Experimental Results from a Laboratory-Scale Molten Salt Thermocline Storage

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Abstract. Single-tank storage presents a valid option for cost reduction in thermal energy storage systems. For low-temperature systems with water as storage medium this concept is widely implemented and tested. For high-temperature systems very limited experimental data are publicly available. To improve this situation a molten salt loop for experimental testing of a single-tank storage prototype was designed and built at Fraunhofer ISE. The storage tank has a volume of 0.4 m^3 or a maximum capacity of 72 kWh_{th}. The maximum charging and discharging power is 60 kW, however, a bypass flow control system enables to operate the system also at a very low power. The prototype was designed to withstand temperatures up to 550 °C. A cascaded insulation with embedded heating cables can be used to reduce the effect of heat loss on the storage which is susceptible to edge effects due to its small size. During the first tests the operating temperatures were adapted to the conditions in systems with thermal oil as heat transfer fluid and a smaller temperature difference. A good separation between cold and hot fluid was achieved with temperature gradients of 95 K within 16 cm.

INTRODUCTION

The two-tank molten salt storage system is the state-of-the-art for large-scale thermal storage in solar thermal power plants. This system is close to ideal regarding a minimization of exergy losses since no mixing of hot and cold salt can occur. However, there is little potential for cost reduction. Moving to a thermocline storage system, where hot and cold fluid are stored in the same tank, may reduce investment costs, since the cost for one tank can be avoided. Beside this obvious benefit a single-tank solution offers other advantages such as simplified inert gas management for the tank ullage, lower heat losses, potential for the utilization of short shaft pumps and a reduced floor space requirement. Latter might be especially beneficial for solar tower plants, retro-fitting of CSP plants with storage but also industrial applications. To improve the acceptance of thermocline systems the quality of the stratification and the thermal efficiency of such a system has to be assessed. While there are dozens of publications dealing with numerical models for single-tank systems, there are almost no experimental data available. There are so far, to the authors' knowledge, no experimental data of molten salt thermocline tanks without filler materials publically available. The presentation of experimental results of a small prototype storage located at Fraunhofer ISE is therefore the scope of this paper.

FUNDAMENTALS OF THERMOCLINE STORAGES AND STRATIFICATION

Thermocline storages are wide spread for hot and chilled water storage systems targeting domestic or district applications, respectively. There have been hundreds of investigations assessing the performance and optimization for this technology. There are several factors promoting or degrading stratification [1]. The primary driving force for stratification is the density difference or actually the relative density difference. The density of molten salt is 1906 kg m^{-3} at 290 °C and 1740 kg m^{-3} at 550 °C, this leads to an absolute density difference of 166 kg m^{-3} or a relative difference of 8.71% for a charging process or 9.54% for a discharging process in case of a system using molten salt as heat transfer fluid. The relative density difference is more than three times higher than in hot water

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storage applications, so far the primary market for thermocline systems. In case of indirect systems with thermal oil as heat transfer fluid where molten salt is only used as heat storage medium the relative density difference for charging is 3.14% which is still higher than hot water systems.

The turbulence at the inlet and associated mixing is the primary cause for the degradation of the stratification. A thermocline tank requires thus a well-designed diffuser at the inlet that dissipates the kinetic energy. However, with increasing density differences the ratio between buoyancy and inertia forces becomes more beneficial and the hot fluid entering the cold storage during a charging process rises to top, therefore reducing the mixing. The other degradation factors are related to heat loss to the ambient and are more challenging, since the heat flux for high-temperature molten systems is much higher than for low-temperature applications. The convective mixing currents which occur at the walls and are caused by heat loss and the higher conductivity of the wall have a much higher impact than the heat loss itself [1]. The fluid cools down at the wall and the higher density leads to a downward flow until the fluid reaches either fluid with the same density or the bottom of the tank. This causes a compensating flow in the center of the tank to replace the displaced fluid. The mixing of hot and cold fluid layers and the associated entropy generation and exergy loss has much higher impact on the performance than the pure heat loss. Due to the higher temperature difference to the ambient and the resulting heat loss, the temperature difference between bulk fluid and boundary layer, that is the driving force for the buoyancy current, is much higher for molten salt systems. However, the size of commercial-scale molten salt tanks is reducing the impact of this effect since the shell-area-to-volume-ratio is decreasing with increasing diameters and the ratio of the wall boundary layer compared to the total tank volume is much smaller. A constructive modification for smaller tanks is the installation of small horizontal baffles at the tank wall. This was investigated by CFD-simulations in [2].

