Experimental investigation of the performance of thermal energy storage with embedded phase change materials as wall insulator

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Abstract. Thermal energy storage (TES) has been widely adopted to bridge the mismatch between energy supply and demand. In general, thermal energy storage is segregated as sensible TES and latent TES whereby both have their own advantages and disadvantages. This study explores the possibility of utilizing the advantages of both sensible and latent TES by embedding phase change materials as a wall of the sensible TES. To investigate the performance of the proposed TES, an experimental set-up of TES with PCM embedded in the wall is developed. Temperature distribution within TES is measured and recorded during charging and discharging process. Several key parameters are evaluated to gauge their influence on the performance of the studied TES. The results indicate that the performance of TES with embedded PCM is superior that that without PCM, indicating the potential of the proposed design for high performance thermal energy storage application.

1. Introduction
The depletion of fossil fuel, alarming pollution due to fossil fuel emission and fluctuating price of fossil fuel has driven global initiative to search for alternative sustainable energy resources. Accordingly, extensive research and development on sustainable energy resources have been intensified over the last decades. Among the studied renewable energy resources, solar and wind energy have attracted the most considerable attention due to its wide availability. Despite the significant efforts devoted on development of these energy resources, their adoptability is relatively low due to its intermittent nature: they are available only on the specific time period; hence, these energies cannot be harnessed continuously. This intermittency creates discrepancy between energy supply and demand. To overcome this issue, an energy storage is needed to bridge the disparity between supply and demand of the energy [1]. Several types of energy storage are currently available, i.e. thermal energy storage, mechanical energy storage, chemical energy storage, electrical energy storage and biological energy storage. Among these energy storages, thermal energy storage has
received considerable attention and adoption due to its simplicity and substantial energy storage capacity.

In general, two types of thermal energy storages are available, i.e. sensible heat energy storage and latent heat energy storage. Among the two, sensible heat energy storage is widely adopted due to its simplicity. It can be found in solar water heater plant, gas district cooling plant and heating, ventilation and air conditioning (HVAC) system of a building. A wide range of materials have been adopted as storage medium in sensible heat storage such as water, thermal oil, molten salt, liquid metal, concrete, rock, gravel and sand [2]. Except liquid metal and thermal oil, sensible heat storage materials are relatively cheap. Moreover, it is usually applicable for high temperature application. Despite its wide adoption and extensive development, sensible heat energy storage possesses intrinsic drawback, i.e. its store energy at elevated temperature promoting heat loss to the environment. Hence, proper insulation is essential to maintain the energy storage at its optimum temperature. Moreover, it requires large volume of storage media to store the energy. Smaller energy storage will need to operate at larger temperature range to achieve similar storage capacity, triggering more heat losses to the environment. Lastly, the temperature within the storage will fluctuate during discharging: as thermal discharge continues the outlet temperature will gradually decrease. To overcome this issue, some study reported that integration of PCM to the sensible heat energy storage enhance the performance of energy storage.

Abdesalam et al [3] evaluated the performance of hybrid thermal energy storage with PCM modules submerged within. They indicated that addition of PCM modules does increase the storage capacity. Underwood et al [4] proposed a compact hybrid thermal storage where a salt-hydrate PCM encapsulated in helical coils inserted into the energy storage tank. The hybrid energy storage offers better energy storage than the conventional sensible energy storage. Becattini et al [5] integrated a combined sensible and latent heat energy storage to an adiabatic compressed air energy storage. Addition of the latent heat to the system reduced the decrease in air outflow temperature during discharging. Galione et al [6] studied multi-layered solid-PCM thermocline thermal storage for concentrated solar power plant. The proposed energy storage consists of several layer of rock and encapsulated PCMs with different melting temperature. Similar concept was proposed by Geissbü hler et al [7] who developed energy storage with layer of rock and steel-encapsulated AlSi12. Both studies highlight the potential of layered hybrid sensible-latent energy storage. Ströhle et al [8] and Zanganeh et al [9] introduce hybrid sensible and latent heat to stabilize the output temperature during discharging. Zauner et al [10] embedded PCM inside thermal energy storage with thermal oil as the heat transfer fluid and storage medium. Frazzica et al [11] tested a small scale hybrid sensible/latent storage system by adding macro-encapsulated PCM to hot water storage tank. They observed increased energy storage capacity per unit volume.

None of these studies, however, investigate the integration of PCM as a wall of sensible heat thermal energy storage. By integrating PCM as a wall, the heat loss from the energy storage can be minimized while increasing the storage capacity of the energy storage. Therefore, this study is conducted to investigate the performance of hybrid thermal energy storage with PCM embedded in its wall and to evaluate important parameters that determine the performance of the studied energy storage. Statistical tools and analysis are implemented to minimize the experimental run while securing the required information for performance evaluation and design purpose. This preliminary study is intended to explore the feasibility to develop thermal energy storage with embedded phase change material as insulator wall cum latent heat energy storage.

