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Partial cycle operation of latent heat storage with finned tubes

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**ABSTRACT**

This work examines a high temperature latent heat storage system, which could find use in future concentrated solar power and other combined heat and power plants. In contrast to lab-based fully charged or totally discharged states, partial load states will be the principal operation states in real-world applications. Hence, a closer look on the partial load states and the effective power rates are worthwhile for a successful implementation of this storage type. A vertical finned shell and tube heat exchanger pipe with a combination of transversal and longitudinal fins is applied. Sodium nitrate with a melting temperature of 306 °C is used as phase change material and thermal oil serves as heat transfer fluid. Temperatures in the storage and the heat transfer fluid as well as the mass flow are measured for data analysis. The state of charge formulation is based on an enthalpy distribution function, where the latent heat of fusion is spread over a specific temperature range.

The data show consistently high power rates for all partial load cycles at any state of charge. The mean power rate for charging is 6.78 kW with a 95.45 % confidence interval of ±1.14 kW for all cycles. The discharging power rate is −5.72 kW with a 95.45 % confidence interval of ±1.36 kW for all cycles. The lowest power rate is measured for the full cycle at the end of charging/discharging. It is caused by a narrow volume, which is not penetrated by fins, near the perimeter of the cylindrical heat exchanger. The state of charge formulation correlates with the storage capacity and enables state of charge based cycling. With the energy balance of the storage, the data validity is proven and further storage parameters are determined. The energy density is as high as 110 kW h m⁻³ and a power rate of 2.28 kW m⁻¹ for the finned tube is confirmed. These values are highly promising for further development and application of latent heat storage systems.
1. Introduction

The Intergovernmental Panel on Climate Change presented a detailed analysis of the impact of global warming and put forward 1.5 °C as target value in its special report in 2018 [1]. Based on that report, the International Renewable Energy Agency published the Climate Change and Renewable Energy Report in 2019 [2] drawing a pathway for future renewable energy systems on the basis of the 1.5 °C goal. Reducing the global CO₂ emissions requires a significant transition to renewable energy sources in all sectors like buildings, power, industry, district heat and transport. Approximately 75% of this transition should be based on renewable energy and electrification of heat and transport, the rest should be reached through energy efficiency policies. In 2020 more than half of the added renewable capacity in power generation have lower electricity costs than modern coal power plants. The prices for solar photovoltaic fell about 82% between 2010 and 2019. Other renewable power generation costs have fallen sharply too, as the new IRENA report on renewable generation costs in 2019 points out [3]. This transformation towards a more renewable energy system requires a fundamental shift in the way how energy systems are conceived and operated.

In this renewable-driven energy transition, storage systems — regardless of the type — will play a key role in operating energy grids with a high share of volatile renewable energy sources. A good overview of global energy storage capacity is provided by the Energy Storage Database [4]. The majority of the available storage capacity is based on pumped hydro. A lower but increasing share is based on batteries and thermal storage systems. Thermal storage systems on a utility scale are used today in concentrated solar power (CSP) plants. Especially during the past five years, the majority of commissioned plants have been designed with TES systems, according to the latest IRENA report. Even though they only account for 0.2% of the renewable power production, CSP plants with storage systems have high capacity factors of up to 60% compared to wind and PV systems.

In any case, high temperature TES systems are a niche application at the moment. At lower temperatures, applications are widely spread from domestic heating to district heating. Predictions and studies on potential needs of storage capacity have been published for Germany. Sterner [5] predicts a share of renewables in power generation of 40% in 2020, with no need of additional storage capacities. For the year 2030 Sterner predicts a share of renewables of up to 63%, which leads to the need of more short term storage systems such as pumped hydro and thermal storage. Especially thermal storage systems will be needed to increase the efficiency of combined heat and power (CHP) plants. Today, CHP-plants are operated as heat demand following processes in order to minimize waste heat, with the trade-off of a bad thermal efficiency of the power cycle. The integration of thermal storage systems could enable modern CHP-plants to be operated as electricity demand following processes (which means at maximum efficiency), by closing the temporal gap between waste heat supply and heat demand. What Sterner could not foresee were the effects of the Covid-19 pandemic on the energy generation situation. For example in Germany, the electricity demand fell by about 29% between April and May 2020. As a consequence, the share of renewables skyrocketed to 60% — a value which Sterner only expected by 2030. Of course it is hard to make serious predictions at the moment but large-scale energy storage might be required earlier than we expected just a couple of months ago.

1.1. Latent heat storage systems

While sensible storage systems are already mature and widely applied, latent heat thermal energy storage systems still remain at the lab-scale and prototype level. Reviews on thermal energy storage systems like the ones from Alva et al. [6] or Zhang et al. [7] provide a good overview of the different methods and applications. For latent heat TES and phase change materials (PCM), Sharma [8] and Nazir et al. [9] are comprehensive articles. In contrast to sensible storage systems, the enthalpy of fusion accounts for high energy densities in narrow temperature ranges with the disadvantages that go along with the phase change (e.g. low thermal conductivity), like Cabeza describes in [10]. Many PCM suffer from low thermal conductivity, which limits the heat transfer ratio significantly. Enhancing the heat transfer for latent heat TES is an ongoing research topic with a wide range of proposed solutions. An executive overview on state of the art enhancement methods is provided by Jegadheeswaran et al. [11]. Encapsulation on macro [12] or micro scale [13] are proposed solutions.
as well as mixing the PCM with particles to increase the heat transfer rate. Adding magnesium particles for ternary carbonate salts [14] or the application of an \( \text{Al}_2\text{O}_3 \) nanoparticle dispersion for nitrate salts [15] are further enhancements. Unfortunately this enhancement method is not suitable for every type of PCM as sedimentation and separation limit its area of application only to a few types of PCMs and additives. For encapsulation, the manufacturing process often is complex and costly, the stability of the encapsulation has to be guaranteed over lifetime. Less research focus is on direct contact PCM storage systems, in which the HTF and the PCM are either the same material [16] or do not mix in the liquid phase [17,18].

