Evaluating the Performance of a Combined SHS-LHS System

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Abstract: In the present work, a combined sensible heat storage-latent heat storage (SHS-LHS) system has been evaluated with Aragonite, which belongs to the category of Limestone, as the sensible heat storage material and Potassium Hydroxide (KOH) as the latent heat storage material. The performance of the combined sensible-latent heat storage system is analyzed and compared with a sensible only heat storage system by evaluating key parameters such as Heat Transfer Fluid (HTF) exit temperature, average temperature of the heat storage system and the amount of energy stored and retrieved during charging and discharging respectively. It was found that a combined sensible-latent heat storage system stabilizes the HTF exit temperature to around the temperature of the phase change material (PCM) during the discharge cycle. This has also been corroborated by other researchers in their experimental work. It was also found for both the systems (sensible and combined) that the larger the pellet diameter, the longer is the time taken by the Thermal Energy Storage System (TESS) to reach the maximum operating temperature. For both the systems, the temperatures remain at the maximum operating temperature for a longer duration at lower HTF flow rates. This helps in maintaining the stability of the temperatures in a TESS for a longer duration, which in turn, to a limited extent, offsets the losses caused due to a rapid reduction in the outlet temperature in a sensible TESS. The amount of energy retrieved from the combined system is larger than the energy that is retrieved from a sensible only TESS. All these findings point to the fact that using a combined sensible-latent TESS is highly advantageous as compared to a sensible only TESS.

Key words: Aragonite, heat transfer fluid, hybrid, latent, sensible, phase change material, potassium hydroxide.

1. Introduction

Hybrid thermal energy storage systems are those that combine two different types of storage systems. The Thermal Energy Storage (TES) systems can be categorized based on several parameters. Some of them are temperature range, primary heat source, storage material, duration of storage and field of application [1]. In sensible heat storage, a change in the temperature of the storage material allows heat storage. Materials in the liquid and solid form are most appropriate for sensible heat storage. Sensible storage is the simplest of all storage methods [1]. Actually, for applications at temperatures lower than 100 °C, the sensible/water system seems to be the best option thanks to its availability, its low cost, and sufficiently high specific heat. Nevertheless, there are ambient heat losses that cause reduction of energy stored during the stand-by periods. This leads to the necessity of careful insulation of the vessels, thus reducing the overall volumetric heat storage density of the system [2]. In latent heat storage, the heat is stored as a result of a phase change in the storage material. In case of latent heat storage, the area of interest is the phase change from liquid to solid state. From a practical perspective, latent storage is used in combination with sensible storage since a temperature difference is required between the source and the heat storage material. The main advantage of latent storage stems from the possibility that heats of melting and of solidification can be charged and discharged with minimized temperature differences and hence minimized exergy losses [1]. The energy density is quite high in case of latent heat storages. The latent heat storage systems are not widely used commercially as much as sensible heat storage systems due to the poor heat transfer rate during heat storage and recovery processes. This can be attributed to the fact that during phase change, the solid–liquid interface moves away from the convective heat transfer surface (during charging in cool storage process and discharging in hot storage process) due to which the thermal resistance of the growing layer of solidified PCM increases, thereby resulting in poor heat transfer rate [3]. Sensible heat storage systems have a limitation where the temperature of the HTF at the end of the discharge cycle drops, thereby reducing the efficiency of the storage system. A latent heat storage system cannot store heat within a large temperature range. These limitations can be overcome by integrating the sensible storage with a latent storage. This integration helps in stabilizing the outlet temperature of the HTF during the discharge cycle to around the temperature of the PCM melting point. In the combined SHS-LHS, benefits can be derived from the high energy density of the PCM and the high power delivering capacity of the sensible storage material. In a SHS-LHS system the PCM minimizes the temperature drop at the outlet during the discharge cycle. In a SHS-LHS system, it is possible to reduce the power loss of the sensible storage. The combination of sensible and latent storage ensures that surge in power demand can be met while satisfying the base load conditions. The sensible storage meets the peak power requirements and the PCM satisfies the base load conditions.