Thermocline tanks are supposed to provide a better performance if large aspect ratios of tank height to tank diameter are realized [1]. This associated to the charging process and distribution of the storage medium at the inlet. Furthermore, if it can be assumed that the thickness of the thermocline zone is independent of the diameter, less storage medium is at an intermediate temperature in the thermocline zone for tall tanks. Whereas tall hot water tanks with aspect ratios > 3 have been realized, the height of molten salt storage tanks was limited so far to approx. 14 m which is caused by a limitation of the pumps shaft length and also to the hydrostatic pressure which is, however, also influenced by the diameter. Instead of using low tanks with huge diameter, also tall tanks with a smaller diameter could be built. A thermocline tank with an almost constant fluid level could utilize short-shaft pumps with an extension of the suction inlet that are placed within the tank or even small pumps that are located in external pump tanks, eliminating another factor for restrictions of the tank height.

DESCRIPTION OF TEST FACILITY

The design of the test facility had to consider some boundary conditions regarding the site and the operation of the system such as daily drainage by gravitation into the drainage tank which affected the position of the individual components. These boundary conditions had a huge impact on the design. Other requirements were the maximum operating temperature of 550 °C and the capability to control the charging and discharging flow between 0% and 100% to investigate the influence of the inlet velocity on mixing.

Layout and Equipment

The main components of the test loop are:

- Pump tank
- Electric heater
- Thermocline storage tank
- Helical coil heat exchanger for cooling
- Drainage tank

All the tanks and heat exchangers are manufactured in stainless steel material (1.4404, 1.4571 or 1.4541). Pump tank and storage tank both have a diameter of DN 600 (d_a 609.6 mm) and a curved bottom but a flat lid. The length of the main cylindrical part of storage tank is around 1200 mm and distance between inlet and outlet is around 1300 mm, it leads to a total volume of approx. 0.4 m^3. A detailed drawing of the storage tank can be seen in Fig. 3. The electric heater has a power of 60 kW and is housed in DN 125 pipe with straight heating elements but without baffles to simplify the draining process. Thermocouples (TC) are mounted on the heating elements itself to avoid that the maximum temperature of the salt is exceeded in the boundary layer. There are two additional thermocouples at the inner wall of the heater to control the temperature during the preheating before the system is filled with molten salt. The heat exchanger for cooling is a helical coil heat exchanger with a helically coiled tube placed in an annulus formed by the outer (DN 200) and inner tube (DN 150) of the shell. Molten salt flows through the shell side and thermal oil through the tube. The special design of the heat exchanger prevents that the maximum film temperature of the thermal oil is exceeded. The cooling capacity of the heat exchanger is also 60 kW. The existing cooling system will be replaced in the next months by a closed loop air-cooling system. The main actuators to operate the system, which is shown in Fig. 1, are:

- 1 vertical cantilever molten salt pump (P1)
- 4 pneumatic operated control valves (V1, V2, V3, V10)
- 2 pneumatic operated globe valves (V4, V5)
- 3 manual drainage valve (V6, V7, V8)
- 1 pneumatic operated venting valve (V9)

All the valves, except the venting valve, are bellow-sealed and have size of DN 25 which is also the size of the piping. Valves from different manufacturers have been chosen during the procurement phase to find the most economical and reliable solution for future systems. The molten salt pump has a capacity of 4 $m^3 h^{-1}$ at total head of approx. 9 m. Mineral-insulated heating cables or coil heaters are attached to all components to warm-up the plant before the operation.