The most advanced heat transfer enhancement method is increasing the heat transfer area by mounting fins on the HTF tubes. Because of their simplicity, fins are used frequently for latent heat TES. A huge variety of fin types is available. Longitudinal and transversal fins are differentiated. The orientation and the fin geometry are further essential parameters. Industrial scale prototypes, like the one presented by Johnson et al. [19], use vertical longitudinally finned heat exchanger tubes, similar to our test-rig. Optimization of fin types and their geometries are frequent research topics investigated by several authors. Zhang et al. [20] focus on fractal-tree-shaped fins, Pizzolatto et al. [21] designed an optimized fin layout through topology optimization, Eslamnezhad et al. [22] compare selected arrangements of fins and Sciacovelli et al. [23] aim to maximize the performance of latent heat TES using time dependent fin shape optimization. Previous experimental investigations with our test-rig showed good results for a combination of transversal and longitudinal fins [24]. Non-finned tubes are applied in a study from Tehrani et al. for high-temperature latent heat storage systems in concentrated solar power plants [25]. The heat transfer surface (the tube surface) can be optimized for different storage materials in order to increase the capacity of the storage system. The discharging efficiency in this systems is generally lower than the charging efficiency, like Tehrani et al. concludes, and costs are higher than two-tank storage systems for solar power plants for this configuration.

Numerical investigations on the melting behavior of PCM were conducted by Koller et al. [26], Walter et al. [27] who also include the solidification process in their research and Diao et al. [28] who examined a different storage type than Koller et al. and Walter et al.. Vogel et al. point out that natural convection plays a significant role in melting for large tube spacing [29]. The effect of natural convection decreases with the fin height — an argument for the proposed combination of longitudinal and transversal fins because adding transversal fins reduce the effectiv fin height. A general design optimization is presented by Rezaei et al. in [30]. Applying a combination of different storage systems and materials is demonstrated by Tehrani et al. et al. in [31]. A combined PCM and sensible storage system for a concentrated solar power plant could not reach the same efficiency as a two tank sensible storage system under the given frame conditions but the combination exhibit higher efficiency than single-PCM solution with non-finned tubes.

1.2. State of charge and partial load operation

For industrial applications, the prediction of the power rate and storage capacity of a latent heat TES are essential. The heat transfer rate between a heated surface and the storage material mainly depends on the thermophysical properties of the storage material and the enhancement method. Latent heat TES typically operate in temperature ranges where, due to the phase change, the thermophysical properties undergo drastic changes, which makes it difficult to predict power rates and capacities. Referring to the low thermal conductivity of PCM Groulx called it the rate problem [32]. In fact, many experimental investigations, including the one by Groulx, show highly volatile power rates during charging and discharging. Mawire et al. [33] examine a medium temperature latent heat TES filled with encapsulated eutectic solder in their work, Rezaei et al. [30] investigate a high temperature latent heat TES using macro-encapsulation and foams as heat transfer enhancement, Couvreur et al. [34] and Zauner et al. [35] carried out experiments on high temperature latent heat TES with an eutectic mixture of \( \text{KNO}_3/\text{NaNO}_3 \) and high density polyethylene respectively and García et al. [36] conducted numerical as well as experimental investigations on a pilot scale latent heat TES for CSP-applications. All with the conclusion of high volatile power rates.

The so called state of charge (SOC) is defined in several publications. Common synonyms are “ratio of accumulated energy (RAE)” [37] and “liquid fraction” [38]. A precise definition of the SOC for the present investigation is provided in the theory chapter. Generally, latent heat TES are operated around the melting point of the PCM. They are charged with a specific temperature offset above the melting point and discharged below the melting point. The enthalpy of fusion and a small amount of specific heat capacities of the PCM account for the capacity of the storage. In a fully charged latent heat TES, the storage material is liquid, in a discharged storage system it is solid. The liquid fraction, as used by Rösler et al. [39] for example, is defined as the ratio of liquid to total PCM. It is frequently used in numerical investigation to visualize the state of the PCM. A definition of the SOC is provided by Barz et al. [40]. They focus on the SOC estimation for latent heat TES using a non-linear state observer model to reconstruct a spatial temperature field in the storage and validate the model with experimental data. To determine the state of charge in experimental PCM storage investigations, different methods are available as Zsembinszki et al. [41] describe in their interesting work on a thermal storage system for cooling applications in buildings. The accuracy of temperature dependent state of charge determination around the melting point could be enhanced by measuring the pressure in the hermetic PCM tank. For high temperature and isobaric PCM conditions like in the present work, the pressure method cannot be applied.

Despite a comprehensive literature review, we could find no high-temperature latent heat TES investigation dealing with partial load operation modes. Similar studies, but on a lower temperature level with a different storage type and PCM are the experimental studies by Gasia et al. [37], which deal with partial load operation modes. In [42] storage times are added to the research as an additional complexity factor. They conclude that the heat transfer rate depends on the SOC and that the storage duration has an effect on the temperature gradients in the PCM. For the storage type considered in [42], the heat transfer rates reveal what Groulx et al. [32] called the rate problem. Immediately after starting to discharge the storage, the power rate declines steadily. From an application perspective, this behavior is disadvantageous. For the majority of the storage capacity, the power rates are really low in the work of Gasia et al. Similar findings are reported by Palomba et al. [43] for an experimental investigation with a plate heat exchanger and low temperature PCM. The power rate is high at the beginning and diminishes rapidly. A comparison with finned tube heat exchanger reveals higher efficiency for the plate heat exchanger with the disadvantage of low pressure difference limits between the PCM and the HTF due to the geometry of the heat exchanger. A numerical partial load investigation was carried out by Arena et al. [44] with a two dimensional axial symmetric model. They found that the state of charge affects the charging and discharging rate for this specific storage type, which confirms the measurements by Gasia et al. mentioned above.

