A REVIEW OF HIGH TEMPERATURE COMBINED SENSIBLE-LATENT HEAT STORAGE SYSTEMS

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Abstract - In order to wean ourselves from non-renewable energy sources, it is important to increase our focus on renewable forms of energy. One of the most abundant and easily available non-renewable forms of energy is the solar energy. Though solar energy is abundantly available, it availability is intermittent in nature. Energy consumption is not constant. It varies based on the demand. In most of the cases, renewable energy sources do not have the capacity to meet peak load demands. This problem can be solved by storing energy and using it later. Thermal energy storage systems came a long way in fulfilling our ever growing energy demands. Based on the method of storage, the thermal energy storage systems can be broadly classified as sensible heat storage, latent heat storage, and thermo-chemical heat storage. Each method of storage has its own advantages and disadvantages. In order to offset the drawbacks of the individual storage systems and to get maximum efficiency out of a thermal energy storage system, hybrid storage systems comprising two different storage systems are used. The objective of this review is to study the details of combined sensible-latent heat storage systems and highlight their advantages, limitations, applications, heat storage materials and heat transfer fluid (HTF) used, and the potential of these combined systems to offset the limitations posed by individual storage systems. In this study, combined sensible-latent heat storage systems pertaining to high temperature applications are presented.

Keywords - energy storage, hybrid storage system, sensible-latent.

I. INTRODUCTION AND OBJECTIVE

Hybrid thermal energy storage systems are those that combine two different types of storage systems. The two main types of hybrid thermal energy storage systems currently being explored and developed are the sensible heat-latent heat storage systems and sensible heat-thermochemical heat storage systems. Each storage system has its own advantages and disadvantages. Thermal energy storage technology can be classified into three main types: sensible, latent and thermochemical storage. The Thermal Energy Storage (TES) 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. We need to keep in mind the volumetric storage density depends on the specific heat capacity, material density and variation in temperature. Sensible storage is the simplest of the three storage methods [1]. The state of the art of commercially available heat storages for domestic applications is dominated by sensible systems, based on water as the heat storage medium. 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, it suffers from the intrinsic limit related to the heat losses to the ambient that causes 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 condensation and of evaporation 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, minus the high pressures, unlike the case of steam accumulators or pressurized water tanks. The LHS systems are not widely used commercially as much as SHS 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 in 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 sensible heat storage-latent heat storage system (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 in other words the peak power requirements can be met all the same satisfying the base load conditions. The sensible storage meets the peak power requirements and the PCM satisfies the base load conditions. The objectives of this review is to study in detail combined sensible-latent heat storage systems and highlight their advantages, limitations, applications, heat storage materials and heat transfer fluid (HTF) used, and the potential of these combined systems to offset the limitations posed by individual storage systems. In this study, combined sensible-latent heat storage systems pertaining to high temperature applications are presented.

ABBREVIATIONS

CFD	Computational Fluid Dynamics
HDPE	High density polyethylene
HTF	Heat Transfer Fluid
LHS	Latent Heat Storage
PCM	Phase Change Material
SHS	Sensible Heat Storage
TES	Thermal Energy Storage

II. CURRENT STATE OF THE ART

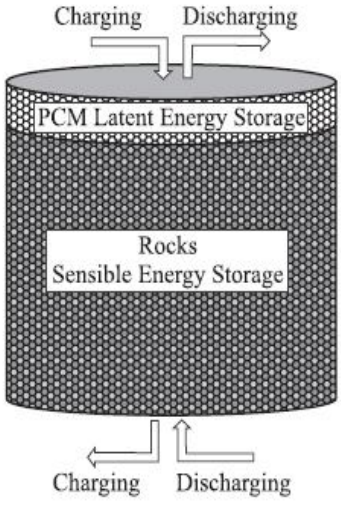


Fig. 1. Scheme of the combined sensible and latent heat concept for thermal energy storage, comprising a relatively small layer of PCM on top of a packed bed of rocks [4]

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. The schematic and configuration of the combined sensible-latent thermal energy storage prototype is shown in Figs. 1 and 2.

