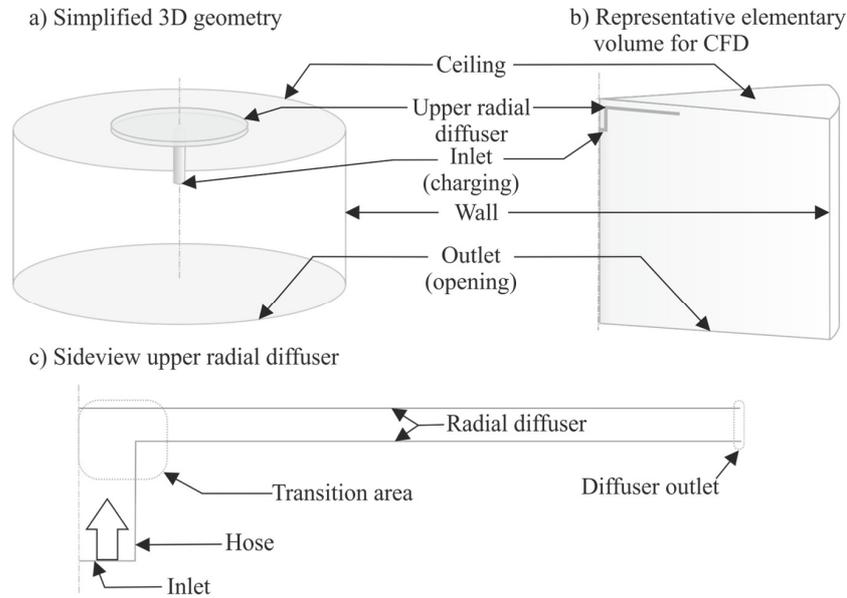


Fig. 2: Schematic view of the simulation model

Tab. 1: Operation conditions and geometrical parameters of the demonstrator

\dot{V}_{in} [m ³ /h]	19.44	T_{in} [°C]	70	$h_{diffuser}$ [mm]	40	d_{store} [m]	5.12
V_{store} [m ³]	116.76	T_{store} [°C]	40	d_{hose} [mm]	68.8	$d_{diffuser}$ [m]	0.96

3. Influence of the position of the charging device

Radial diffusers in flat bottom tanks are usually floating or mounted fix in the store without any moving parts (fig. 1a, b). Thus, the diffuser is located below the water surface, resp. the storage ceiling. To investigate the influence of reducing this distance, especially by mounting the charging device directly to the ceiling, a simplified simulation model was used, which does not consider a free water surface. It assumes a constant velocity profile at the entry of the tank (corresponds to the outlet of the charging device). Hence, the radial diffuser is not yet simulated.

Fig. 3 illustrates the calculated temperature fields for three different cases. As the distance towards the ceiling increases, the thermocline grows and the average temperature in the hot zone decreases while an unfavorable non-isothermal free stream due to convection develops. This free stream causes strong mixing of hot charging fluid and cooler storage fluid significantly reducing the layering quality.