1.3. Partial load operation modes - a rate problem?

Most experimental data of latent heat TES are available for full cycles. Not much focus has been given to partial load states. Partial load storage states could result in low discharging power rates compared to full cycles, like Tehrani et al. [31] conclude in their work about thermal storage for CSP plants. According to the researches from Gasia et al. and Groulx et al. power rates of latent heat TES are low for a high fraction
of solid PCM especially during discharging (solidification). This is due to the fundamentally different heat transfer mechanisms which are dominant at solidification and melting processes. During solidification, the heat transfer surface is covered with solid PCM immediately after starting to discharge, leading to a conduction-based heat transfer for further solidification. The opposite effects apply to the melting process which results in a convection-based heat transfer during melting. Due to the low thermal conductivity of sodium nitrate low power rates are expected for higher fraction of PCM during discharging. In order to evaluate the efficiency of the novel fins introduced in [24] for partial load states the following experimental investigations had been carried out within this work:

- Determine the power rate for partial load states for the examined storage type
- Analyze the fin effectiveness for heat transfer enhancement
- Analyze the effect of the state of charge on the power rate

The following research questions are addressed in the discussion section:

- Impact of melting/solidification behavior on the power rate and the SOC
- Implications for industrial application

The effect of the power rate on the SOC is discussed and the impact of melting and especially solidification is shown in the results. The SOC definition as presented in the following theory chapter 3, is analyzed and special attention is paid to the applicability of SOC controlled latent heat TES operation.

2. Material and methods

2.1. Experimental set-up

The experimental set-up for the present investigation was applied in several previous investigations. It consists of a TES filled with phase change material (PCM). The storage vessel is a vertical steel tube filled with PCM. A vertical longitudinal finned tube in the center of the casing serves as heat exchanger between the PCM and the heat transfer fluid (HTF). The heat exchanger consists of: aluminum fins mounted on a steel tube. The HTF flows inside the steel tube from the top to the bottom or revers. The set-up is described in detail in our prior publications [24,45]. In Fig. 1 the cross section and the discretization of the storage volume of the finned tube latent heat TES is illustrated.

Detailed storage parameters are presented in Table 1. The storage is filled with sodium nitrate (NaNO₃) as PCM and Therminol® VP-1 is utilized as HTF. The melting point of sodium nitrate (306 °C) matches flow temperatures of parabolic through CSP plants, and it could be used to store heat to power steam cycles with live steam properties of e.g. 275 °C and 60 bar. The storage casing and the tubing are made of steel P235GH and the aluminum fins consist of aluminum EN-AW6060 manufactured by extrusion molding. The whole storage system is designed for a maximum temperature of 400 °C and the HTF tube for a nominal pressure of 16 bar. The PCM container is non-pressurized and insulated with 250 mm of ceramic wool in order to minimize heat losses to the surrounding. Auxiliaries are a thermal oil plant supplying the test rig with 320 kW of heating and cooling power and a process control system for the operation of the test rig. HTF mass flows of up to 3 kg s⁻¹ can be realized. Automatic operation of the test rig is available, and measured data are stored on the data server of the control system. The data analysis was done in MATLAB.

![Fig. 1. Storage cross section and discretization of the storage volume incl. radial and vertical position of the temperature sensors and a picture of the non-insulated test rig.](image-url)

| Table 1 | Summary of experimental parameters: Test rig geometry, data/properties of HTF and PCM, operating parameters. |
|--------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Parameter                | Description                                                                                                                   |
| Storage type             | Vertical shell and finned tube                                                                                                  |
| Fin type                 | Combination of arborescent longitudinal and transversal fins                                                                   |
| Fin material             | Aluminum EN-AW6060                                                                                                             |
| Fin outer diameter       | 180 mm                                                                                                                         |
| Finned tube length       | 2500 mm                                                                                                                        |
| Number of transversal fins | 5                                                                                                                                  |
| Number of finned tubes   | 1                                                                                                                               |
| Heat transfer tube material | Steel P235GH, DN25                                                    |
| Volume fractions         | 82.5% PCM, 14.7% Aluminum, 2.8% Steel, 0.1% HTF                                                                             |
| Heat transfer fluid      | Therminol® VP-1 [46]                                                                                                           |
| Mass flow range          | 1 kg s⁻¹                                                                                                                       |
| Storage material         | Sodium nitrate, NaNO3                                                                                                          |
| Melting temperature      | 306 °C [47]                                                                                                                   |
| Density at 306 °C liquid | 1.908 kg dm⁻³ [47]                                                                                                             |
| Enthalpy of fusion       | 178 kJ kg⁻¹ [47]                                                                                                               |
| Mass in section 1 / 2 / 3 | 17.90 kg m⁻³ / 18.77 kg m⁻³ / 25.37 kg m⁻³                                    |
| Operating parameters     |                                                                                                                                  |
| Operating temperature range | ±30 °C around the melting point                              |
| Storage capacity         | 7.91 kWh                                                                                                                       |
| Mean charging power rate | 6.78 kW                                                                                                                        |
| Mean discharging power rate | −5.72 kW                                                                |
| Nominal energy density   | 110.41 kWh m⁻³                                                                                                                 |
| Net energy density       | 98.00 kWh m⁻³                                                                                                                  |

![Diagram](image-url)
2.2. Sensor set-up

The PCM temperature is measured in radially and axially distributed layers directly in the PCM. Several testing points are positioned directly in the sodium nitrate for the purpose of melting behavior detection. In Fig. 1 the non-insulated storage and a vertical and radial cross section are shown. In each vertical section (one vertical section is enclosed by two transversal fins), three temperature testing points are distributed uniformly in vertical direction between the transversal fins in each radial layer. In the previous study [24], the temperature distribution along the vertical axis was analyzed. With the combination of transversal and longitudinal fins, which is applied in our test-rig, the global melting behavior is axially symmetric. In radial direction, three layers of testing points are available, as presented in Fig. 1. With the assumption of axial-symmetric melting, the temperatures in each radial section can be averaged vertically. Then, each temperature testing point layer represents the mean temperature of one radial section. All sections represent similar PCM mass fractions in order to enable comparison and to avoid inequalities for the weighting average.