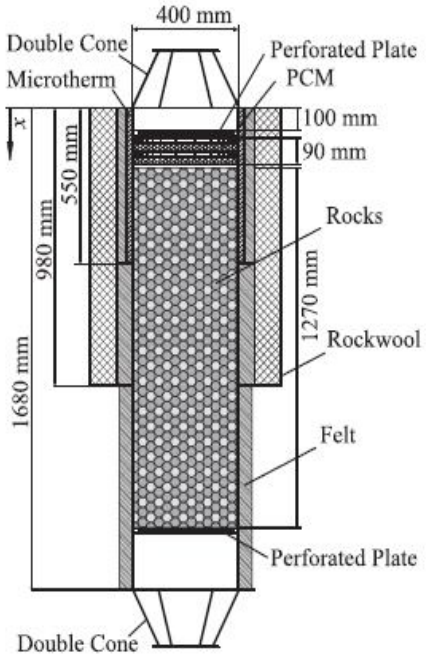


Fig. 2. Configuration of the lab-scale prototype [4]

Air is used as the Heat Transfer Fluid (HTF) and a 21 kW electric heater is used to heat the incoming air. During charging, the heated air enters from the top of the prototype and exits at the bottom. During the discharge process, air enters from the bottom and exits at the top. The operating temperature during charging ranges between 600-700 °C and that during discharge is 25 °C. The authors in their work have investigated two configurations. One configuration consists of the rocks and PCM arrangement and the other configuration consists of only rocks. The purpose of the latter configuration is to compare the performance of the SHS-LHS system with the standalone sensible storage system. Four runs were carried out, two each for “rocks+PCM” and “rocks only” configuration. Runs 1 and 2 correspond to the "rocks+PCM" configuration and runs 3 and 4 correspond to the “rocks only” configuration. 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.

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 whereas $AlSi_{12}$ is used to store latent heat. The authors have evaluated thermo-fluid dynamics behavior of the combined SHS-LHS system by

employing a computational fluid dynamics approach. In this work, they have accounted for the effect of radial void-fraction variation, which is also known as channeling. Radial void-fraction variation is caused due to a small value of the characteristic vessel-to-particles diameter ratio. In this study, the authors have developed a 2D computational fluid dynamics (CFD) model to simulate the behavior of the combined SHS-LHS system which uses air as HTF. Further, a lab-scale combined SHS-LHS prototype system was used to validate the numerical model by comparing the CFD simulation results with experimental data. The lab-scale combined SHS-LHS prototype system used for this study is shown in Fig. 3.

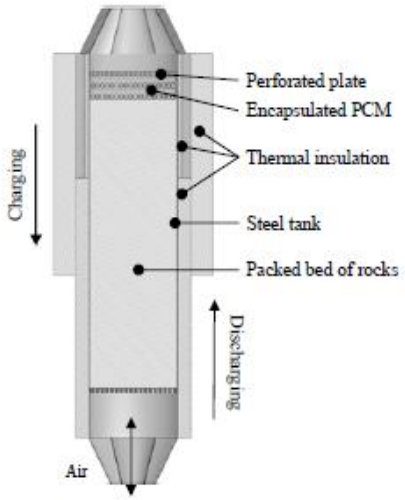


Fig. 3. Schematic of the pilot-scale combined TES [5]

$AlSi_{12}$ is used as the PCM for the latent section. The PCM was encapsulated in AISI 316 steel tubes. The encapsulated PCM was positioned on top of the packed bed and distributed into four layers. Each layer consists of 17 tubes each and the tubes are oriented at an angle of 45°, with an average void-fraction of 0.55. 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. Thermal energy of the HTF is transferred to the entire TES. During discharging, the direction of flow of the HTF was reversed and air at ambient temperature was fed through the prototype from the bottom.

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. The authors have corroborated this with the numerical model. Further, the authors point out that due to the small tank-to-particle diameter ratio, the thermo-fluid dynamics behavior of the combined TES prototype was significantly affected by the radial variation of the void-fraction. Becattini et al. [6] have experimentally and numerically investigated the world's first pilot-scale advanced adiabatic compressed air energy storage plant with combined sensible/latent thermal-energy storage. The combined thermal-energy storage comprises of sensible and latent units with maximum capacities of 11.6 MWh^{th} and 171.5 kWh^{th}, respectively. The latent thermal-energy storage comprises a steel tank with 296 stainless-steel tubes encapsulating an Al–Cu–Si alloy as phase-change material. Four charging/discharging cycles were involved while investigating the combined thermal-energy storage. Each cycle had a duration of 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. A schematic of the pilot plant is shown in Fig. 4. 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 cavern is 120 m long and has a diameter of 4.9 m and confined by two concrete plugs and steel doors. Fig. 5 shows a schematic of the combined SHS-LHS.