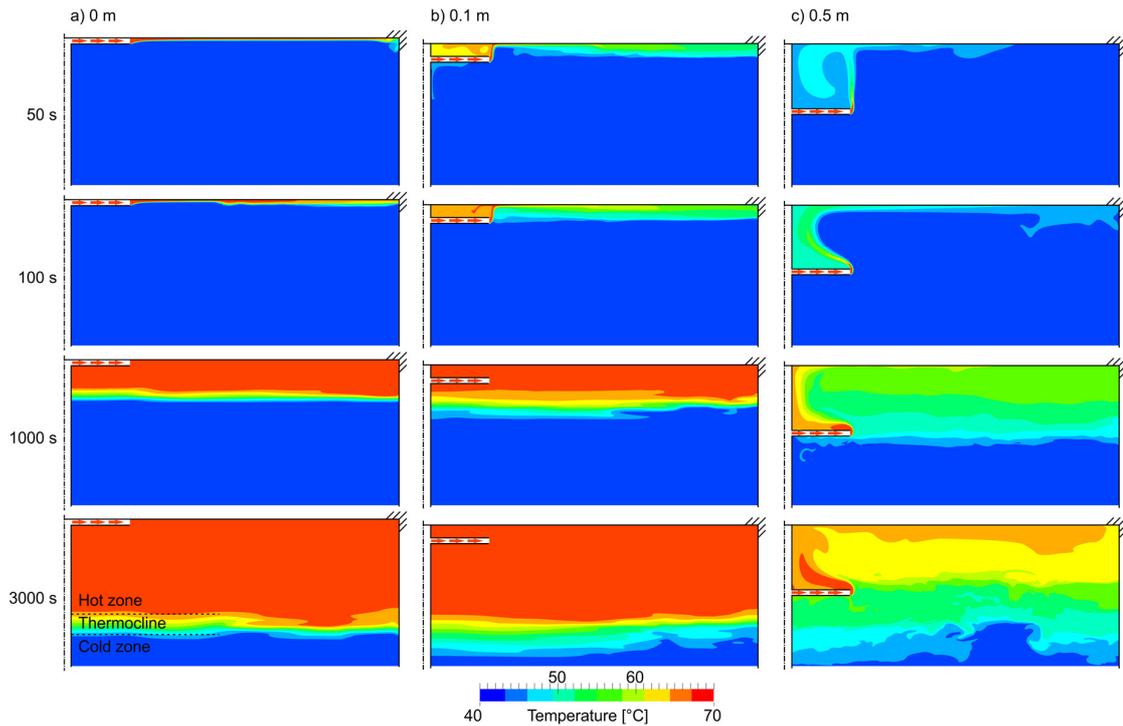


Fig. 3: Evolution of the calculated temperature field inside the storage tank for different distances between the charging device and the ceiling

To determine the quality of the stratification the volume averaged temperature in the hot zone as well as the average height of the thermocline are used for evaluation. The height corresponds to a volume averaged height over the entire radius of the simulation model according to the 90/10%-principle (Findeisen et al., 2016). Tab. 2 compares the results obtained. The thermocline doubles its height if the distance between diffuser and ceiling increases to 10 cm and is more than tenfold its height if the distance is 50 cm. At the same time the average temperature in the hot zone drops to 69.64 °C, resp. 67.42 °C. Thus, the stratification quality strongly depends on the position of the charging device.

Tab. 2: Results for different distances between the radial diffuser and the ceiling after 3000 s of charging

Distance between radial diffuser and storage ceiling [m]	0.0	0.1	0.5
Average thermocline height (90/10%-Method) [m]	0.09	0.18	0.99
Average temperature in the hot zone [°C]	69.99	69.64	67.42

Furthermore, since the hot fluid cannot be removed from above the charging device, the corresponding storage volume as well as the heat stored there is unusable. In addition, as soon as the hot fluid cools down, thermal inversion can permanently destroy the stratification in the tank. Charging directly along the storage ceiling completely eliminates these drawbacks and therefore promises substantial improvements, also because the floating ceiling is well insulated.

4. Investigation of the discharging- and charging behaviour

With a minimal distance between the charging device and the floating ceiling, hot water is sucked in directly along the ceiling in case of discharging, which allows the full use of the hot zone. But mounting the charging device to the ceiling goes along with an elimination of a hydrostatic pressure relief above the charging device. Since the store operates with a maximum temperature up to 98 °C this means that there is a risk of falling below the steam pressure limit. The pump is in feed mode, the charging device sucks in and thus discharges the storage tank. Hereby, the flow can be disrupted by local steam formations (e.g. cavitation) or other transient effects, which can lead to operational failures or even a breakdown of the entire discharging system. In order

to ensure operational safety during discharging, it is therefore necessary to optimize the diffuser geometry in order to minimize the local pressure drop. There is usually no risk for the charging behavior. Instead, for this operational case the influence of different diffuser geometries on the quality of the thermal stratification will be investigated.

The various geometries of charging and discharging systems (CDS) are shown in fig. 4. Starting from a reference case with a sharp edge from the connection hose to the diffuser and straight diffuser walls (CDS_0) the transition area between the hose and the radial diffuser will be modified. Hence, CDS_1 has a round transition with a constant radius and CDS_2 to CDS_4 have a free form transition area. Furthermore, different diffuser styles (CDS_2a/b) as well as build-in parts (CDS_5) and guiding plates at the outlet are part of the study. Besides of the demonstrator (tab. 1) the investigation also considers three representative storage sizes (tab. 3).