In addition to the PCM temperatures in the storage, the inlet and outlet temperatures of the HTF as well as the HTF mass flow are recorded. The measured HTF mass flow and the HTF temperatures allow an exact determination of the actual power rate of the storage. For the estimation of the losses to the surrounding, temperature recording of the HTF inlet and outlet temperatures is necessary. For this reason, the idea of introducing a polynomial function because of their simplicity and practicability.

2.3. Measurement cycles

The definition of the state of charge is presented in Section 3. At this point, we anticipate some ideas from that section. The SOC is a number between 0 and 1, being 0 when the storage is fully discharged and 1 when fully charged. In Fig. 2 the partial load states are shown schematically. For latent heat TES, the SOC mainly consists of the enthalpy of fusion. Thus, the PCM is solid at SOC = 0 and liquid at SOC = 1. It is difficult to calculate the SOC by measuring the temperature in the storage because theoretically the temperature would be equal to the melting temperature for all SOC values between 0 and 1. In practice, the temperature field of the PCM exhibits a gradient during charging and discharging, leading to a heterogeneous temperature distribution in the storage. For this reason, the idea of introducing a melting range by defining a solidification and liquefaction temperature seems viable. With this approximation of the melting behavior, the SOC is 0 or 1 when the weighted average temperature of all three sections has reached $T_s$ or $T_l$.

In this study, the charging and discharging cycles are SOC-controlled and not time-controlled. For the present experiments, the SOC is calculated in the control system, based on the measured temperatures. For full cycles, the SOC is oscillating between 0 and 1, for partial cycles between specific partial states and 0 or 1. The storage is operated between the two states until stationary cycling is reached.

The HTF inlet temperature for charging and discharging was set to 336 °C and 276 °C respectively, which results in a temperature difference of ±30 °C around the melting point. The mass flow was set to 1 kg s$^{-1}$. The SOC is cycled between 0.00 and 0.25, 0.50, 0.75 and 1.00. The cycle $SOC_{0-1.0}$ represents the full cycle, the others represent partial load cycles. In Fig. 2 the different partial load states are illustrated schematically. For charging, the main heat transfer mechanisms are convection and conduction while for discharging the solid layer around the fins grows and conduction is the major heat transfer mechanism. Due to the fins, the real melting front wont be circular, melting takes place around the fin contour first. A detailed numerical melting analysis is provided by Walter et al. in [27].

3. Theory

Different mathematical formulations of the phase change for numerical investigations or analysis of measurements are provided in [48]. Analytical solutions of the phase change — the so-called Stefan problem — are available for very simple geometries only [49]. Dutil et al. [50] present the most common techniques for modeling the phase change. Modern IT equipment allows CFD (computation fluid dynamics) simulation of phase change in three dimensions including the effect of natural convection [29].

For analysis of measurement data, the phase change formulation is based on temperature values measured in the PCM. Hence the latent heat of fusion is distributed to a specific temperature range like Rösler et al. presents in [39]. For this distribution, several mathematical functions can be applied. Rösler applied the Error function. In [24] we applied a polynomial function because of their simplicity and practicability.

![Fig. 2. Schematic SOC illustration of the different heat transfer mechanisms during melting/solidification.](image)
3.1. Enthalpy of fusion distribution

To calculate the state of charge based on temperature measurements in the PCM, a function for the specific enthalpy depending on the temperature, has to be developed. For pure substances, a first order phase transition is accompanied by discontinuous changes of the extensive state variables in theory. Eq. (3.1) shows a function for the specific enthalpy of a PCM which satisfies this behavior.

$$h(T) = h_{\text{st}}(T) + L H(T - T_m)$$  (3.1)

The Heaviside step function $H(x)$ shown in Eq. (3.1) can be applied to mathematically formulate an isothermal phase change. Such a sharp phase transition will only occur in a system with an infinitesimal volume or with a PCM with an infinite thermal conductivity. Since none of these two requirements apply to the test rig examined in this work, the enthalpy of fusion is distributed over a characteristic melting range. Due to this distribution, an apparent specific heat of the PCM is calculated as it can be seen in Eq. (3.2).

$$c_{\text{app}}(T) = \begin{cases} c_s(T), & T_{lv} \leq T < T_s \\ c_m(T) + c^*(T), & T_s \leq T \leq T_l \\ c_l(T), & T_l < T \leq T_{urv} \end{cases}$$  (3.2)

The apparent specific heat capacity $c_{\text{app}}$ can be written in the form given in Eq. (3.2) consisting of a function $c_s$ for the solid range (below $T_s$), a function $c_l$ for the liquid range (above $T_l$) and a combination of a linear function $c_m$ and a fourth degree polynomial function $c^*$ in the melting range (between $T_s$ and $T_l$). The function $c_m$ represents the sensible part of the specific heat in the melting range and is calculated by a simple linear interpolation between $c_s(T_s)$ and $c_l(T_l)$. The validity of the functions is limited to the lower range temperature ($T_{lv}$) and the upper range temperature ($T_{urv}$). To distribute the enthalpy of fusion over the melting range, the fourth degree polynomial function is designed in a way, that its integral from $T_s$ to $T_l$ equals to the enthalpy of fusion, as described in Eq. (3.3). The exact equations and parameters for each specific heat function are provided in [24].

$$L = \int_{T_s}^{T_l} c^*(T) \, dT$$  (3.3)

Further, the function for the specific enthalpy is calculated by integrating Eq. (3.2) including the enthalpy at the reference temperature $T_{\text{ref}}, h_0$.

$$h(T) = \int_{T_0}^{T} c_{\text{app}}(T) \, dT + h_0$$  (3.4)

Integration of Eq. (3.4) for sodium nitrate leads to Eq. (3.5).