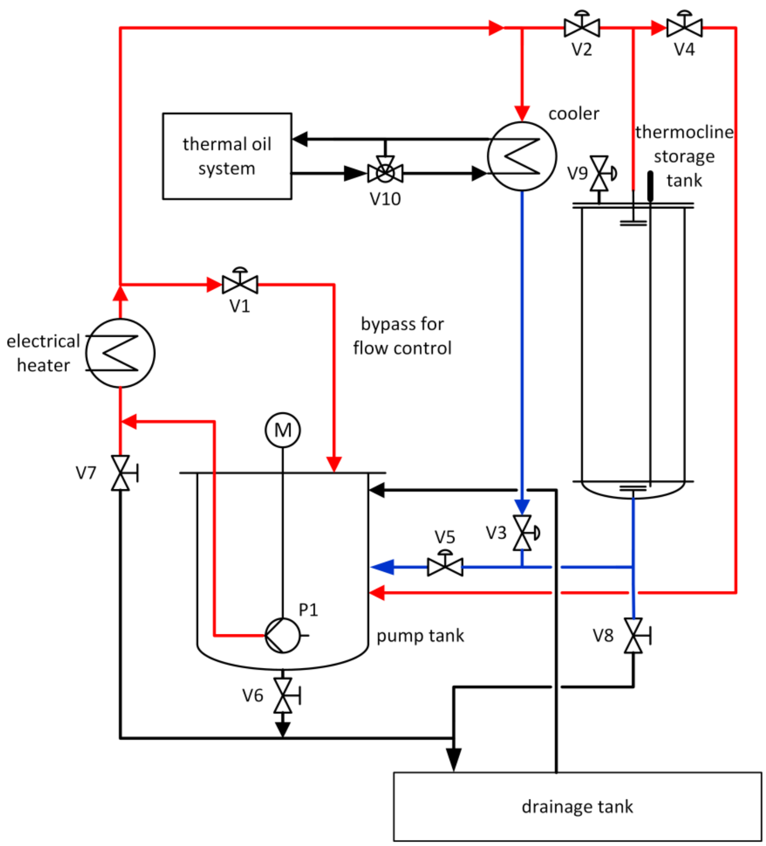

FIGURE 1. Layout of the single-tank test facility.

For the operation control the following sensors are used to determine the state of the plant:

- more than 100 temperature sensors (4-wire RTD & TC type K)
- 1 continuous level measurement sensor (guided wave radar) in the pump tank
- 2 flow measurement devices (ultrasonic clamp-on)

Operation Modes

At the beginning all the salt is located in the drainage tank where also the melting takes place. For that purpose mineral insulated (MI) heating cables with a power of 16 kW are mounted on the side and the bottom of the drainage tank. Heating cables are attached to every tank, pipe and valve of the plant to heat the plant to 290 °C before filling it with molten salt.

In total 48 individual heating circuits are used to control the temperature of the components. The power of the heating circuits is continuously controlled via semi-conductor contactors. The control signals for the semi-conductor contactors are calculated by software PI controllers of the control software. It allows a detailed monitoring of the temperature and the power consumption for the heat tracing equipment. Temperature monitoring relays guarantee that maximum temperature of the heating cables and the salt is not exceeded. These relays can be operated in a window mode, checking an upper and lower temperature limit. They also prevent that the temperature falls below the freezing temperature if the software control fails. In this case the monitoring relays operate the heating circuit around the lower threshold temperature with a hysteresis control method.

As soon as all the components are warmed-up, the molten salt is pushed from the drainage to the pump tank from where it is pumped to the storage tank. An overflow systems guarantees that the thermocline tank is always filled. A slightly rising level in the pump tank indicates that the thermocline tank is completely full. Valve V9 which was initially open, is closed to seal the storage tank. To homogenize the temperature in the entire system, especially in the thermocline tank before the charging process, the salt is circulated through the thermocline tank with a high flow rate and the electric heater is controlled to aim at the lower storage reference temperature. The temperature distribution is controlled via the thermocouple tree in the thermocline tank. The charging process is illustrated in Fig. 2 a.

At the beginning of the charging process V1 is open and V2 closed and the molten salt inventory in the pump is circulated through the electric heater to be heated to the target inlet temperature of the thermocline tank. As soon as the molten salt has reached the target temperature, V1 is slightly closed and V2 slightly opened. Valve V1 and V2 and the speed of the pump are used to control the charging flow rate. Only a small portion of the molten circulated through the heater is routed to the thermocline tank, the major part flows through the bypass back to the pump tank. The flow meter at the upper inlet of thermocline tank is used to monitor the flow rate. While the hot salt enters the tank at the top, the cold salt is pushed out of the storage at the bottom of the tank and flows back to the pump through valve V5 which is always fully open during a charging process. Valve V3 and V4 are always closed during a charging process. The cold salt is mixed in the pump tank with hot salt returning through the bypass from the electric heater. As soon as the thermocline tank is completely charged, the discharge process starts. This process is shown in Fig. 3.