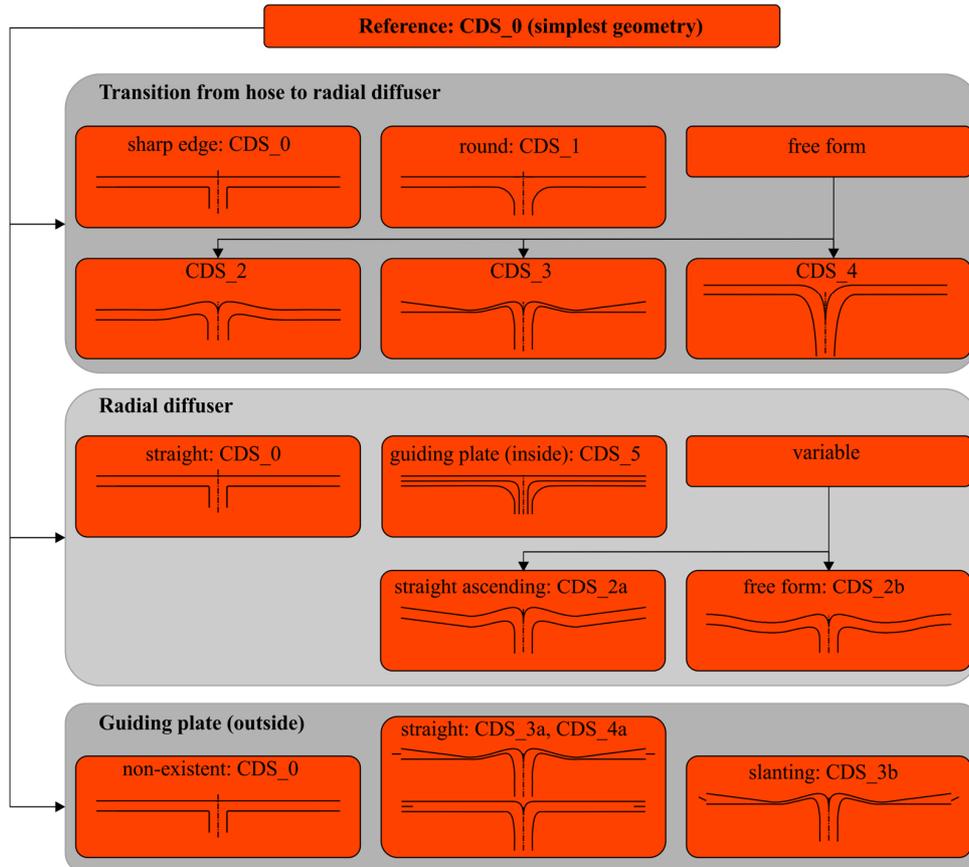


Fig. 4: Investigated diffuser shapes

Tab. 3: Overview of simulated storage sizes

Name	V_{store} [m ³]	d_{store} [m]	$d_{diffuser}$ [m]	$h_{diffuser}$ [mm]	d_{hose} [mm]	\dot{V}_{in} [m ³ /h]	Fr [-]	Re [-]
demonstrator	116	5.12	0.96	40	68.8	20	0.57	4209
store 1	1000	10.84	2.00	80	200.0	167	0.86	17658
store 2	3500	16.46	3.60	120	371.0	583	0.91	34334
store 3	6000	19,69	5,00	120	486,0	1000	1,12	42378

4.1 Discharging behaviour

Aim of the study is to improve the flow inside the charging device since the pressure in the radial diffuser must not fall below the steam pressure limit. Thus, it is important to minimize the local pressure drop. Besides of different storage sizes the investigation also takes into account different atmospheric pressure levels.

The minimum absolute pressure inside the charging device for three different atmospheric pressure levels and the steam pressure limit for 95 °C, resp. 98 °C is illustrated in fig. 5 for selected geometries. Whether the pressure falls below the steam pressure of 98 °C strongly depends on the atmospheric pressure. Whereas for 0 m above sea level (a.s.l.) there is only a risk for the reference diffuser with a sharp edge (CDS_0), in case of 500 m a.s.l. nearly every simulated geometry case, except of the optimized free form CDS_4, falls below the limit. For an atmospheric pressure level according to 1000 m a.s.l. the pressure in CDS_1, resp. CDS_4 is above the steam pressure only if the liquid temperature is reduced to 95 °C.