$$h(T) = \begin{cases} 0.001607T + 0.9262, & T_{lv} \leq T < T_s \\ 0.0044(T - T_s)^5 - 0.1312(T - T_s)^4 + 1.0481(T - T_s)^3 + 0.0016(T - T_s)^2 + 1.8904(T - T_s) + 421.8600, & T_s \leq T \leq T_l \\ 1.65(T - T_l) + 630.1896, & T_l < T \leq T_{urv} \end{cases}$$  (3.5)

The distribution of the latent heat over a specific temperature range enables differentiable and steady enthalpy formulations. The selection of the suitable temperature range between $T_s$ and $T_l$ has to be done by iteration and depends mainly on the discretization of the storage. For the experiments, which were carried out in the course of this work, the solidification temperature $T_s$ was set to 300°C and the liquefaction temperature $T_l$ to 312°C. The resulting trends of the apparent specific heat and the specific enthalpy as well as the separate functions for the sensible and latent part are shown in Fig. 3.

3.2. SOC formulation

The amount of stored energy is an essential parameter for energy storage systems in general. The ratio of stored energy to the total amount of storable energy is called “ratio of accumulated energy” [37] or “ratio of energy” [44]. The term “state of charge” appeared more suitable and is based on the definitions in [40]. Slight differences in the definition may appear due to the inclusion of the sensible heat within the melting range, but this seems to be a realistic approach. A classification of available techniques for the determination of the SOC including experimental analysis is provided by Zsembinszki et al. [41]. With the specific enthalpy function derived in Section 3.1 the SOC can be defined as:

$$SOC(T) = \frac{\bar{h}(T) - h(T_s)}{h(T_l) - h(T_s)}$$  (3.6)

With this formulation (Eq. (3.6)) the SOC is 0 at $T = T_s$ and 1 at $T = T_l$. The denominator represents the specific energy which can be stored in the PCM when heating from the solidification temperature $T_s$ to the liquefaction temperature $T_l$. The average specific enthalpy $\bar{h}(T)$ of the storage material is calculated as a weighted arithmetic mean over the three sections displayed in Fig. 1.

$$\bar{h}(T) = \frac{\sum_{i=1}^{3} m_i h(T_i)}{\sum_{i=1}^{3} m_i}$$  (3.7)
In Eq. (3.7) $m_i$ represents the mass of PCM in section $i$ and $h(T_i)$ the specific enthalpy at the averaged temperature $T_i$ of the PCM in section $i$. The exact values of $m_i$ are given in Table 1. In Fig. 4 the connection between the specific enthalpy of the storage material $h(T)$ and the SOC can be seen. The SOC definition in Eq. (3.6) is only applicable when the storage is cycled exactly across the melting range, which is fine for the investigations carried out in this study. Nevertheless, in real application the storage will also be operated above and below that range. The enthalpy distribution function derived in Eq. (3.5) is valid for temperatures between 100 °C and 400 °C. Therefore the formulation of the SOC can be expanded to a wider temperature range by replacing $T_s$ and $T_f$ in Eq. (3.6) with the new temperatures that should be associated with SOC = 0 and SOC = 1 respectively.

In all mentioned references, including the present formulation, the SOC formulation is storage-temperature dependent. In the melting range, theoretically the temperature in the storage remains constant. With an temperature depended SOC formulation, the SOC would not be steady. In praxis, the temperatures in the discretized regions are not homogeneous. The challenges coming along with this assumption will be discussed in Section 4.

3.3. Data analysis

In order to make a statement about the partial load behavior of latent heat TES, the data collected is used to calculate the power rate of the storage.

$$P_{HTF} = m_{HTF} \left( h_{in} - h_{out} \right)$$

(3.8)

As can be seen in Eq. (3.8) the power rate is calculated by applying the first law of thermodynamics to the HTF-stream. Which means, that this power rate also includes the losses.

To validate the measured data, the energy balance for the storage is calculated by applying the first law of thermodynamics to the whole storage as it is shown in Eq. (3.9).

$$U_{TES}(t) - U_{TES}(0) = \int_0^t P_{HTF}(t) \, dt - \int_0^t P_{loss}(t) \, dt$$

(3.9)

The left side of Eq. (3.9) represents the stored energy for a certain operation time $t$ of the storage. The right side includes the energy input by the HTF and the losses for the operation time $t$. With the measured temperature data and Eq. (3.5), the left part of the energy balance expands to

$$\int_0^t P_i(t) \, dt = \int_0^t \sum_{i=1}^3 m_{Alu} c_{Alu} \left( T_i(t) - T_i(0) \right) + \sum_{i=1}^3 m_{PCM} \left( h_i(t) - h_i(0) \right).$$

(3.10)

Energy stored in the aluminum fins Energy stored in the PCM

The stored energy is calculated for aluminum and PCM only, steel parts and insulation are neglectable due to their little mass and little heat capacity. The losses had been determined in previous investigations and are temperature dependent between 350 W and 440 W for 276 °C and 336 °C respectively. A linear function is applied for the losses.

3.4. Estimation of measurement errors

To estimate the impact of the uncertainties of the measured data on the calculated power rate, the Gaussian law of error propagation is applied to Eq. (3.8), which leads to Eq. (3.11).

$$\delta P^2 = \left( \frac{\partial P}{\partial m} \right)^2 \delta m^2 + \left( \frac{\partial P}{\partial h_{in}} \right)^2 \delta h_{in}^2 + \left( \frac{\partial P}{\partial h_{out}} \right)^2 \delta h_{out}^2$$

(3.11)

$$\delta h_i = c_p(T_i) \delta T_i$$

(3.12)

The temperature sensors in the HTF had been calibrated in order to minimize the error. After calibration, the accuracy of the calibrated sensors is about ±0.1 K at operation temperature (see Table 2). This leads to a measurement error based on Eq. (3.11) of ±0.343 kW. This measurement error has no significant influence on the results.

