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Experimental validation of a design model for latent thermal energy storage extended with sensible heat

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Abstract. Latent thermal energy storage can be a key technology for a green energy transition by matching fluctuating heat demand and supply. In order to implement a storage system, it needs to be designed which requires estimating the outlet temperature of a system for a given geometry and time history of the heat transfer fluid's mass flow rate and inlet temperature. Currently, design methods are either overly simplistic, focusing solely on e.g. the phase change time or requiring the solution of partial differential equations which can be computationally expensive. The present paper proposes a novel approach where a latent thermal energy storage system is decomposed into a heat transfer fluid vessel, a sensible storage system and a storage system with only latent heat. Computationally inexpensive models are available for all three of these sub heat exchangers. A heat exchanger model is obtained by connecting the sub heat exchangers in parallel. This novel approach is used to model an industrial scale shell and tube latent thermal energy storage heat exchanger. The predicted outlet temperature is compared to the measured outlet temperature and the design model obtains good agreement.

1. Introduction

Thermal energy storage (TES) systems can help balance energy supply and demand as fossil fuels are phased out. There are three types of TES: sensible where the storage material is single phase, latent where the storage material undergoes a phase change and thermo-chemical which employs reversible chemical reactions or sorption processes. The present paper focusses on Latent Thermal Energy Storage (LTES) systems.

In order to implement a storage system, it needs to be designed and sized to fit the energy system requirements. The design requirements for a TES system are summarized as a set of Key Performance Indicators (KPIs) which can be divided into technical, economical and life-cycle indicators [1]. According to Beyne et al. [2], all technical indicators can be determined from the geometry of the system, the material properties and the interaction of the TES system with its environment. This interaction takes on two main forms: heat transfer with the environment and the outlet state of the Heat Transfer Fluid (HTF) for a given inlet state of the HTF and initial state of the system.

Predicting the outlet state for a given geometry and inlet is akin to the rating problem for a conventional heat exchanger. Therefore, early attempts focused on methods developed for conventional heat exchangers such as the effectiveness-number of transfer units (NTU) method. Tay et al. proposed an averaged effectiveness method where the average outlet temperature of a single phase HTF is predicted during the melting stage [3]. The approach is successful at predicting the average outlet temperature and can be expanded to include the size of the system as a parameter which allows the method to be used for sizing. The downside of the method is that only the average outlet temperature can be predicted and not the outlet temperature as a function of time. The charging time energy fraction method was developed as an alternative technique which predict the outlet temperature as a function of time [4, 5]. However, this method does not allow sizing of the system. Alternatively to these experimentally fitted methods, a numerical simulation of the storage system can also be done where either the flow equations in the PCM are solved to estimate the natural convection (e.g. [6]) or the natural convection is modeled as an effective thermal conductivity (e.g. [7]). In either case, the model requires time stepping in order to simulate a charging-discharging cycle which due to the duration of the cycle requires significant computational resources.

Recently, Beyne et al. [8, 9] proposed an approximate analytical method which predicts the outlet temperature of an LTES system. The method simplifies the sensible and latent heat as only latent heat at a singular phase change temperature. The method is computationally fast compared to numerical approaches, allows sizing of the system, which the charging time energy fraction method does not, and predicts the complete outlet temperature as a function of time where the averaged effectiveness method only predicts an average. However, due to the treatment of the sensible heat, the accuracy of the approach is low especially for cases with a high Stefan number (ratio sensible to latent heat).

A model for sensible thermal energy storage systems (STES) was proposed which employs a similar derivation as the latent model of Beyne et al. [10]. The model requires a numerical inverse Laplace transformation, however it still is computationally efficient compared to finite volume approaches.