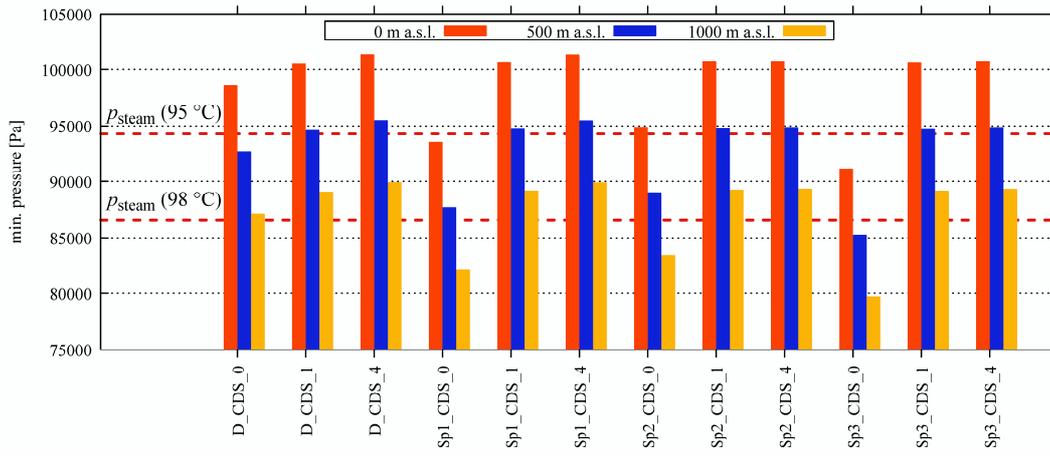


Fig. 5: Minimum static pressure inside the radial diffuser for different atmospheric pressure levels

Fig. 6a shows the pressure field for the reference radial diffuser CDS_0 with a sharp edge between the connection of the hose and the radial diffuser, where the pressure drops locally for about 10 kPa. As a result of the geometry optimization, the free form diffuser CDS_4 (fig. 6b) reduces the local pressure drop to 1.2 kPa. This value corresponds exclusively to the dynamical pressure conversion due to the acceleration of the fluid. Thus, by using a free form diffuser the local pressure drop inside the charging device can be minimized.

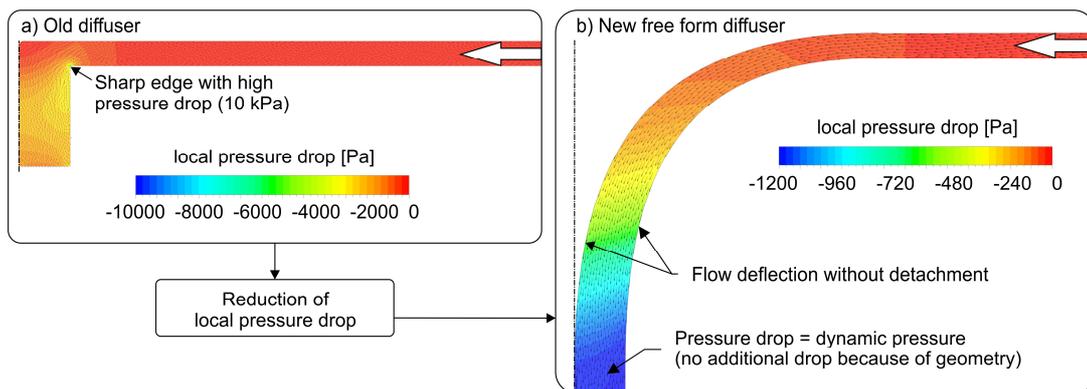


Fig. 6: Local pressure drop in a radial diffuser during discharging with 98 °C hot water; CDS_0 (a) and CDS_4 (b)

4.2 Charging behaviour and development of the thermal stratification

The diffuser shapes were also investigated regarding their performance during charging of the tank. Fig. 7 displays the temporal evolution of the averaged height of the thermal stratification using the example of the demonstrator. It is important to notice, that the criteria is not valid until the thermal stratification is fully developed. This is the case during the first 500 s. In the further development no significant differences can be observed between the investigated diffuser shapes. The same yields for the other simulated stores (fig. 8). There is no remarkable difference between the geometries. Since the stratification quality is already very high

due to the direct mounting of the diffuser at the ceiling no further improvements can be observed. Thus, a very high stratification quality is possible and independent of the diffuser geometry. But, as test simulations with different diffuser heights suggests, this counts only as long as there are no negative velocities at the diffuser outlet because of suction effects. The dimensioning of the radial diffuser is therefore still important.