During a discharging process valve V2 and V5 are always closed. Valves V1 and V3 as well as the speed of the pump are used to control the discharging flow rate. In this case, the second ultrasonic flow meter at the lower inlet of the storage is used to monitor the flow rate. The electric heater is usually switched off during a discharging process since the temperature in the tank is higher than the required inlet temperature during discharging. The helical coil heat exchanger is used to cool down the molten salt to the desired inlet temperature. As the cold salt enters at the bottom of the tank, the hot salt at the top is pushed out of the storage and flows back to the pump tank. After the end of every test all the valves including the manual valves V6, V7, and V8 are opened to drain the salt back into the drainage tank which is properly insulated. Even without heating this tank during the night, the salt remains liquid and only has to be heated slightly at the next day before it can be pushed again in the pump tank.

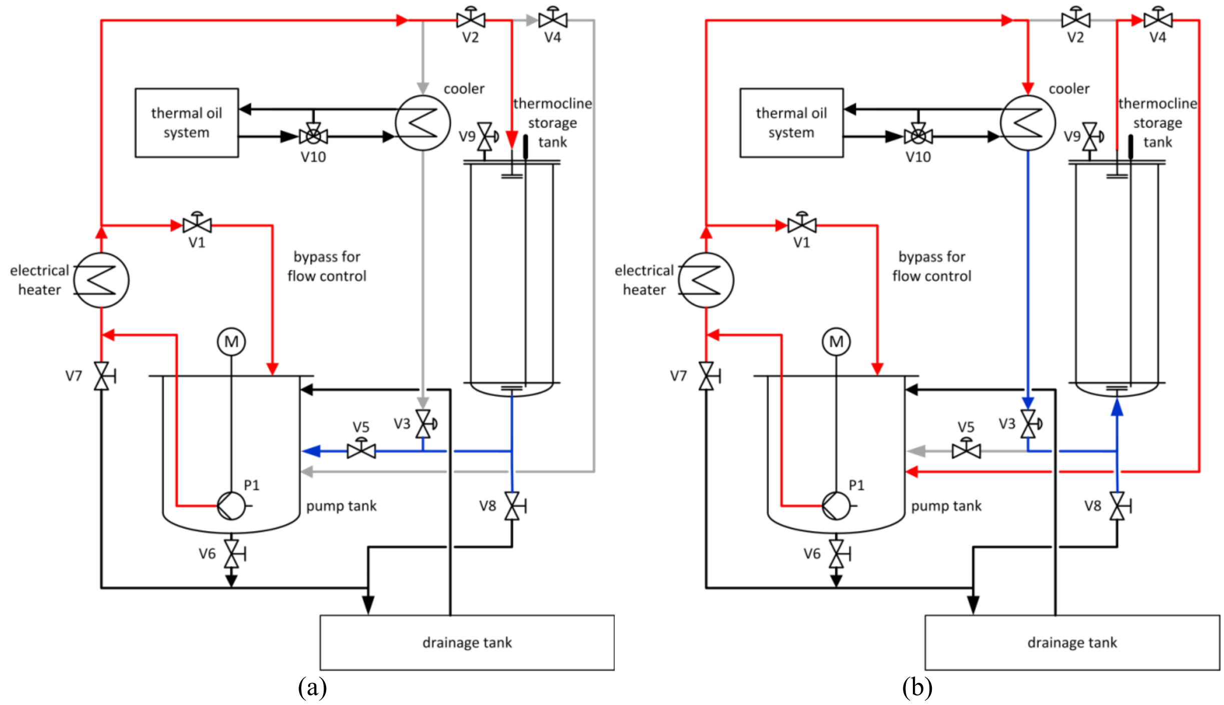

FIGURE 2. Illustration of the charging (a) and discharging process (b).