There are thus computationally efficient models available: one for latent heat and one for sensible heat. Combining both models would allow to improve the modeling of LTES systems with higher Stefan numbers. Three approaches have been proposed in literature. Firstly, Ding et al. [11] assumed the storage material to have a uniform temperature until the phase change starts. A such, the storage system undergoes a purely latent stage after undergoing a purely sensible stage. Therefore, the approach of Ding et al. [11] will be called the time series approach. Secondly, Beyne et al. [12] proposed to model the heat exchanger as a series connection of a STES system and a LTES system. This will be called the space series approach. A third approach is adding all sensible heat to the latent heat and using the latent heat only analytical model. As this third approach only uses a latent heat model, it will be referred to as the latent heat only model.

The present paper compares the three approaches based on an experimental validation. This is the first experimental validation for the approach of Ding et al. [11] and the approach of Beyne et al. [12] as well as the first time these approaches are compared. The next section first introduces the experimental test case.

2. Experimental setup description

The LTES heat exchanger is a shell and tube heat exchanger which was previously described in [4]. The shell has a rectangular cross section of 0.706 by 0.5 m with a total length of 7.43 m and is constructed from P265GH steel. A total of 36 steel tubes are placed in the shell with a length of 6 m, an inner diameter of 14.9 mm and an outer diameter of 21.3 mm. Each tube has 545 radial hexagonal fins with a thickness of 1 mm and an apothem of 4.3 cm. The HTF is a thermal oil (Therminol 66) which flows through the tubing while the shell side is filled with an eutectic mixture of KNO_3-$NaNO_3$ at a total PCM mass of 3637 kg. Table 1 lists the relevant PCM and steel properties. The Therminol 66 properties are determined using the Coolprop library [13].

The setup is instrumented with temperature, pressure and mass flow rate sensors. The relevant measurements for the present discussion are the inlet and outlet bulk temperature and mass flow rate of the HTF. The temperatures are measured using Pt100 sensors with an accuracy of ±0.6 °C at the phase change temperature. The mass flow rate of the thermal oil is measured using an orifice plate flow meter with an accuracy of 1 %.

Table 1: Relevant material properties [4].

Eutectic KNO_3-$NaNO_3$		
Liquidus temperature	T_l	223 °C
Solidus temperature	T_s	221 °C
Latent heat	h_{lat}	100 kJ/kg
Specific heat capacity liquid	c_{pl}	1.335 kJ/kgK
Specific heat capacity solid	c_{ps}	1.567 kJ/kgK
Solid density	ρ_s	2050 kg/m³
Liquid density	ρ_l	1960 kg/m³
Steel		
Density	ρ	7850 kg/m³
Specific heat capacity	c_p	490 J/kgK
Thermal conductivity	K	45 W/mK

The experimental procedure starts with an initialization phase where HTF is circulated at 190 °C. Once the outlet temperature of the system reaches steady state conditions, the inlet temperature setpoint is increased to 250 °C and is controlled using a 250 kW electrical heater. The HTF is pumped by a constant speed pump where the mass flow rate is controlled using a PID controlled three-way valve. The experiment is terminated once the PCM has completely molten.

3. Model

The present paper compares three modelling approaches for LTES systems based on experimental data. Figure 1 gives a schematic overview of the model architectures. On the left hand side of the figure, a cross section of the storage system is shown, with 36 HTF tubes outfitted with hexagonal fins. The PCM is contained within the rectangular shell.

The studied experiment starts at an initial temperature of 190 °C and has an inlet temperature setpoint of 250 °C. Based on the amount of steel, PCM and HTF in the system, the total stored heat for a temperature change between 190 °C and 250 °C is determined. This stored heat can be subdivided into two categories: sensible heat and latent heat. The average melting temperature of the PCM is 222 °C.