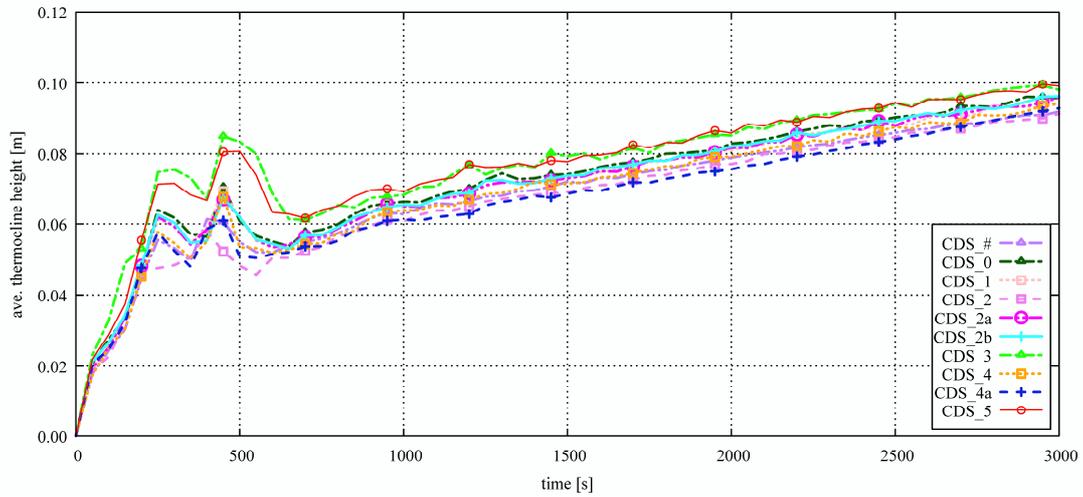


Fig. 7: Temporal evolution of the average height of the thermocline for different diffuser geometries in the demonstrator

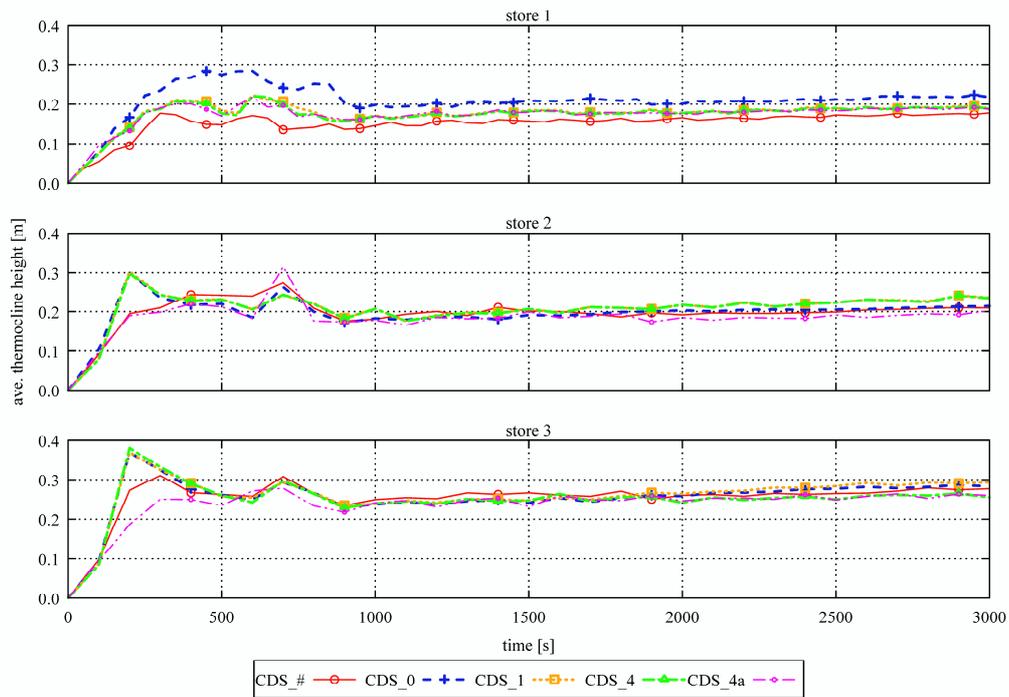


Fig.8: Temporal evolution of the average height of the thermocline for selected diffuser geometries in stores with a volume of 1000, 3500 and 6000 m³