2. Literature Review

Zanganeh *et al*. [4] have experimentally investigated a combined sensible–latent heat for thermal energy storage at 575 °C. $AlSi_{12}$ (88% Al and 12% Si by mass) encapsulated in stainless steel tubes is used for storing latent heat, whereas rocks are used for storing the sensible heat. Air is used as the Heat Transfer Fluid (HTF). The operating temperature during charging ranges between 600-700 °C and that during discharge is 25 °C. One configuration consists of the rocks and PCM arrangement and the other configuration consists of only rocks. The mass flow rates and charging times for “rocks+PCM” and “rocks only” were similar. The ambient temperature of the storage system at the start of the charging process was 25 °C. The discharging process continued till the storage system returned back to the initial ambient temperature i.e., 25 °C. The final top temperature of the charging period for the “rocks + PCM” setup is about 10 °C lower than that for the “rocks only” setup. The authors attribute this to the melting process involved in the “rocks + PCM” setup. It can be further observed that the outflow temperature during discharge drops faster at first for the “rocks + PCM” set up, but stabilizes later. The outflow temperature of the “rocks only” setup drops below that of the “rocks + PCM” setup after about 70 minutes of discharging. In comparison, in the “rocks + PCM” setup the outflow temperature is stabilized for about 90 minutes after which the PCM solidifies and the temperature begins to drop. The outlet temperature of air was higher for about 20 minutes in case of the combined SHS-LHS as opposed to the sensible only system. These observations demonstrate that the combined SHS-LHS system plays a pivotal role in stabilizing the outlet temperature to around the melting temperature of the PCM while the PCM is partially molten.

Zavattoni *et al*. [5] have investigated a combined SHS-LHS system comprising of a packed bed of gravel and $AlSi_{12}$. The packed bed of gravel comprises of a mixture of different rocks types such as limestone, quartzite, sandstone and gabbro. This mixture of rocks is used to store sensible heat where as $AlSi_{12}$ is used to store latent heat. During charging, the HTF which is the high-temperature air, up to 595 °C, was fed through the TES from the top of the system. During discharging, the direction of flow of the HTF was reversed and air at ambient temperature was fed through the prototype from the bottom. The charging process lasted for 3.25 hours and the system was discharged until reaching dead-state condition. This study shows that adding a small amount of PCM at the top of the packed bed allows the HTF temperature to stabilize around the PCM melting temperature.

Becattini *et al*. [6] have experimentally and numerically investigated an adiabatic compressed air energy storage plant with combined sensible/latent thermal-energy storage. The latent thermal-energy storage comprises a steel tank with 296 stainless-steel tubes encapsulating an Al-Cu-Si alloy as the phase-change material. Four charging/discharging cycles were involved while investigating the combined thermal-energy storage. The duration of each cycle was about 3 hours and air inflow temperatures of up to 566 °C. The experimental results showed that the latent thermal-energy storage reduced the drop in the air outflow temperature during discharging. During charging, hot compressed air enters the cavern through an insulated pipe that directs the air to the top of the TES. The air is cooled by flowing through the thermocline TES. The cooled air then exits the TES at the bottom and enters the cavern. During discharging, the flow is reversed: cold air from the cavern enters the TES at the bottom, gets heated, leaves the TES at the top, and exits the cavern through the insulated tube. The experiments with the combined sensible/latent storage consisted of four cycles (charging/discharging). Before the first charging phase, in order approach steady cycling conditions more quickly, the TES was pre-charged. In this work, the authors have concluded that the latent TES reduced the decrease in the air outflow temperature during discharging. This demonstrates the potential of sensible/latent TES as an attractive option for industrial-scale high-temperature storage.

3. Objectives

The objectives of this work is to evaluate the performance of a combined sensible-latent heat storage system and compare it with a sensible only heat storage system in order to determine whether using combined sensible-latent heat storage systems help in minimizing the drastic HTF temperature drop at the exit of the TESS. The study was carried out to evaluate the effect of pellet diameter and HTF flow rate on the HTF exit temperature, average bed temperature, and energy stored/retrieved. Three pellet diameters 0.01 m, 0.02 m, and 0.03 m along with three HTF flow rates 0.01 kg/s, 0.015 kg/s, and 0.02 kg/s were selected. In the first case, the pellet diameter was varied and the HTF flow rate was kept constant at 0.02 kg/s. In the second case, the HTF flow rate was varied and the pellet diameter was kept constant at 0.02 m. A schematic of the combined sensible-latent storage system is shown in Fig. 1.

Table 1. Properties of the KOH and Aragonite

	Potassium Hydroxide (KOH)	Aragonite ($CaCO_3$)
Melting Temperature (°C)	380	825
Heat of fusion (kJ/kg)	149.7	57.35
Dynamic viscosity (Pa-S)	3.7×10^{-3}	0.36×10^{-3}
Thermal Expansion Co-efficient (1/K)	3.15×10^{-4}	65×10^{-6}
Specific heat capacity in solid state (J/kg-K)	1470	822.3
Specific heat capacity in liquid / molten state (J/kg-K)	1481.32	1250
Thermal Conductivity in solid state (W/m-K)	0.5	2
Thermal Conductivity liquid / molten state (W/m-K)	0.514	1
Density in solid state (kg/m³)	2044	2830
Density liquid / molten state (kg/m³)	1765.2	2700

