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Testing and Model Validation of a 100 kWh_{th} Radial Packed-Bed Thermal Energy Storage System

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Abstract.

This study presents the design, shakedown testing, and modeling of a 100 kWh_{th} radial packed-bed. Air is used as a heat transfer fluid and 3/8" pea gravel is used as the storage medium. Preliminary testing has demonstrated the formation of a thermocline within the packed-bed. An air charging temperature of 450 °C was achieved resulting in a charging power of 26.5 kW_{th}. The radial packed-bed was charged for 5 hours and discharged for 5 hours. Minimal temperature variation was observed at the bottom, middle, and top axial locations of the radial packed-bed which suggests that buoyancy and hydrodynamics in the injection well had a minimal effect on the uniformity of air flow along the bed height during charging and discharging. This indicates that the forced convection in a radial direction is dominating the flow regime compared to the buoyancy. The findings of this study suggest an increased air duct diameter through the air heater will increase the charging temperature and increase air mass flow through the system. Increased mass flow through the packed-bed is hypothesized to shorten the thermocline length. Modeled and measured results are compared, and it is here determined that a more comprehensive CFD model will aid in the understanding of air flow and thermocline evolution within the packed-bed.

Keywords: Packed-Bed, Radial, Thermocline, Energy Storage

Introduction

The transition from dispatchable fossil-fuel-based energy generation to intermittent renewable sources will require energy storage to match the energy supply with demand. Thermal energy storage (TES) is the most suitable form of energy storage for thermal electricity generation plants and can provide thermal-to-thermal round-trip efficiencies of 50% to >90% with a solar thermal input [1]. Packed-bed TES utilizes a bed of gravel or rocks that is heated by a stream of heat-transfer fluid (HTF). When needed, the sensible heat is recovered by flowing the HTF in reverse through the packed-bed to provide heat for industrial processes or electricity via conventional steam and/or supercritical CO_2 power cycle. This is an attractive solution because it is composed of inexpensive geomaterials, can store energy for days to months, and can be retrofitted into existing thermal generation stations such as coal power plants.

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Packed bed thermal energy storage has been demonstrated at a variety of scales and in various configurations. A pilot scale packed-bed thermal energy storage system with an axial-flow configuration has been demonstrated by Siemens Gamesa Renewable Energy, demonstrating a 130 MWh_{th} facility [2]. An unconstrained 1.5-2.5 MWh_{th} packed-bed in a radial configuration, stacked at the natural angle of repose, has been demonstrated at Stellenbosch University [3,4]. Radial packed-bed thermal energy storage, in which the air flows radially from an injection well, has been demonstrated at lab scale (~50 kWh_{th}) by the KTH Royal Institute of Technology [5]. Radial packed-bed thermal energy storage has advantages over axial configurations, such as reduced heat loss, with the bulk of the high temperature in the core of the packed-bed, and lower parasitic power consumption due to the decreasing HTF velocity with distance from the core.

In this paper, we present the design, shakedown testing, and modeling of a 100 kWh_{th} radial packed-bed. The developed radial packed-bed utilizes pea gravel as a storage medium and air as a HTF. Shakedown testing, which featured a 5 hour charge followed by a 5 hour discharge cycle, demonstrated the formation of a thermocline within the radial packed-bed, and key performance metrics, including injection temperature and influence of buoyancy, were assessed. Modeled and measured results are compared, and system design and modeling improvements are identified.