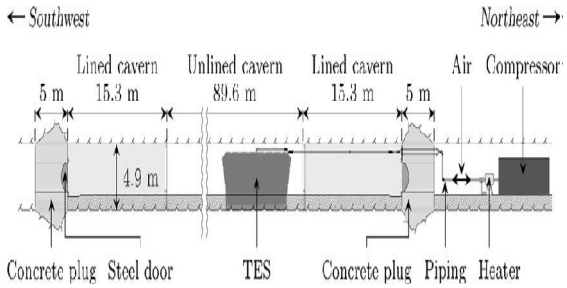


Fig. 4. A schematic of the pilot plant [6]

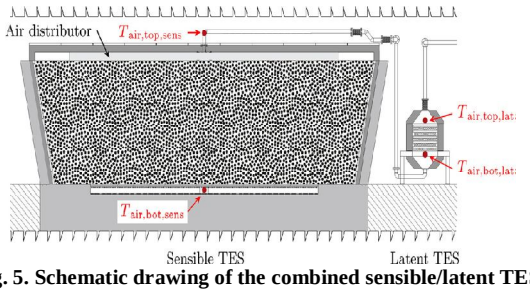


Fig. 5. Schematic drawing of the combined sensible/latent TES and locations of air inflow/outflow temperature measurements [6]

In this study, the authors have designed and constructed a separate latent storage to store the PCM. They point out to many advantages in doing so. First, the cross-sectional area of the latent storage can be chosen independently of that of the sensible storage to give good heat-transfer rates and hence melting behavior of the PCM. Second, a separate latent storage provides the possibility to switch between experiments either with only the sensible TES or with the combined TES by disconnecting and

reconnecting the pipe linking the two storages. Third, at least for the current pilot-scale plant, a separate latent storage was easier to construct and adapt than if the encapsulated PCM had been placed in the sensible storage, which would have required the removal of its steel cover and the pipe attached to the cover. Fourth, with a view to the possible use of industrial-scale combined storages, a separate latent storage allows the PCM to be inspected and/or replaced more easily.

Table 1. Sensible-Latent Heat Storage Systems

Institution	Materials	Melting Temperature (°C)	Operating Temperature Range (°C) And other parameters	Energy Output (kW) / Capacity (kWh)	Nature of System - Prototype/ Commercial
ETH Zurich, Switzerland	Latent Storage: $AlSi_{12}$(88% Al and 12% Si by mass) Sensible Storage: Rocks HTF: Air	575 °C	25 °C to 600–700 °C	42 kWh	Prototype Tank position: vertical Heating source: 21 kW electric heater
Department of Innovative Technologies, Manno, Switzerland	Latent (PCM) storage: $AlSi_{12}$ Sensible storage: Gravel HTF: Air	573-577 °C HTF Inlet Temperature = 595°C	22°C - 595°C	42.3 kWh^{th}	Prototype
ETH Zurich, Switzerland	Latent(PCM) storage: Al–Cu–Si alloy (68.5Al26.5Cu5Si (wt%)) Sensible storage: Rocks (mafic rocks, felsic rocks, limestones, sandstones, and quartz-rich conglomerates)	509–527 °C	Ambient to 566 °C and pressure of 7 bar Maximum operating pressure: 33	Sensible - 11.6 MWh^{th}, Latent - 171.5 kWh^{th}	Pilot-Scale Plant Heating source: Electrical Heater

Table 1 discusses the different sensible-latent heat storage systems, the sensible and latent materials used, the melting temperature of the PCMs, operating temperatures, energy output and the nature of the system. The highest energy output is obtained from the system that uses Al–Cu–Si alloy as the latent material, which is 171.5 kWh^{th}. The systems that use $AlSi_{12}$ (a eutectic alloy containing 88% aluminum and 12% silicon by mass) generate around 42 kWh^{th} of energy. The operating temperature for all the three systems is in the range of 0°C to 600°C. All the three systems shown in Table 1 use air as the HTF and rocks/gravel as the sensible heat storage material.

CONCLUSIONS

All the work done by different researchers on high temperature sensible-latent heat storage systems has one common agreement, i.e., the coupling of the sensible heat storage with the latent heat storage plays a pivotal role in stabilizing the outlet temperature to around the melting temperature of the PCM. In some cases, adding even a small amount of PCM at the top of the packed bed allows the HTF temperature to stabilize around the PCM melting temperature. Further, experiments show that a combined sensible-latent storage system fulfills both the peak as well as base load requirements. Even though there is a lot of scope for improvement like improving the quality of the eutectics and exploring more coatings for PCM capsules in order to prevent corrosion, overall, the combined sensible-latent heat storage systems hold a promising future for energy storage systems.

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