4. Results and discussion

A typical full load temperature trend is presented in this section, more temperature trends are available in Appendix A. The power rates are presented as a function of the SOC for all examined partial and full load cycles. Fig. 5 shows the temperature trends for a representative experiment when cycling the TES between SOC = 0.00 and SOC = 1.00. $T_{HTF1}$ and $T_{HTF2}$ represent the inlet and outlet temperature of the thermal oil, controlled by the thermal oil plant. The first minutes after switching between heating and cooling, the inlet temperature needs to settle. The mass flow is controlled to 1 kg s⁻¹. The corresponding temperature testing points in the PCM $T_s$, $T_f$ and $T_l$ rise during charging and decrease while discharging. The expected phase change plateau can be seen for discharging clearly. For charging the plateau is not as evident which is probably caused by the natural convection in the liquid PCM. The SOC controlled cycle is operated between 0 and 1, the SOC trend is analog to the mean temperature trend in the storage due to the enthalpy and SOC definition.

The SOC formulation provides a measureable quantity to determine the storage state. It allows an estimation of the storage capacity but implicates some disadvantages. Due to the stable temperature plateau at the melting temperature – especially while discharging – the temperature based enthalpy distribution leads to a non uniform SOC gradient.
Fig. 6. Exemplary raw data used for analysis: temperature and \( \text{SOC} \) trends for the full load cycle.

for discharging like in Fig. 5. The impact of this disadvantage is discussed in Section 4.2. Temperature trends for other \( \text{SOC} \) based cycles are provided in Appendix A and measurement data of the individual cycles are available as supplementary material.

4.1. Power rates

In Figs. 6 and 7 the power rates for the partial and full load cycles are shown. For comparison, the switching point between charging and discharging or reverse is used as reference point of the curves. The power rate is normalized with the mean charging power rate of 6.78 kW. Each cycle starts at \( \text{SOC} = 0.0 \) or \( \text{SOC} = 1.0 \) and is charged/discharged until the expected partial load \( \text{SOC} \) is reached. Then, the operation mode is changed and the storage is discharged/charged until \( \text{SOC} = 0.0 \) or \( \text{SOC} = 1.0 \) is reached again.

The mean power rate for charging is 6.78 kW with a 95.45 % confidence interval of \( \pm 1.14 \) kW for all cycles. The mean discharging power rate is \(-5.72\) kW with a 95.45 % confidence interval of \( \pm 1.36 \) kW for all cycles.

In Fig. 6 the power rate for charging exhibit comparable trends for all partial load cycles. The full cycle \( \text{SOC}_{0.0-1.0} \) has the lowest charging power rate with 68 % of the nominal power rate at the end of charging. For discharging, the power rate is generally a little lower due to the losses to the surrounding. The lowest measured discharging power rate is 54 % of the nominal power rate. Compared to non-finned latent heat TES where the power rate for discharging is an order of magnitude lower at the end of discharging (e.g. [37]), the heat transfer enhancement with fins is remarkable.

In Fig. 7 the power rates for partial load cycles starting from \( \text{SOC} = 1.0 \) are shown. Similar power rates for all cycles compared to Fig. 6 can be seen. The discharging power rate is slightly lower due to the losses. But both, the charging and discharging power rates are continuously higher than 68 % of the nominal value for charging (6.78 kW) and discharging (\(-5.72\) kW). The switch over from discharging to charging takes a little longer for this cycles, the \( \text{SOC} \) continues to decrease for some minutes until the temperatures in the storage begin to increase again. This effect is caused by the thermal inertia of the PCM. In general, also this partial load power rates are high for all partial load cycles.

4.2. Energy balance

For establishing the energy balance, the storage capacity is determined by integrating the power rate of the HTF. The energy balance over the storage is calculated by comparing the HTF based energy with the PCM temperature based energy formulation (Eq. (3.9)). In Fig. 8 the PCM based energy over the HTF energy is shown for a) charging and (b) discharging. The red line indicates the full load cycle \( \text{SOC}_{0.0-1.0} \) and the blue lines the partial load cycles.

For charging (Fig. 8a), both formulations show a similar trend and a final value around 9.000 kW h is reached for the full load cycle. The HTF based formulation shows a slightly higher value at the end due to losses to the surrounding which are not taken into account for the PCM.
Fig. 7. Power rates for different \( SOC \) cycles starting from \( SOC = 1 \).

Fig. 8. Energy balance for (a) charging phases, starting at \( SOC_0 \) and (b) discharging phases, ending at \( SOC_0 \).

For the two ways of determining the stored energy, the PCM-based way exhibit different challenges. PCM-based determination may have higher uncertainties around the melting point (like in Fig. 8b) but HTF-based energy calculation suffer from an accumulated integration error due to losses to the surrounding and measurement uncertainties. For the operation strategy, a combination of both may lead to the highest accuracy. Developing a weighted state of charge should be focused in another research paper.

5. Conclusion

A high temperature latent heat thermal energy storage with sodium nitrate as phase change material is presented in this experimental investigation. The 3 m high, finned shell and tube heat exchanger with 280 kg phase change material exhibit promising power rates in all investigated states. The inlet and outlet temperature of the heat transfer fluid as well as temperature testing points in the phase change material allow detailed data analysis. In contrast to previous researches, the investigation of partial load states of the phase change material and the resulting power rates are the main aspect of this work. The storage is cycled between different partial load and full load states to examine the behavior of the storage system in this intermediate states. Temperature and power trends are compared and the energy balance is calculated for validation of the measured data.

Novel partial load cycles of this storage type are presented and discussed. The mean power rate for charging is 6.78 kW with an 95.45% confidence interval of \( \pm 1.14 \) kW for all cycles. The discharging power rate is \(-5.72\) kW with an 95.45% confidence interval of \( \pm 1.36\) kW for all cycles. In contrast to non-finned and other latent heat thermal energy storage systems, the suggested system provides high power rates for all partial and full load states. The heat transfer enhancement with this fin type was implemented successfully.