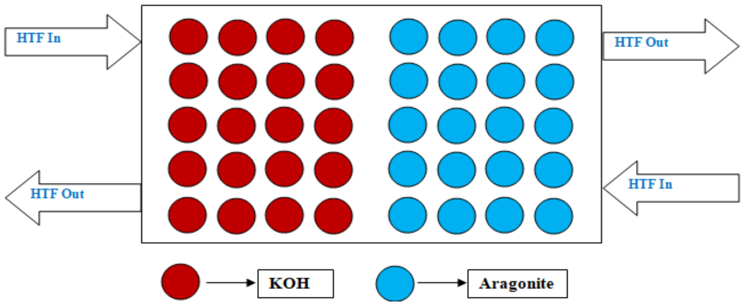

Fig. 1. A schematic of the combined sensible-latent heat storage system.

4. Results and Discussion

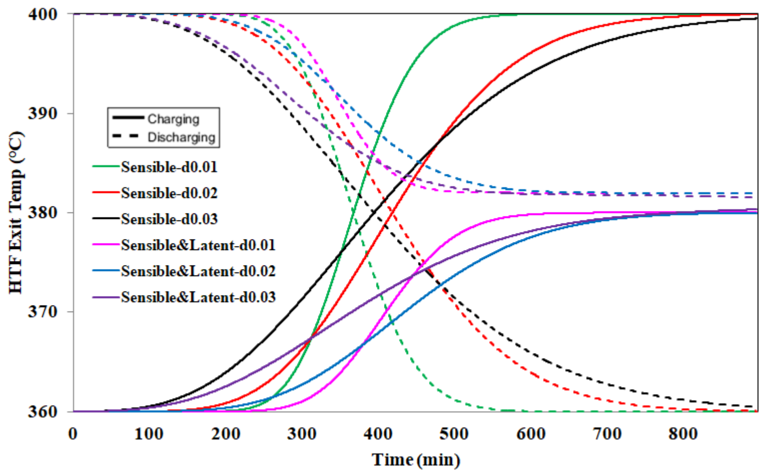

Fig. 2. HTF exit temperature (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s)

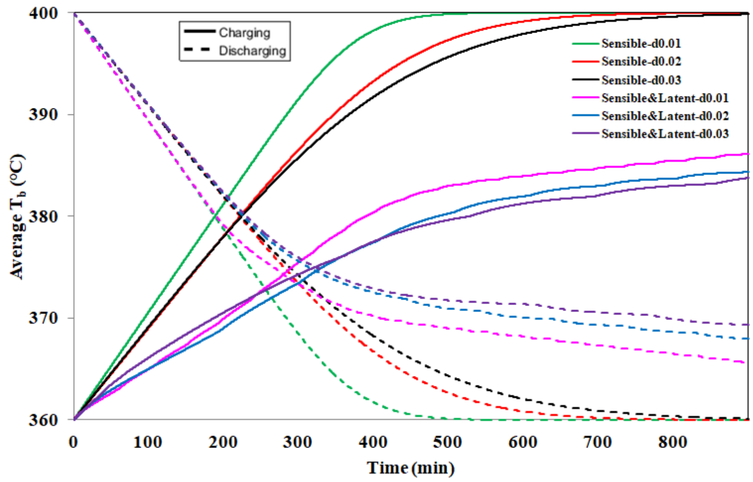

Fig.3. Average bed temperature (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s).

For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the HTF exit temperature to reach the maximum operating temperature (400 °C) also increases and during discharging, as the pellet diameter increases, the time taken for the HTF exit temperature to return to the initial temperature of the TESS (360 °C) also increases. For the combined TESS, during both the charging and discharging cycles, the HTF exit temperature stabilizes around the melting temperature of the PCM (380 °C).

This can be observed in Fig. 2. For the sensible TESS, during charging, as the pellet diameter increases, the time taken for the TESS bed to reach the maximum operating temperature increases and during discharging, the time taken by the TESS bed to return to the initial temperature also increases. For the combined TESS, for both the charging as well as discharging cycles, the temperature of the TESS bed is stable around the melting temperature of the PCM. This can be observed in Fig. 3. On an average, the sensible TESS stores more energy in a shorter time than the combined TESS. The amount of energy retrieved from the combined TESS is higher than the sensible TESS. This can be observed in Fig. 4. This may be attributed to high thermal losses in case of the sensible TESS. On the other hand, a combined TESS experiences comparatively lesser thermal losses, which may be attributed to the presence of a PCM.