Storage Tank Setup and Instrumentation

For the evaluation of the experimental results, several thermometers are located inside and outside the storage. Two 4-wire RTDs are located at the ports at the top and bottom of the storage, they will be used in combination with the flow rate to calculate the dis-/charging power of the system. Additionally there are three 4-wire RTDs inserted through the lid of the tank which measure the temperature distribution explicitly in the upper 10% of the storage to monitor the mixing during the beginning of the injection of hot fluid. A vertical thermocouple tree with 15 thermocouples is used to obtain the vertical temperature distribution. Furthermore, three 4-wire RTDs in a steel jacket are welded to the top, center and bottom of the inner wall of the cylindrical section of the storage tank. 14 thermocouples are mounted on the outer wall of cylindrical section and are placed on the same height as the upper 14 sensors of the thermocouple tree. The distance between the thermocouples are 8 cm. Additional there another 14 thermocouples mounted between the primary and secondary insulation which will be described later. The instrumentation is shown in Fig. 3.

A cascaded insulation is applied to reduce the wall heat flux and investigate the influence of the heat loss on the stratification. This precaution was taken to avoid that edge effects can dominate the system due to its small size and bad shell-area-to-volume ratio. The thermocline prototype has a shell area of 6.67 m^2 per m^3 tank volume, large commercial tanks with 38 m diameter have ratio of 0.1 m^2 m^{-3}. The tank and its surroundings consist of six different layers, the first layer is the tank wall, and the second layer are the thermocouples on the outside of the tank wall. The fourth layer which is the first insulation layer consists of cylindrical microporous insulation shells. There is a flexible ceramic fiber insulation, the third layer, beneath the hard shells to compensate tolerances of the outer diameter the tank wall and the inner diameter of the hard shells. Furthermore, this soft layer also absorbs the thermal expansion of the tank and avoids that there is a gap between the different pieces of the hard shells. 14 heating cables are mounted in circumferential direction on the primary insulation along with thermocouples for the temperature control and represent the fifth layer of the system. The secondary and main insulation is the sixth and last layer of the system.

As mentioned above the heat loss can cause a degradation of the stratification since the colder and denser fluid close to the wall sinks to bottom and can cause convective mixing currents. To reduce the heat loss, the temperature of the heating cables is controlled to be 5 K below the measured temperature by the thermocouple tree at the same vertical position in the storage. This arrangement results in a heat loss reduction by factor 10 compared to the option with a single insulation layer and the temperature of the boundary layer at the wall will be much closer to the bulk temperature. The temperature difference in radial direction in the tank should be much smaller than 0.5 K which also requires an outer wall temperature close to the bulk temperature. The heating cables can therefore not be mounted directly on the wall since the uncertainties of the sensors and the stability of the control could not guarantee that the heating cable temperature would not exceed the bulk temperature if the target temperature for the heating cable control would be e.g. 1 K below the bulk temperature. It could lead to salt heating from the outside which is not desirable.

FIGURE 3. Instrumentation of the thermocline storage tank.

Another major parasitic effect which leads to a degradation of the stratification and which is probably the most important one is the mixing near inlets. To address this aspect a double-plate radial diffuser was attached to the inlet pipes of the storage tank. The fluid enters the diffuser axially and flow is diverted into to radial direction. The velocity decreases towards the outer diameter of the diffuser plates and reduces the amount of mixing between the hot incoming fluid and the cold fluid initially in the tank.

EXPERIMENTAL RESULTS

At the beginning of the test period only tests with a lower temperature difference and lower absolute inlet temperature have been performed as they would occur in the storage system of the ORC-PLUS project or in parabolic trough systems with thermal oil as heat transfer fluid. The focus during the initial tests was to evaluate the capability to establish a good stratification in the tank at all despite its small size and unfavorable area-to-volume-ratio. One of the stratification profiles for a charging process with relatively small temperature difference is shown in Fig. 4. It is important to keep in mind that the height of thermocline should not be evaluated in a non-dimensional way as relative thickness compared to the tank height but in an absolute value since the height of the tank does not affect the thickness of the thermocline directly. The absolute thickness of the thermocline as it is shown in Fig. 4 would almost be the same if the tank would be twice as tall, the relative thermocline size would be much smaller, though. Another important aspect is that the temperature profile can only be evaluated at discrete locations in the storage tank where the thermocouples are located.