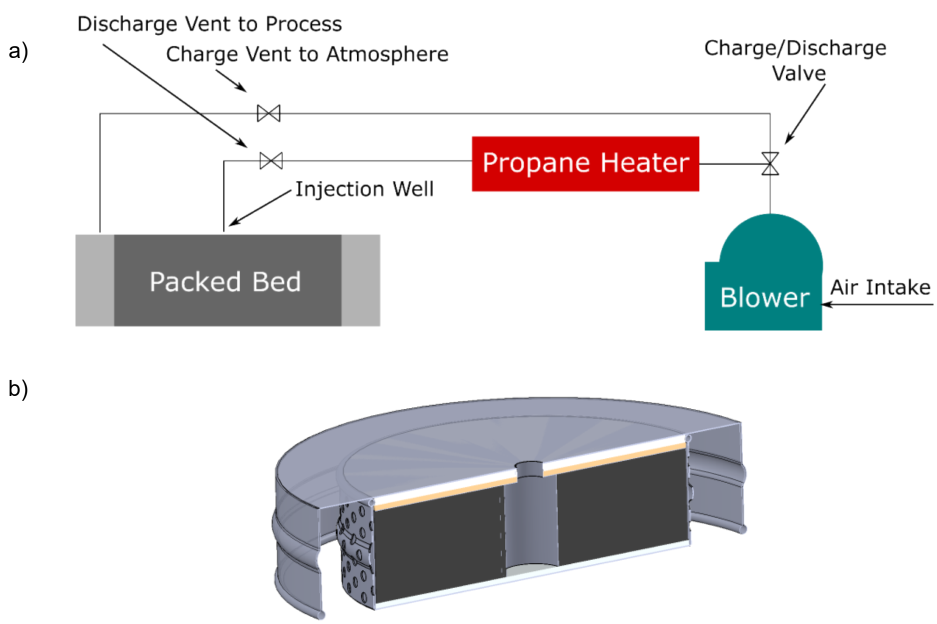

Figure 1. a) Radial packed-bed system schematic. b) Packed-bed cross-section.

Methods

Test Apparatus

The experimental test apparatus features a 1.8 m diameter, 0.6 m high packed-bed with a 0.5 m diameter injection well. A schematic of the packed-bed system is shown in Fig. 1 and images of the system are shown in Fig. 2. The radial packed-bed consists of a readily available agriculture stock tank that is filled with approximately 1900 kg of 3/8" pea gravel. The pea gravel was washed and dried prior to filling the bed to promote uniform flow distribution and reduce contaminants such as fine silt/sand which can cause undesirable pressure drop. The packed-bed utilizes an air HTF with a targeted charging temperature of 500 °C. In practice, air will be heated by a solar thermal process or resistive heaters powered by renewable electrical generation sources. Here, however, air is blown through a 5 cm diameter, 2.5 m long stainless-steel tube that is heated in a propane tube furnace. The air tube is packed with stainless steel wool to increase the heat transfer between the air and externally heated tube. The direction of air flow through the packed-bed for charging and discharging is controlled by a set of duct slide gates/valves as indicated in Fig. 1a. It is noted that this experimental design is based on lessons learned from previous packed-bed thermal energy storage experiments and facilities [2–6,16].

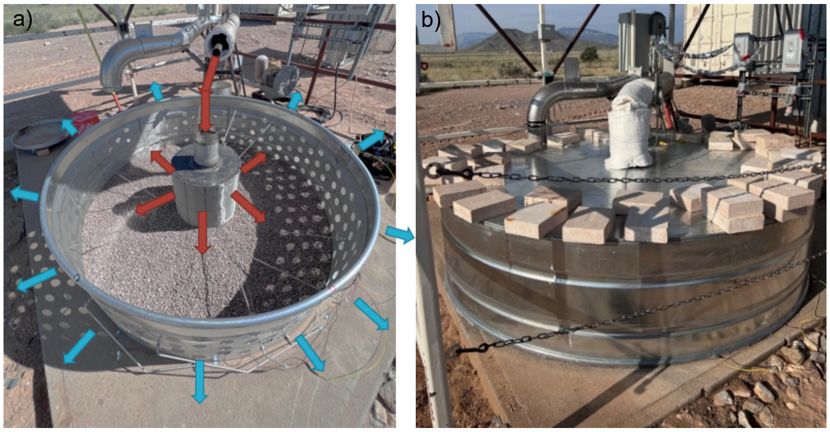

Figure 2. a) Partially filled and open radial packed bed with the charging flow direction indicated. b) Filled and covered radial packed bed on the test stand.

The packed-bed was instrumented with K-type thermocouples at locations indicated in Fig. 3 to obtain a comprehensive temperature profile within the bed. Thermocouples were placed around the bed circumferentially, radially, and at the bottom, middle, and top of the axial plane. Thermocouples were positioned at the same radial distance and height in three circumferential positions, denoted by the A, B, and C sections, to measure the circumferential temperature distribution within the bed. Circumferential spacing between each thermocouple prevented measurement error due to conduction through adjacent thermocouple probes. Section A featured an additional set of radial measurements at the top and bottom of the bed to assess the temperature distribution in the axial direction. This thermocouple layout will prompt a comparison to other state-of-the-art radial packed-bed facilities that utilize an axial thermocouple layout [5].