To understand the underlying mechanisms and to illustrate and clarify effects that determine the resulting thermocline height a Large Eddy Simulation (LES) was performed. Fig. 9a shows the density current with its characteristic properties. The result pointed out, that there are mainly two mixing areas. The first one is situated along the height of the radial diffuser (fig. 9c) and the second one is located below the radial diffuser (fig. 9d). Interesting is, that, at least in flat bottom tanks with relatively high diameters, the collision of the density current against the side wall did not significantly influence mixing.

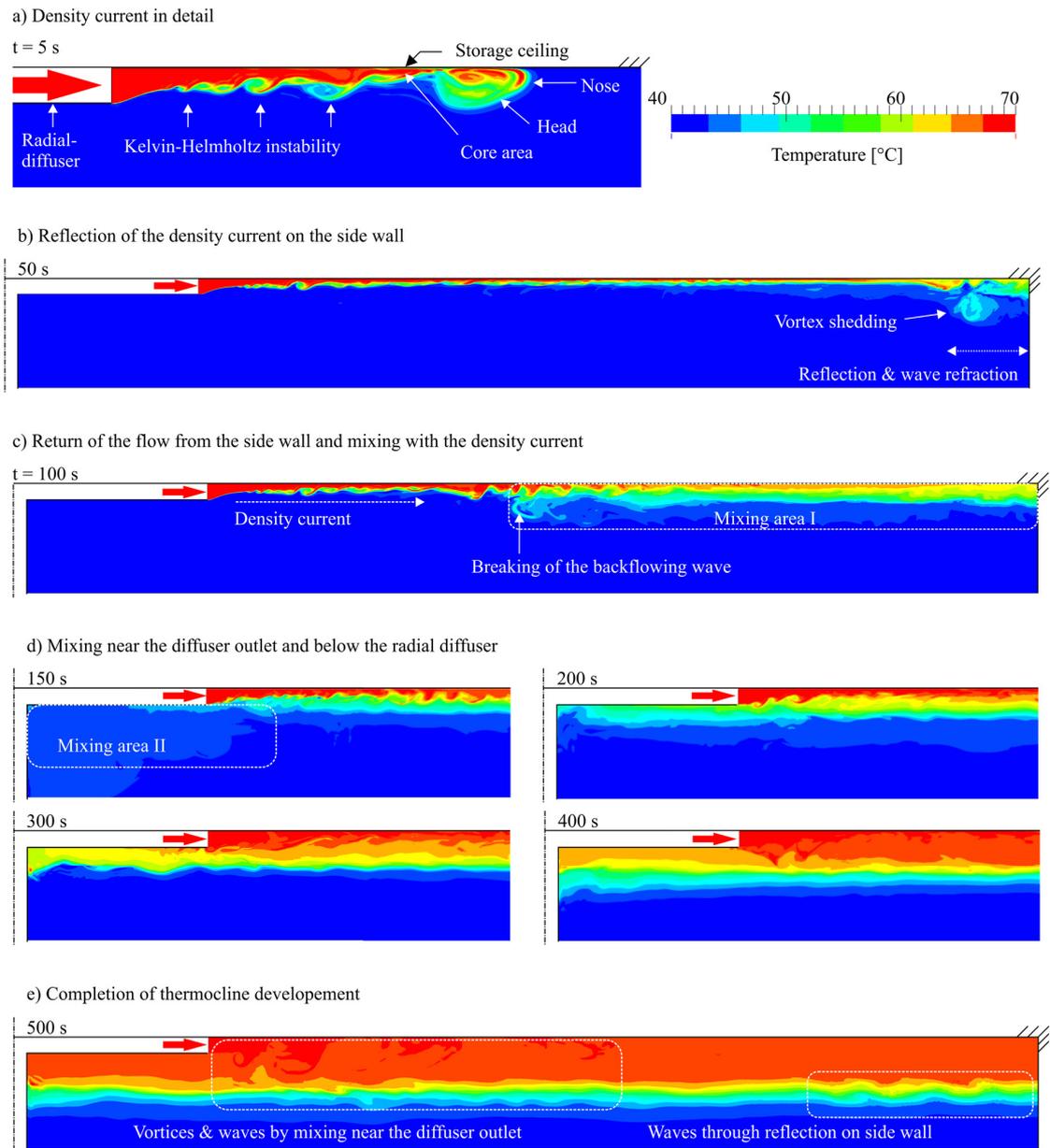


Fig. 9: Temperature field in the cross section area of the cylindrical storage during the development of the thermal stratification