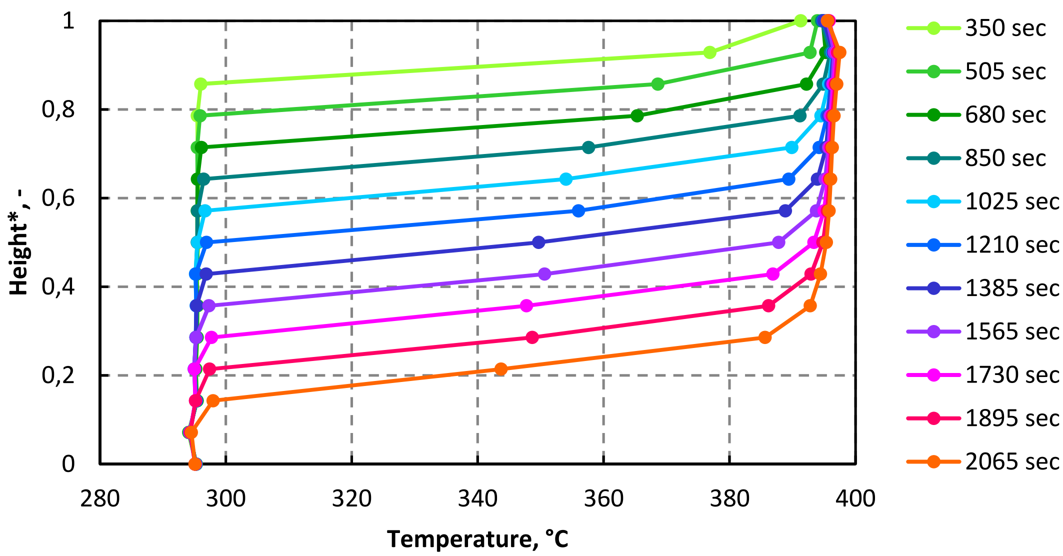

FIGURE 4. Stratification profile during a charging process with a small temperature difference.

Showing the temperature as function of the time, as it is often done, does not really provide useful information especially if the charging velocity is not known. For the sake of comparison is done nevertheless in Fig. 5, a better approach will be presented in Fig. 6. Figure 5 can be used to obtain the time which is required until the thermocline has passed one sensor. If the flow rate and fluid velocity is known, the spatial resolution of the thermocline can be derived which is still rather complicated compared to Fig. 4. However, the data in Fig. 5 could still be used to derive the temperature gradients which would occur in the components connected to the storage such as heat exchanger, in case of indirect systems or solar field and steam generator in case of direct systems. Figure 6 shows the maximum temperature difference of all measurements points within one measurement interval and also for each interval the maximum temperature difference that occurs between 2 or three measurement points. The fluctuating nature of the blue and red line is related the discrete sensor positions and whether the beginning and end of the thermocline is captured by sensor during at the corresponding time. A quantitative analysis reveals that maximum temperature gradients of 10.7 K cm^{-1} have been achieved, thus the maximum temperature difference within 8 cm is 85.76 K. The maximum difference within 16 cm is 96.9 K. If these temperature differences are compared to the total difference at a specific time in the storage, it can be seen that 95% of the total temperature difference occurs within 16 cm and 85% within 8 cm. It can be seen in Fig. 4 and 5 and especially in Fig. 6 that the thermocline increases with the time. In the case of this small prototype, this maybe mainly caused by the impact on heat loss and big inertia of the tank compared to the amount of molten salt.