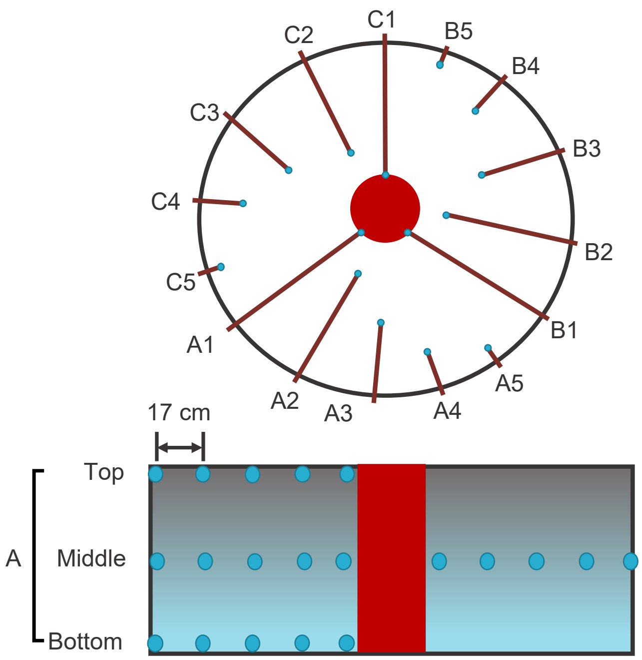

Figure 3. Thermocouple measurement locations.

Approach

Experimental

Maintaining a steep thermocline within a packed-bed is critical for reducing exergy losses. This work seeks to assess several design parameters, including the bed charging rate, gravel size, number of cycles, and storage time, for their influence on the thermocline length in a radial packed bed. This paper highlights the first phase of this campaign which is the preliminary, or commissioning, testing.

Preliminary testing was conducted to assess the performance of the packed bed using the following metrics:

1. Thermocline development - Determined by a temperature gradient >300 °C over the radial length of the packed-bed (460 °C/m)
2. 500 °C HTF injection temperature – Pass or fail
3. Buoyancy and preferential flow effects along the bed height – Determined by an axial temperature gradient <100 °C over the height of the bed (<167 °C/m)
4. Storage material durability (i.e. lack of rock attrition) – Visually assessed

The bed is charged for 5 hours and discharged for 5 hours, and there is not a hold period between charging and discharging in this campaign. The influence of gravel size, charge rate, number of cycles, and storage time will be assessed in future studies.

Numerical

For the purpose of thermal energy storage (TES), this work analyzes a method for transferring heat to and from axial, radial, and spherical packed particle beds by passing hot or cold air through the porous bed. The work is based upon the pioneering work of [7] as well as upon the more recent publications of [8-15]. Although the analytical model developed by Schumann is correct in so far as it goes, the model is not easy to apply directly to engineering problems. Some of the inputs to the Schumann model are not readily available, and the non-dimensional independent variables y and z are difficult to interpret and apply directly to engineering problems. Furthermore, Schumann assumes that the heat transfer fluid (HTF) has constant mass density, but the mass density of air is inversely proportional to absolute temperature at constant pressure, and the dynamic viscosity of air is also a weak function of temperature. Using computers that was not available to Schumann in 1929, it is possible to investigate the effect of the varying density, heat capacity, thermal conductivity and viscosity of air upon thermocline behavior.

The characteristics of the evolving temperature distribution in both the air and in the solid particles due to the airflow through the particle bed during the charging, storage and discharging phases are evaluated. The parasitic power needed to pump air through the repository for charging and discharging is also considered. Furthermore, during the storage phase, the extent to which natural air convection degrades the thermocline is also considered.

The basic thermocline problem [7] is first generalized, which assumes an axial prismatic configuration with constant-density (liquid) axial flow, to include radial and spherical geometries with variable-density (gas) HTF. Finally, the behavior of a particular utility-scale TES repository is demonstrated, and we make a recommendation for a practical TES design configuration.