2. Experimental methodology
To evaluate the performance of sensible heat energy storage with integrated PCM wall, an experimental set up is developed and examined. The experimental set up comprises two concentric cylinders: the inner cylinder is made of 2-mm-thick aluminium and the outer cylinder is made of
Thermoset to act as insulation. The inlet for the heat transfer fluid is located higher than the outlet. The experimental set up is shown in Fig. 2 while details on the geometric parameters are summarized in Table 1. Water is used as the heat transfer fluid while commercial grade paraffin wax (n-Octadecane) is used as the phase change materials. The melting point for this paraffin wax is 59-60 °C.

Type K thermocouples are used to measure the temperature and are connected to data logger (OMEGA OM-DAQPRO-5300) to record the data. Water inlet to the energy storage is supplied by water bath (Thermo Cool Tech 320) at controlled temperature and flow rate. Prior to the experimental runs, calibration of the thermocouples is conducted to make sure the precision of the measured data. Once calibration is conducted, experiment is carried out as follows: (i) Water bath is started with inlet temperature set as per experimental design shown in Table 2, (ii) The hot water is supplied to the TES until the temperature of water and PCM in the TES has reached equilibrium at the supplied temperature of HTF, (iii) Once the TES is fully charged, the water is replaced with a room temperature water and supplied to the TES in the same manner for TES discharging, (iv) The cold or cooler water is supplied until the TES core temperature and PCM temperature has reached equilibrium at the supplied temperature of HTF, (v) Throughout this experiment, the TES inlet, outlet and PCM core temperature is recorded using the data logger. To ensure reproducibility of the experimental result, each experimental run was repeated three times.

| Parameters | Value | Unit |
|------------|-------|------|
| $h_T$      | 0.16  | m    |
| $d_{Ti}$   | 0.16  | m    |
| $d_{To}$   | 0.24  | m    |
| $d_P$      | 0.01  | m    |
| $s_t$      | 0.022 | m    |
| $s_b$      | 0.032 | m    |
In this study, three key parameters that is expected to be crucial in dictating the performance of the studied TES are evaluated, i.e. HTF inlet temperature, HTF mass flow rate and mass of PCM used. Table 2 presents three different values which are chosen for each investigated parameter. To optimize the required experimental time and resources in evaluating the importance of these key parameters, adopted statistical tools and analysis are adopted. This experimental design is based on Taguchi method which is adopted to evaluate the effect of each parameter and decide the best design parameter combination for TES evaluation. The analytical statistic is carried out by using Minitab software.

**Table 2. Levels of independent variables for the L12 orthogonal array**

| Parameters                  | Level 1 (kg/s) | Level 2 (kg/s) | Level 3 (kg/s) |
|-----------------------------|----------------|----------------|----------------|
| Mass flow rate              | 0.006          | 0.009          | 0.013          |
| HTF inlet temperature (°C)  | 40             | 60             | 80             |
| Mass of PCM (kg)            | 1.0            | 1.5            | 2.0            |

**Table 3. Experimental design matrix and results**

| Run No. | Mass flow rate (kg/s) | HTF inlet temperature (°C) | Mass of PCM (kg) | TES charging efficiency (%) | TES discharging efficiency (%) | Overall TES efficiency (%) |
|---------|-----------------------|-----------------------------|------------------|-----------------------------|-------------------------------|---------------------------|
| 1       | 0.006                 | 60                          | 1.0              | 25.9                        | 81.9                          | 20.25                     |
| 2       | 0.009                 | 80                          | 1.0              | 30.1                        | 84.6                          | 25.75                     |
| 3       | 0.009                 | 40                          | 1.0              | 25.3                        | 79.4                          | 14.64                     |
| 4       | 0.013                 | 60                          | 1.0              | 17.4                        | 86.2                          | 18.97                     |
| 5       | 0.013                 | 40                          | 1.5              | 21.6                        | 64.4                          | 13.71                     |
| 6       | 0.006                 | 40                          | 1.5              | 26.7                        | 86.4                          | 23.04                     |
| 7       | 0.006                 | 80                          | 1.5              | 33.2                        | 77.4                          | 25.28                     |
| 8       | 0.013                 | 80                          | 1.5              | 34.8                        | 72.0                          | 24.94                     |
| 9       | 0.006                 | 60                          | 2.0              | 17.8                        | 64.3                          | 16.19                     |
| 10      | 0.009                 | 40                          | 2.0              | 14.9                        | 66.0                          | 8.97                      |
| 11      | 0.009                 | 80                          | 2.0              | 35.3                        | 73.3                          | 27.04                     |
| 12      | 0.013                 | 60                          | 2.0              | 27.1                        | 54.4                          | 14.07                     |

The performance of the studied TES is evaluated by adopting an approach previously used by Li et al [14] which based on energy analysis. In this approach the performance of the studied energy storage is presented in term of charging efficiency, discharging efficiency and overall efficiency.