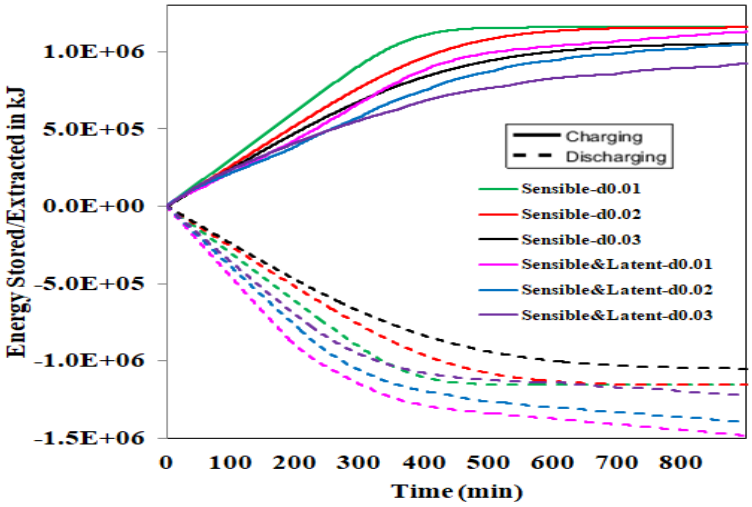

Fig. 4. Energy stored/extracted in kJ (d=0.01m, 0.02m, 0.03m, ṁ=0.02 kg/s).

For the sensible TESS, during charging, as the HTF flow rates are increased, the time taken for the HTF exit temperature to reach the maximum operating temperature decreases and during discharging, increasing HTF flow rates lead to the HTF exit temperatures dropping at a faster rate. For the combined TESS, during both charging and discharging, as the HTF flow rates are increased, the HTF exit temperatures stabilize around the PCM melting temperature at a faster rate. This can be observed in Fig. 5. For the sensible TESS, during charging, as the HTF flow rates are increased, the time taken for the average temperature of the TESS bed to reach the maximum operating temperature decreases. During the discharge cycle, as the HTF flow rates are increased, the time taken for the average temperature of the TESS bed to return to the initial TESS bed temperature decreases. In case of the combined TESS, for both the charging and discharging cycles, the temperature of the combined TESS is stable around the melting temperature of the PCM. This can be observed in Fig. 6. In case of both the systems, increase in the mass flow rates leads to a reduced energy storage time. On an average, the sensible TESS stores more energy in a shorter time than the combined TESS. The amount of energy retrieved from the combined TESS is higher than the sensible TESS. This can be observed in Fig. 7. Further, from Fig. 4 and Fig. 7, it can be inferred that the sensible TESS stores energy at a faster storage rate as compared to the combined TESS thus making the sensible storage systems more suitable for peak load conditions. On the other hand, a larger amount of energy is retrieved from the combined TESS as compared to the sensible TESS thus making the combined storage systems more suitable for base load conditions.

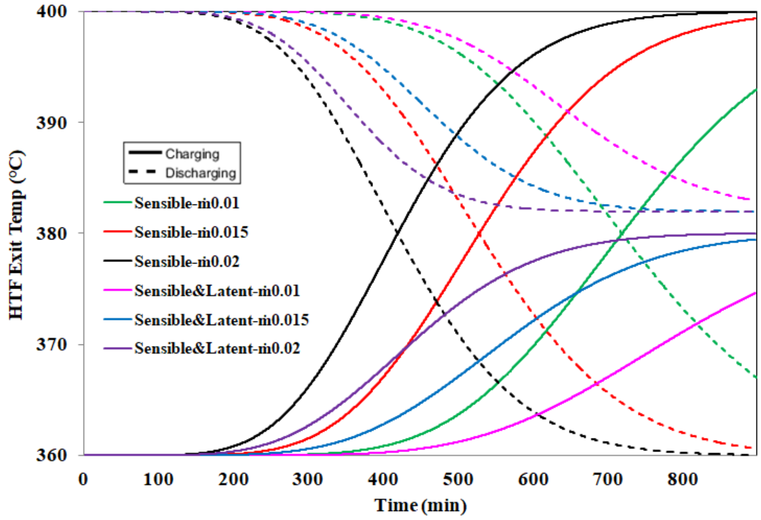

Fig. 5. HTF exit temperature (ṁ=0.01 kg/s, 0.015 kg/s, 0.02 kg/s, d=0.02m).