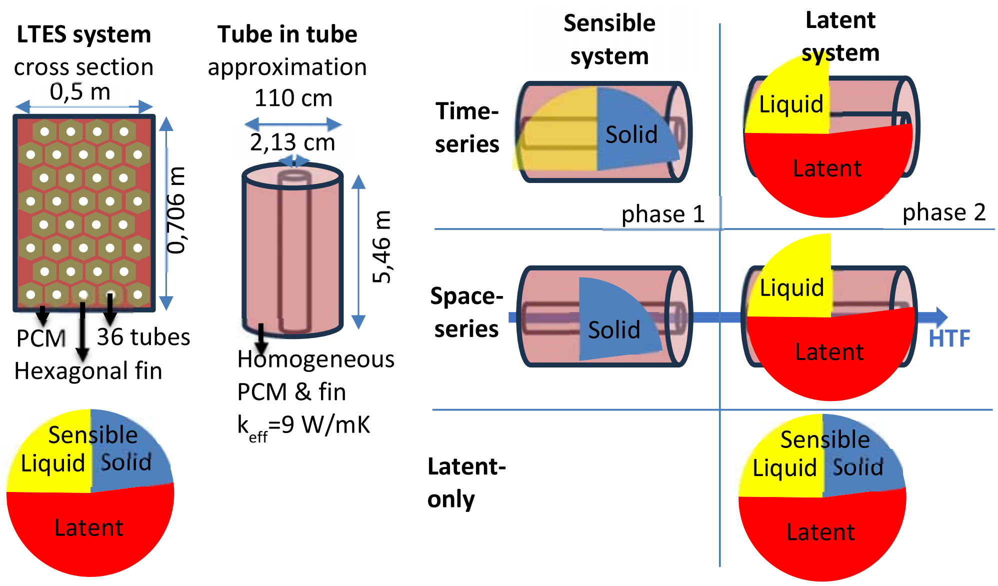

Figure 1: Schematic overview of the modelling approaches compared in this paper.

The sensible heat can thus be categorized as a part associated with the solid phase of the PCM (below 222 °C) and a part associated with the liquid phase of the PCM (above 222 °C). The pie chart below the LTES system shows the distribution of the three parts of the stored heat: sensible liquid, sensible solid and latent heat.

The paper describing the experimental setup [4] contains a numerical model for the charging of the LTES system. In this model, the shell and tube heat exchanger is modeled as a parallel connection of 36 tube in tube heat exchangers. The fins and natural convection in the PCM are fitted by an effective thermal conductivity of 9 W/mK where the HTF convective heat transfer coefficient is determined using the Gnielinski correlation. The heat losses are fitted by an overall heat loss coefficient of 33.5 W/K. The tube-in-tube heat exchangers are discretized in 2D based on the axisymmetry of the tube and solved numerically. Since a numerical model based on a tube-in-tube geometry can predict charging, the current modeling strategy is based on a tube-in-tube geometry with homogeneous PCM properties. This is depicted in the middle of Figure 1.

The three modelling approaches are shown on the right hand side of the figure. The time-series approach splits the charging of the LTES system in two phases: a sensible phase and a latent heat phase. During the sensible phase, the storage material is assumed to be at a bulk temperature with a constant heat transfer resistance to the material. Once the storage material reaches the phase change temperature, a latent phase is started which contains both the latent heat and the liquid sensible heat. The space series approach splits the heat exchanger in two parts: one sensible heat exchanger with the solid sensible heat and one latent heat exchanger with the liquid sensible and latent heat. Both heat exchangers are connected in series. The third approach models all heat as latent heat. The sensible heat is thus added to the latent heat in order to include the entire internal energy change of the system.

Both the time-series and space-series approach adds part of the sensible heat to the latent heat model. The latent heat model tracks the movement of the phase change front through the heat exchanger [8]. In order to obtain melting at the front, both the latent heat of phase change is required as well as the sensible heat to raise the liquid bulk temperature. Therefore, the liquid sensible heat is added to the latent heat model.

The sensible system model is described in [10] and the latent system model is described in [8]. Due to the page limit, the details of the sub models are not included in the present paper. The latent system model is the same for all three approaches except for the inclusion of the solid sensible heat in the latent-only approach. The sensible system model is slightly different for the space-series and time-series approach. The time-series approach assumes a uniform storage material temperature which is not required in the space-series approach.