Results

The radial packed-bed was charged and discharged for 5 hours each with a measured mass flow rate of 0.06 kg/s and a packed-bed pressure drop of 0.05 kPa. Figure 4 shows the temporal evolution of the thermocline in 1-hour intervals during charging at the middle axial height of the packed-bed in each circumferential section. The peak temperature at the injection well, located at radial distance 0.23 m, was approximately 450 °C in Sections A and B. The resulting charging power of the system was 26.5 kW_{th}. The temperature at radial distance 0.23 m of Section C was significantly lower than that of Sections A and B. This discrepancy is likely due to a cluster of dirt within the bed that is causing non-uniform flow near this thermocouple. The results for Section A and B, and at radial locations greater than 0.23 m in Section C, show good agreement, suggesting uniform flow is present throughout most of the bed. This result highlights the importance of removing impurities from the backed bed storage media, such as dirt, to promote uniform flow.

Figure 5 shows the simulated charging thermocline for the 1D semi-analytical numerical model. Model results are shown at 1-hr intervals. The simulated thermocline is observed to be much steeper than the measured thermoclines. Notably, the simulated thermocline gradient remains constant as a function of time while the experimental gradients become less steep with time. A comparison of the experimental and simulated results suggests that the experimental system cannot be accurately represented by a plug flow model assumption as currently developed. Assumptions of boundary conditions and quantifying parameters in the numerical modelling can contribute to deviations from the experimental measurements. Ho et. al [16] previously demonstrated that Computational Fluid Dynamics (CFD) modeling can reasonably predict radial packed-bed temperature profiles in a bench-top experiment. Thus, a detailed CFD model will also be developed to better understand the air flow and thermocline evolution within the packed-bed.

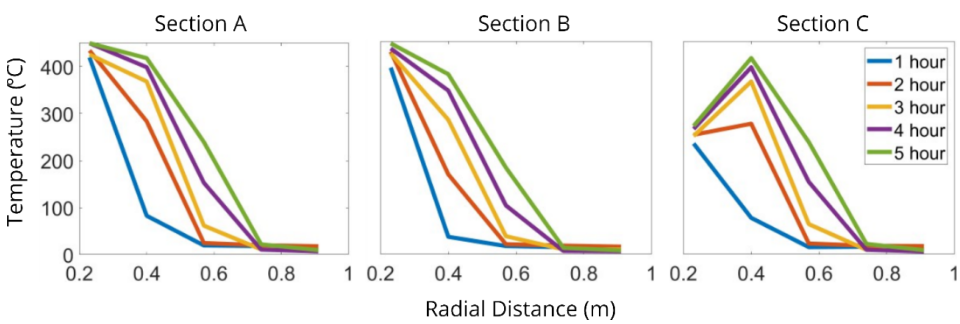

Figure 4. Temporally resolved thermocline evolution within the packed-bed at the middle axial height. Results for circumferential sections A, B, and C are shown.

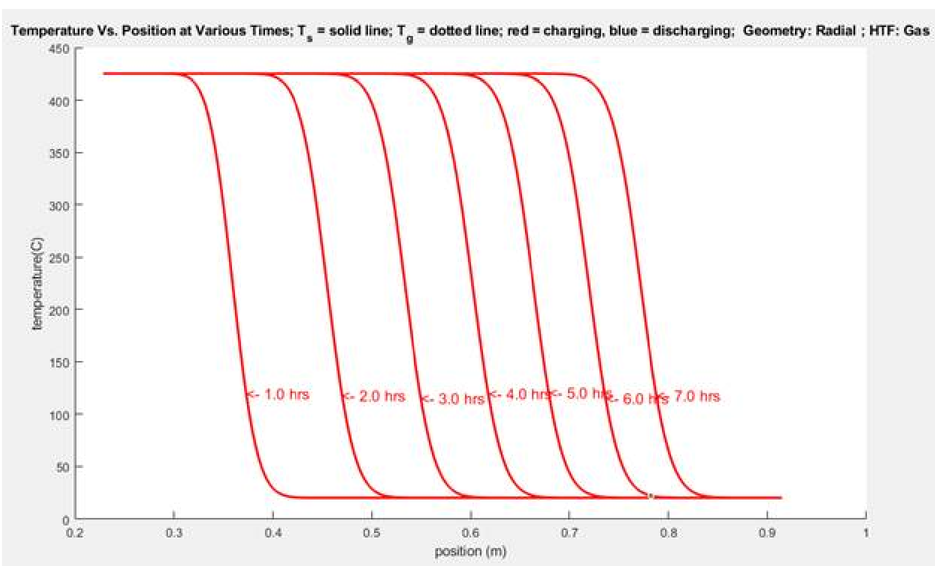

Figure 5. Simulated thermocline evolution.