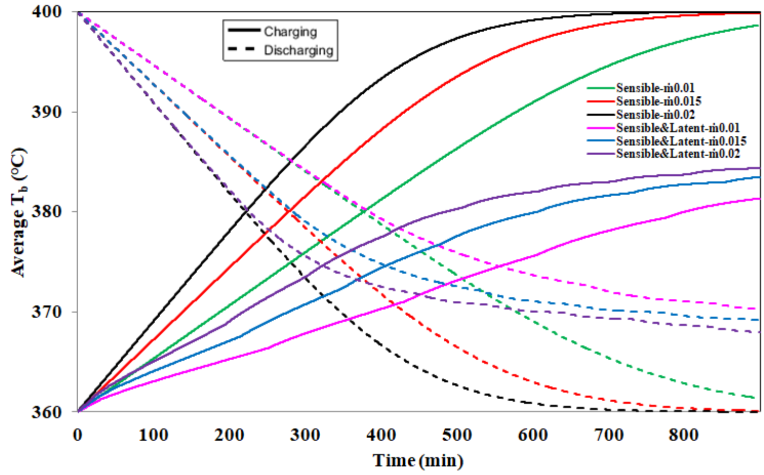

Fig. 6. Average bed temperature (ṁ=0.01 kg/s, 0.015 kg/s, 0.02 kg/s, d=0.02m).

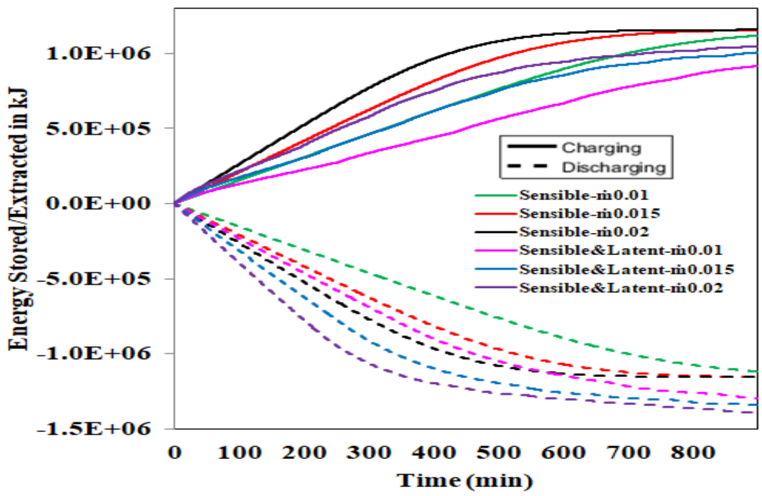

Fig. 7. Energy stored/extracted in kJ (ṁ=0.01 kg/s, 0.015 kg/s, 0.02 kg/s, d=0.02m).

5. Conclusions

Temperatures in TESSs with sensible storage materials are known to increase and decrease rapidly as compared to combined sensible and latent TESSs. This trend can be observed in the HTF exit temperature plots. The temperatures in a combined sensible and latent TESS are less prone to rapid fluctuation and this trend too can be observed in our work. One of the main disadvantages of the sensible TESSs is the drastic fall in the HTF exit temperatures during the discharge cycle. This can be avoided by using a combined sensible and latent TESS, which is one of the main objectives of using this type of combined system. It is clearly evident from the HTF exit temperature plots that the HTF exit temperature is stabilized to around the temperature of the PCM during the discharge cycle. It can be appreciated that the HTF exit temperature for the combined sensible and latent system during the discharge cycle does not fall back to the initial TESS temperature of 360 °C, but on the contrary it continues to be stable around the PCM melting temperature. This trend has been proven by Zanganeh et al. [4], Zavattoni et al. [5], and Becattini et al. [6] in their experimental work. On an average, the sensible TESS stores 6% more energy than the combined TESS and the energy retrieved from the combined TESS is 19% more than that of the sensible TESS. On an average, the energy storage rate of the sensible TESS is 15% higher than that of the combined TESS during both charging and discharging.

To the best of knowledge of these authors and based on the literature explored, Aragonite has not been evaluated as a sensible heat storage material. Future work could be aimed at exploring the performance of a combined sensible-latent heat storage system with Aragonite and different suitable high temperature application PCMs namely KNO_3 and $NaNO_3$ especially KNO_3 as it is known to yield a high amount of energy when used as a latent heat storage material. In this work, the corrosive effects of the PCMs on the pellets have not been evaluated. Future research could include a investigation of the corrosive effects of the PCMs on the pellets. One suggestion is to explore the possibility of coating the inner surface of the pellets with high temperature anti-corrosion coatings. This is important in order to prevent the damage of the pellets and subsequent damage to the TESS itself due to the corrosive effects of the PCMs. Future work could also include evaluating the service life of the PCMs and carrying out a cost-benefit analysis.

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