To summarize the results regarding the charging behaviour fig. 7 illustrates the correlation between stratification quality and the Froude number Fr used for the radial diffuser design (Findeisen et al., 2017), resp. the storage volume and the height of the diffuser. Due to the high density difference and the moderate loading volume flow a rather conservative design with $Fr = 0.57$ is present in the demonstrator. In store 3, the Froude number is significantly higher at 1.06, but still within the framework of the usual recommendation of $Fr \approx 1$ (Urbanek, 2012). It can be seen, that the height of the thermocline increases by a factor of about three with a double Froude number. Since in the examples shown the same difference in density exists, here, the height of the thermocline mainly depends on the impulse of the flow.

The diffuser height has a similar tendency to the Froude number on the stratification quality. This correlation is obvious. As previously stated, for the same density differences the impulse of the volume flow rate is decisive and the diffuser height now determines the flow impulse as the outflow velocities are quiet similar. The LES simulation illustrated this correlation qualitatively (fig. 9): The mixing area I is approximately as high as the gap at the diffuser outlet and the final thermocline has approximately twice the height. The additional mixing occurs in the mixing area II. The differences between the different diffuser variants of store

1 and 2 as well as between the variants of store 3 are also determined by mixing area II (because of vertical speed differences in the near field; see Findeisen et al., 2017).

The compact storage tanks considered in this study have a height to diameter ratio of about one. In larger storage tanks likely more mixing takes place due to the increasing mixing surface on the underside of the jet. On the other hand, in stores with a significantly smaller diameter compared to their height other effects dominate (Lohse, 2012).

The results show for a specific operating point that the stratification quality depends on the store diameter, the Froude number and the diffuser height, which is already contained in the Froude number. In addition to the diffuser height, the Froude number also considers the operating parameters. It is therefore well suited for the dimensioning of radial diffusers. In general, buoyancy forces should outweigh inertia forces and therefore smaller Froude numbers should be preferred. In the present case a more conservative interpretation is recommended as the very low thermocline height of the demonstrator proves.

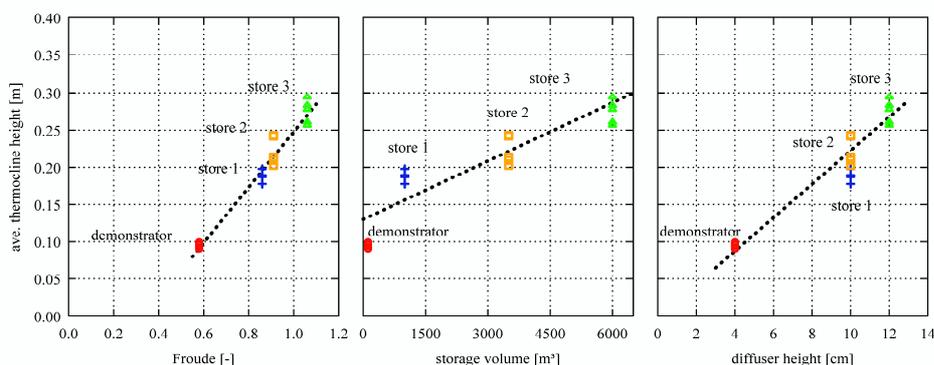


Fig. 9: Results of the average height of the thermocline from all simulated diffuser geometries after 3000 s for different Froude numbers, storage volumes and diffuser heights

5. Conclusion and Outlook

The performance of radial diffusers with different shapes was investigated for a single design point in different hot water storage sizes using CFD. Due to an optimized position of the diffuser in the tank the thermal stratification could be significantly improved. This offers various other advantages and underlines the benefits of a new storage type with a floating ceiling. A new free-form radial diffuser with a flow optimized shape was presented, which enables charging and discharging with temperatures up to 98 °C by reducing the risk of falling below the steam pressure limit. Furthermore, the application of LES identified mixing areas during the beginning of the loading process determining the resulting stratification quality.

6. Acknowledgement

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