**3. Results and discussion**

In this study, the performance storage performance of TES with PCM wall and without PCM wall is evaluated. For the configuration with PCM wall, the PCM space is fully filled with 2 kg of PCM while for the configuration without PCM, the space is filled with water. Inlet hot water, at 80°C is then supplied to the TES until it is fully charged. The HTF supply is then stopped and the core temperature of the TES is measured and recorded. The results are presented in Fig. 2 for both configurations. As can be observed, the time required for the core temperature to drops from 80°C to 40°C for TES with PCM wall is significantly longer than those without. This is a firm indication that PCM wall provides better insulation for the thermal energy stored within TES.
4. Conclusion
An experimental investigation on the performance of a novel thermal energy storage with PCM embedded as a wall insulator has been conducted. An experimental set up of thermal energy storage has been developed and calibrated to obtain temperature data for calculation and analysis of the performance of the studied thermal energy storage. Several key parameters are evaluated to examine their influence on the performance of thermal energy storage. On insulation aspect, it was confirmed that addition of PCM on the TES wall does enhance insulation performance of the TES. Thus it can store the energy for an extended period as compared to one without. A more detailed operating and geometrical parameters evaluation are currently being conducted to comprehensively evaluate the influence of these key parameters to the performance of thermal energy storage. This study is expected to shed the light on the basic mechanism of heat transfer and energy storage in this hybrid thermal energy storage and the influence of important parameters on the performance of the proposed energy storage.

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References
[1] Kurnia JC, Sasmito AP. Numerical investigation of heat transfer performance of a rotating latent heat thermal energy storage. Applied Energy 2018; 227: 542-554. doi:10.1016/j.apenergy.2017.08.087.
[2] Alva G, Lin Y, Fang G. An overview of thermal energy storage systems. Energy 2018;144:341–78. doi:10.1016/j.energy.2017.12.037.
[3] Abdelsalam MY, Sarafraz P, Cotton JS, Lightstone MF. Heat transfer characteristics of a hybrid thermal energy storage tank with Phase Change Materials (PCMs) during indirect charging using isothermal coil heat exchanger. Solar Energy 2017;157:462–76. doi:10.1016/j.solener.2017.08.043.
[4] Underwood CP, Shepherd T, Bull SJ, Joyce S. Hybrid thermal storage using coil-encapsulated phase change materials. Energy and Buildings 2018;159:357–69. doi:10.1016/j.enbuild.2017.10.095.

[5] Becattini V, Geissbühler L, Zanganeh G, Haselbacher A, Steinfeld A. Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 2: Tests with combined sensible/latent thermal-energy storage. Journal of Energy Storage 2018;17:140–52. doi:10.1016/j.est.2018.02.003.

[6] Galione PA, Pérez-Segarra CD, Rodríguez I, Torras S, Rigola J. Multi-layered solid-PCM thermocline thermal storage for CSP. Numerical evaluation of its application in a 50MWe plant. Solar Energy 2015;119:134–50. doi:10.1016/j.solener.2015.06.029.

[7] Geissbühler L, Kolman M, Zanganeh G, Haselbacher A, Steinfeld A. Analysis of industrial-scale high-temperature combined sensible/latent thermal energy storage. Applied Thermal Engineering 2016;101:657–68. doi:10.1016/j.applthermeng.2015.12.031.

[8] Ströhle S, Haselbacher A, Jovanovic ZR, Steinfeld A. Upgrading sensible-heat storage with a thermochemical storage section operated at variable pressure: An effective way toward active control of the heat-transfer fluid outflow temperature. Applied Energy 2017;196:51–61. doi:10.1016/j.apenergy.2017.03.125.

[9] Zanganeh G, Commerford M, Haselbacher A, Pedretti A, Steinfeld A. Stabilization of the outflow temperature of a packed-bed thermal energy storage by combining rocks with phase change materials. Applied Thermal Engineering 2014;70:316–20. doi:10.1016/j.applthermeng.2014.05.020.

[10] Zauner C, Hengstberger F, Mörzinger B, Hofmann R, Walter H. Experimental characterization and simulation of a hybrid sensible-latent heat storage. Applied Energy 2017;189:506–19. doi:10.1016/j.apenergy.2016.12.079.

[11] Frazzica A, Manzan M, Sapienza A, Freni A, Toniato G, Restuccia G. Experimental testing of a hybrid sensible-latent heat storage system for domestic hot water applications. Applied Energy 2016;183:1157–67. doi:10.1016/j.apenergy.2016.09.076.

[12] Ferreira SLC, Bruns RE, Ferreira HS, Matos GD, David JM, Brandão GC, et al. Box-Behnken design: An alternative for the optimization of analytical methods. Analytica Chimica Acta 2007;597:179–86. doi:10.1016/j.aca.2007.07.011.

[13] Box GEP, Behnken DW. Some New Three Level Designs for the Study of Quantitative Variables. Technometrics 1960;2:455–75. doi:10.2307/1266454.

[14] Li G. Sensible heat thermal storage energy and exergy performance evaluations. Renewable and Sustainable Energy Reviews 2016;53:897–923. doi:10.1016/j.rser.2015.09.006.