The influence of buoyancy and injection well hydrodynamics on the axial temperature gradient within the packed-bed was assessed for dynamic states by comparing the measured thermocline profiles at the top middle and bottom of Section A at hours 1 and 5 of bed charging and discharging. The result for charging is shown in Fig. 6. Good agreement is observed between the bottom, middle, and top thermoclines at hours 1 and 5. A similar result was observed during discharging. These results suggest that buoyancy had negligible effect on the thermocline over the duration of bed charging and discharging. An assessment of buoyant effects during holding periods will be considered during future testing to fully capture the influence of buoyancy on the radial packed-bed proposed in this study.

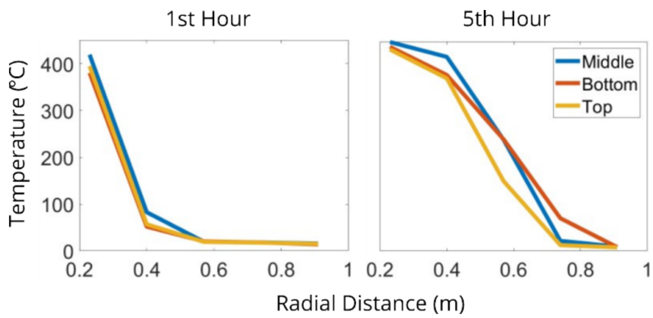

Figure 6. Section A thermoclines at the bottom, middle, and top axial planes at hour 1 and 5 of the charging cycle.

Performance metric 1, involving the development of a thermocline, was met during shakedown testing as a temperature difference of >400 °C was observed over the radius of the packed-bed (615 °C/m). Although a thermocline was developed, the gradient of the thermocline must be improved to reduce exergy loss and improve overall storage efficiency. It is hypothesized that greater air flow through the packed-bed will improve the thermocline due to increased convective heat transfer compared to conductive heat transfer. Repetitive thermal charge-discharge cycling is also a well-known significant factor contributing to thermocline degradation. A less steep thermal gradient poses a challenge to the exergy efficiency as stated earlier in the paper, and this influence will be studied in future work.

Performance metric 2, involving the achievement of a 500 °C injection temperature, was not met during the initial shakedown testing. A peak injection temperature of 450 °C, however, was achieved. This result is within 10% of the targeted temperature and resulted in a heating power of 26.5 kW_{th}. To achieve the 500 °C injection temperature, the propane air heater design will be modified. Specifically, the 5 cm diameter air duct within the propane tube furnace will be increased to 10 cm to increase heat transfer surface area and slow the flow velocity. This modification will improve the system in two ways: 1) Increase injection well temperature and 2) Decrease the pressure drop through the heated air duct resulting in an increased air mass flow rate through the packed-bed.

Performance metric 3, involving minimal buoyancy and hydrodynamic effects within the injection well, was met for bed charging and discharging. A near negligible axial temperature gradient was observed during charging and a small (<167 °C/m) axial temperature gradient was observed during discharging. This influence, however, must be investigated during a system hold between charging and discharging.

Performance metric 4, involving the durability of the storage media, could not be assessed during the shakedown testing. Limited number of test cycles were performed, thus additional testing is required to assess the attrition of 3/8" pea gravel.

Conclusions

This study presented the design, shakedown testing, and modeling of a 100 kWh_{th} radial packed-bed thermocline. Preliminary shakedown testing demonstrated the formation of a thermocline within the radial packed-bed; however, thermocline length should be decreased by increasing the HTF mass flow rate through the packed-bed. Minimal temperature variation was observed at the bottom, middle, and top axial locations, and the temperature was uniformly distributed through the height of the radial packed-bed. This result suggested that buoyancy and hydrodynamics within the injection well had a minimal effect on the system during charging and discharging. The measured charging temperature was within 10% of the target and a charging power of 26.5 kW_{th} was achieved. The findings of this study suggest an increased air duct diameter through the propane heater will increase the injection well temperature and increase air mass flow through the system. Modeled and measured results were compared, and it was determined that the experimental system cannot be accurately represented by a plug flow model as currently developed. A more comprehensive CFD model will be developed to better understand the air flow and thermocline evolution within the packed-bed. The experiment will be modified to allow for faster charging and for multiple tests in future work, and the influence of bed charging rate, gravel size, number of cycles, and storage time on thermocline length will be investigated.

Competing interests

The authors declare no competing interests.

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