4. Experimental validation

The predictions of the three modelling approaches are compared to experimental data with inlet temperature setpoint of 250 °C and mass flow rate of 1.87 kg/s on Figure 2. The prediction of the three approaches are shown in blue lines. In the initial phase, the latent only model is less accurate since it does not include any sensible heat. The time-series approach has a similar accuracy as the as the space-series approach up to 0.3 hours. At 0.3 hours, the time series approach drops significantly below the measured outlet temperature. Since the time-series approach assumes a uniform storage material temperature, the latent phase can only start when all storage material is at the phase change temperature. In reality, the storage material will locally reach the phase change temperature sooner and as a result the time-series approach overestimates the start of the latent phase. The predicted temperature of the time-series approach makes a discontinuous jump around 0.6 hours. The discontinuous jump is the result of switching from the first order-sensible phase model to the latent system model. The space-series approach does not have this issue. After 0.6 hours the predictions of the time-series approach and space-series approach are very similar.

After about 2 hours of charging, the predictions of all three models deviate more strongly from the experiments. From about 3 hours into the charging, the latent-only prediction is closer to the measured outlet temperature than the other two approaches. However, this does not mean that the latent-only model better predicts the physical processes happening in the storage system. This can be understood by taking a closer look at the efflux of energy integrated in time or the sum of the stored energy and the heat losses (Figure 3). The time-series and space series model match the measurement quite closely. However, around 3 hours the integrated efflux stabilizes to the total internal energy change. The measured integrated efflux increases further beyond this point due to heat losses. The setup is insulated however significant heat losses up to 10 % of the stored energy are reported during charging [4]. As neither the sensible heat, nor the latent heat sub model estimate the heat losses, the modeling approaches are no longer accurate near the end of charging when the effect of heat losses becomes more significant.

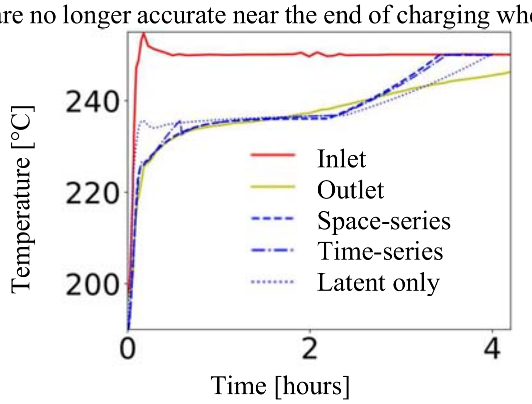

Figure 2: Comparison of measured inlet temperature (red line) and outlet temperature (yellow line) and predicted outlet temperature for the space-series, time-series and latent heat only model.

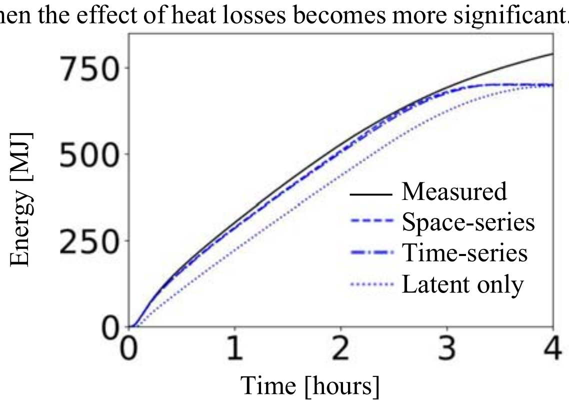

Figure 3: Comparison of measured integrated efflux of energy and predicted integrated efflux of energy for the space-series, time-series and latent heat only model.

5. Conclusion

Design and sizing of LTES systems remains a challenging task. The modelling approaches compared in this paper can help alleviate the task as the outlet temperature of the system is predicted with reasonable accuracy. The input to each of the approaches is minimal: based on the geometry of the system and the properties of the materials both the sensible and latent heat are modeled. The space-series and time-series approach obtain a better accuracy compared to the latent heat only approach. However, the absence of losses reduces the accuracy at the final stages of charging for all three modeling approaches.

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