The distribution of the latent heat of fusion around the melting point as equivalent heat capacity was chosen for the state of charge calculation. In this form, the state of charge depends on temperature measurements in the storage. They are easy and convenient to apply to a thermal storage. But the distribution of the latent heat leads to uncertainties around the melting point especially for discharging. For a more detailed determination of the storage state, the charged and discharged energy has to be measured. Due to losses to the surrounding, costly mass flow measurement equipment and low repeatability of the heat transfer fluid based energy calculation has to be combined with other techniques.

For potential applications, the prediction of the power rate as well as the storage capacity are of high importance. Performance indicators of the vertical finned latent heat thermal energy storage with combined...
transversal and longitudinal fins show highly promising power rates for all partial and full load cycles. The energy density of this storage type is as high as 110 kW h m$^{-3}$ and the specific mean discharging power rate is as high as 2.28 kW m$^{-3}$. For high temperature thermal energy storage systems, this type of storage seems to be highly promising.

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**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

The temperature trends from the experimental investigation of the different partial load cycles are available as additional data. Representative cycles were chosen for the data analysis and provided as comma-separated-value data files. The data is provided in a 60 s transversal and longitudinal fins show highly promising power rates for all partial and full load cycles. The energy density of this storage type is as high as 110 kW h m$^{-3}$ and the specific mean discharging power rate is as high as 2.28 kW m$^{-3}$. For high temperature thermal energy storage systems, this type of storage seems to be highly promising.

**Data availability**

The temperature trends from the experimental investigation of the different partial load cycles are available as additional data. Representative cycles were chosen for the data analysis and provided as comma-separated-value data files. The data is provided in a 60 s rasterized table including the power rate, the as PCM. In: IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland: 2018.

**References**

[1] IPCC, editor. Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland: 2018.

[2] IRENA. Climate change and renewable energy: National policies and the role of communities, cities and regions. (Report to the G20 climate sustainability working group). Abu Dhabi: International Renewable Energy Agency; URL https://www.irena.org/publications/2019/Jun/Climate-change-and-renewable-energy.

[3] IRENA. Renewable power generation costs in 2019. Abu Dhabi: International Renewable Energy Agency; URL https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.

[4] US Department of Energy. In: US Department of Energy, Office of Electricity & Energy Reliability, editor. DOE global energy storage database. 2019. URL http://www.sandia.gov/esssl/global-energy-storage-database-home/.

[5] Sterner M, Stadler I. Handbook of energy storage: Demand, technologies, integration, Berlin and l.s.l: Springer Berlin; 2018.

[6] Alva G, Lin Y, Fang G. An overview of thermal energy storage systems. Energy 2018;144:341–78. http://dx.doi.org/10.1016/j.energy.2017.12.037.

[7] Zhang H, Bairam A, Tiznobaik H, Shin D, Santhanagopalan S. Microencapsulation of molten salt in stable silica shell via a water-limited sol-gel process for high temperature thermal energy storage. Appl Therm Eng 2018;136:268–74. http://dx.doi.org/10.1016/j.applthermaleng.2018.03.059.

[8] Tian H, Du L, Wei X, Deng S, Wang W, Ding J. Enhanced thermal conductivity of ternary carbonate salt phase change material with Mg particles for solar thermal energy storage. Appl Energy 2017;204:525–30. http://dx.doi.org/10.1016/j.apenergy.2017.07.027.

[9] Yanweii H, Yurong H, Zhenduo Z, Dongsheng W. Effect of AL2O3 nanoparticle dispersion on the specific heat capacity of a eutectic binary nitrate salt for solar power applications. Energy Convers Manage 2017;142:366–73. http://dx.doi.org/10.1016/j.enconman.2017.03.062.

[10] Martin V, He B, Setterwall F. Direct contact PCM-water cold storage. Appl Energy 2010;87(8):2652–9. http://dx.doi.org/10.1016/j.apenergy.2010.01.005.

[11] Neumayer T, Tsutoba M, Sagara A, Okinaka N, Akayama T. Performance analysis of heat storage of direct-contact heat exchanger with phase-change material. Appl Therm Eng 2013;58(1–2):108–13. http://dx.doi.org/10.1016/j.applthermaleng.2013.03.041.

[12] Krimmel S, Stamatou S, Wöltchek J, Walter H. Experimental characterization of the heat transfer in a latent direct contact thermal energy storage with one nozzle in labor scale. Int J Mech Eng 2018;3(3):83–97, URL 2367-8968.

[13] Scharinger-Urschitz G, Walter H, Haider M. Heat transfer in latent high-temperature thermal energy storage systems—Experimental investigation. Energies 2019;12(7):1264. http://dx.doi.org/10.3390/en12071264.

[14] Tehrani SSM, Taylor RA, Saberi P, Diarco G. Design and feasibility of high temperature shell and tube latent thermal energy storage system for solar thermal power plants. Renew Energy 2016;96:120–36. http://dx.doi.org/10.1016/j.renene.2016.04.036.

[15] Rezaei E, Barbato M, Ortona A, Haussener S. Design and optimization of a latent heat storage (LHS) unit using fractal-tree-shaped fins. Appl Energy 2020;259:114102. http://dx.doi.org/10.1016/j.apenergy.2019.114102.

[16] Pizzolato A, Sharma A, Maute K, Sciaccavelli A, Verda V. Design of effective fins for fast PCM melting and solidification in shell-and-tube latent heat energy storage systems using topology optimization. Appl Energy 2017;208:210–27. http://dx.doi.org/10.1016/j.apenergy.2017.05.050.

[17] Elsamennazad H, Rahimi AB. Enhance heat transfer for phase-change materials in triple-tube heat exchanger with selected arrangements of fins. Appl Therm Eng 2017;113:813–21. http://dx.doi.org/10.1016/j.applthermaleng.2016.11.067.

[18] Sciaccavelli A, Gaggiardi F, Verda V. Maximization of performance of a PCM latent heat storage system with innovative fins. Appl Energy 2015;137:707–15. http://dx.doi.org/10.1016/j.apenergy.2014.07.015.