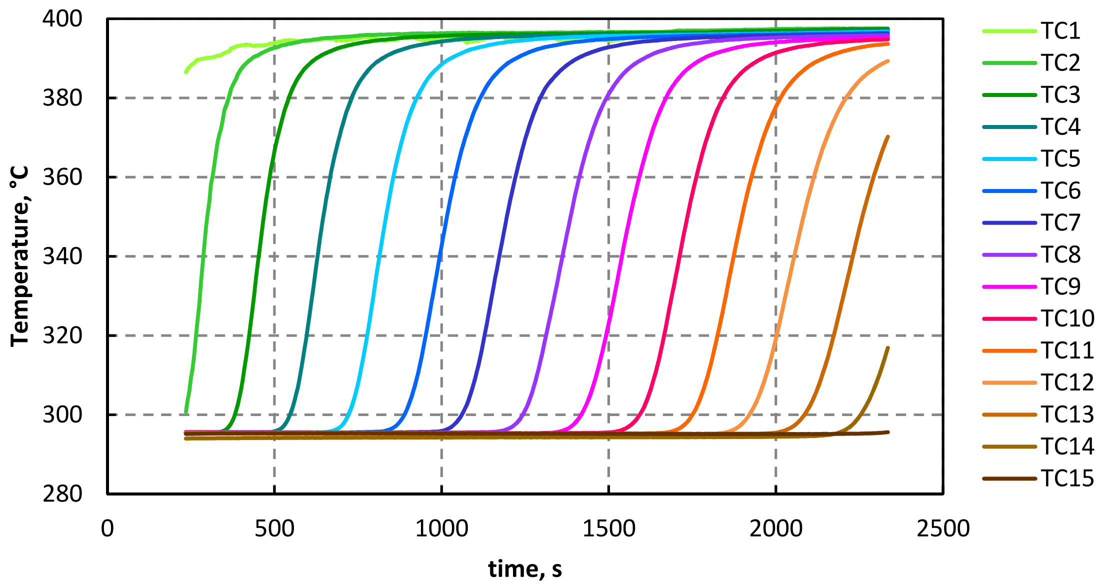

FIGURE 5. Temperature as function of the time for the different sensor positions (TC1 = top, TC15 = bottom).

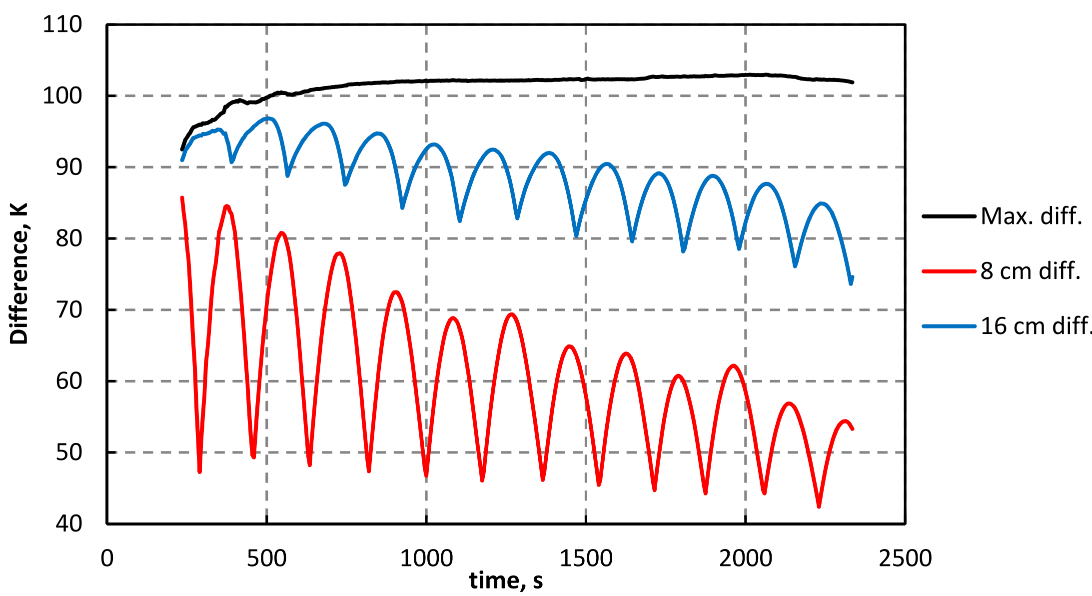

FIGURE 6. Maximum total temperature difference and maximum temperature difference between 2 and 3 measurement points.

CONCLUSION

The first stratification results have been obtained with the molten salt loop and single-tank storage prototype designed and built at Fraunhofer ISE. The initial tests have been performed with lower temperature differences as they would occur in systems with thermal oil as heat transfer fluid. 95% of the total temperature change in the tank takes place within 16 cm where the absolute temperature difference is up to 96 K. Even though, the stratification is very good, it can be observed that the thermocline is increasing during the charging process which might be related to the heat loss. The control strategy for the heating cables around the storage will be optimized to reduce this effect. The operating temperature and also temperature difference will be slowly increased to observe the effect of the higher density difference and higher heat loss at elevated temperatures. More information will be given in the presentation.

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