[19] Scharinger-Urschitz G, Walter H, Haider M. Heat transfer in latent high-temperature thermal energy storage systems—Experimental investigation. Energies 2019;12(7):1264. http://dx.doi.org/10.3390/en12071264.

[20] Rezaei E, Barbato M, Ortona A, Haussener S. Design and optimization of a high-temperature latent heat storage unit. Appl Energy 2020;261:114330. http://dx.doi.org/10.1016/j.applenergy.2019.114330.

[21] Mostafavi Tehrani SS, Shoraka Y, Nithyanandam K, Taylor RA. Cyclometric performance of cascaded and multi-layered solid-PCM shell-and-tube thermal energy storage systems: A case study of the 19.9 MWe Gemasolar CSP plant. Appl Energy 2019;233:234–944–905. http://dx.doi.org/10.1016/j.apenergy.2018.10.024.

[22] Vogel J, Johnson M. Natural convection during melting in vertical finned tube latent thermal energy storage systems. Appl Energy 2019;246:38–52. http://dx.doi.org/10.1016/j.apenergy.2019.04.011.

[23] Rezaei E, Barbato M, Ortona A, Haussener S. Design and optimization of a high-temperature latent heat storage unit. Appl Energy 2020;261:114330. http://dx.doi.org/10.1016/j.apenergy.2019.114330.

[24] Masiere A, Lefena TM, Ekwomadu CS, Shobo AB. Performance of a medium temperature eutectic sodium packed bed latent heat energy storage system for domestic applications. J Energy Storage 2020;28:101294. http://dx.doi.org/10.1016/j.est.2020.101294.

[25] Couvreur K, Beyne S, Timmerman JW, et al. Experimental behavior of a 1016 kW th fin-tube latent heat storage using eutectic KNO3-NaNO3 as PCM. In: Université de Lleida, editor. Advances in thermal energy storage. Edicions de la Universitat de Lleida; 2019, p. 451–60.
[35] Zauner C, Hengstberger F, Eitel M, Lager D, Hofmann R, Walter H. Experimental characterization and simulation of a fin-tube latent heat storage using high density polyethylene as PCM. Appl Energy 2016;179:237–46. http://dx.doi.org/10.1016/j.apenergy.2016.06.138.

[36] Garcia P, Gloum M, Rouqué S. Experimental and numerical investigation of a pilot scale latent heat thermal energy storage for CSP power plant. Energy Procedia 2015;69:842–9. http://dx.doi.org/10.1016/j.egypro.2015.03.102.

[37] Gasia J, de Gracia A, Pérez G, Arenas S, Cau G, Cabeza LF. Use of partial load operating conditions for latent thermal energy storage management. Appl Energy 2018;216:234–42. http://dx.doi.org/10.1016/j.apenergy.2018.02.061.

[38] Oró E, de Gracia A, Castell A, Farid MM, Cabeza LF. Review on phase change materials (PCMs) for cold thermal energy storage applications. Appl Energy 2012;99:513–33. http://dx.doi.org/10.1016/j.apenergy.2012.03.058.

[39] Rüdiger F, Brüggemann D. Shell-and-tube type latent heat thermal energy storage: Numerical analysis and comparison with experiments. Heat Mass Transf 2011;47(8):1027–33. http://dx.doi.org/10.1007/s00231-011-0866-9.

[40] Barz T, Seliger D, Marx K, Sommer A, Walter SF, Bock HG, Körkel S. State and state of charge estimation for a latent heat storage. Control Eng Pract 2018;72:151–66. http://dx.doi.org/10.1016/j.conengprac.2017.11.006.

[41] Zsembinszki G, Orozco C, Gasia J, Barz T, Emhofer J, Cabeza LF. Evaluation of the state of charge of a solid/liquid phase change material in a thermal energy storage tank. Energies 2020;13(6):1425. http://dx.doi.org/10.3390/en13061425.

[42] Gasia J, de Gracia A, Zsembinszki G, Cabeza LF. Influence of the storage period between charge and discharge in a latent heat thermal energy storage system working under partial load operating conditions. Appl Energy 2019;235:1389–99. http://dx.doi.org/10.1016/j.apenergy.2018.11.041.

[43] Palomba V, Branca V, Fratizza A. Thermal performance of a latent thermal energy storage for exploitation of renewables and waste heat: An experimental investigation based on an asymmetric plate heat exchanger. Energy Convers Manage 2019;200:112121. http://dx.doi.org/10.1016/j.enconman.2019.112121.

[44] Arena S, Casti E, Gasia J, Cabeza LF, Cau G. Numerical analysis of a latent heat thermal energy storage system under partial load operating conditions. Renew Energy 2018;128:350–61. http://dx.doi.org/10.1016/j.renene.2018.05.072.

[45] Urschitz G, Walter H, Hameter M. Laboratory test rig of a LIHTES (latent heat thermal energy storage): Construction and first experimental results. J Energy Power Eng 2014;8:1838–47.

[46] Solutia Europe SA. Datasheet therminol VP1: Vapour phase liquid phase heat transfer fluid 12 °C to 400 °C.

[47] Bauer T, Laing D, Tamme R. Characterization of sodium nitrate as phase change material. Int J Thermophys 2012;33(1):91–104. http://dx.doi.org/10.1007/s10765-011-1113-9.

[48] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LIHTESS). Renew Sustain Energy Rev 2010;14(2):615–28. http://dx.doi.org/10.1016/j.rser.2009.10.015.

[49] Lamberg P, Sirén K. Approximate analytical model for solidification in a finite PCM storage with internal fins. Appl Math Model 2003;27(7):491–513. http://dx.doi.org/10.1016/S0307-904X(03)00080-5.

[50] Dutil Y, Rousse DR, Salah NB, Lassue S, Zalewski L. A review on phase-change materials: Mathematical modeling and simulations. Renew Sustain Energy Rev 2011;15(1):112–30. http://dx.doi.org/10.1016/j.rser.2010.06.011.