Combined mechanical and thermal loading of a hot air-packed rock bed -a test rig for thermal energy storage

F. Elsayed[1], H. Laubscher[1], K. Allen[1], F. Dinter[1]
Department of Mechanical & Mechatronic Engineering, Stellenbosch University, South Africa
frankdinter@sun.ac.za
Tel: +27 (0)21 808 4024

Abstract

There is a lack of extensive studies in thermal energy storage literature on the influence of temperature on the mechanical behavior of rocks or industrial waste in packed bed thermal energy storage (TES) concepts; none report experimental data published on the degradation of rocks upon combined thermal & mechanical loading imposed by weight of upper rock stack.
In this study a test rig is built for testing an air-rock bed thermal energy storage (TES) concept under realistic loading conditions by thermal cycling to 500-600°C with a heating rate of 2°C/min under high mechanical load (24 tons>240 kN using heavy duty compression springs) simulating more realistically the performance of a rock bed and the technical challenges that are present in terms of rock integrity under combined thermal and continuous mechanical load imposed by the weight of 15m of rocks on the bottom rock stack. The test rig would be the first time to simulate the actual harsh loading conditions for a large MW scale rock bed TES concept. Rock cracking and disintegration into smaller pieces will be evaluated using sieve sheets similar to the technique used in civil and mining industry to classify granular materials size. Additionally, the mechanical integrity of the rocks will be evaluated by visual and weight loss measurements.

Keywords: Thermal Energy Storage; Hot air; Packed rock bed; rock integrity.

1. Introduction

Concentrating solar power (CSP) plants are gaining more importance as a contributor into the renewable energy mix. In particular, thermal solar storage is the main attractive feature of CSP in comparison to PV and wind energy power plants as the output of the plants can be decoupled from the sun presence following the peak demand in evening hours. Grid operators can now think of CSP plants as peaker plants that help peak the increased demand in particular hours. In order to supply power to meet demand at night or when the sun is obscured by clouds, CSP plants need thermal energy storage (TES). Currently, two-tank molten salt thermal energy is the used system which has been commercially proven and is considered “state of the art” [1]. At present it is relatively expensive – Kolb et al. estimated that, for their reference central receiver plant, it can contribute about 11% to the normalized cost of electricity [2]. Thus there is good reason to seek lower-cost thermal storage alternatives.

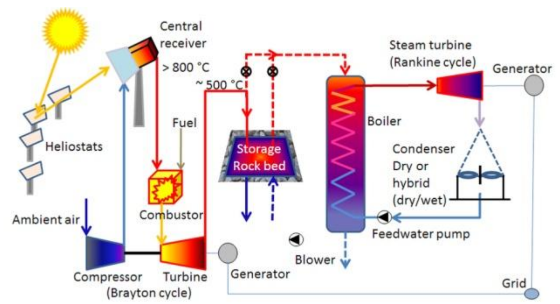

Fig. 1. SUNSPOT cycle solar power plant schematic [2].

One such alternative is a rock bed, see Fig. 1, which makes use of air as the heat transfer fluid.The Stellenbosch University Solar Power Thermodynamic (SUNSPOT) cycle uses solar power to generate electricity during the day and stores hot air in a thermal storage facility for power generation at night. Air and rock are low-cost, readily available materials that potentially allow for cheaper storage systems than molten salt systems.

The rock bed concept is suitable for use upstream of a steam Rankine cycle as shown in Figure 1. The heated air from a central receiver or gas turbine exhaust is forced through the rock bed by means of a fan. During discharging, the air flow direction is reversed and the fan blows cold air into the bed. This air is heated up and subsequently used to produce steam in a boiler.

One important aspect to address when dealing with thermal cycling of rocks is their thermal stability. Cracking and disintegration of the rocks due to thermal instability can result in significant pressure drop over the thermal storage bed with subsequent increased pumping costs. [2,3]

2. Rock Bed Storage Concept

The rock bed storage concept is shown in Figure 2 [5]. The hot air is introduced into the rock bed from the centre of its base by means of a duct. The air then flows outward to the surface of the bed and is exhausted to the atmosphere. The rock pile could be covered by a containment structure, which must be air-tight if there is a blower on the cold side. If a blower is placed on the hot-side, the roof can be permeable, and is only needed to keep debris and moisture off the rock bed. It can be dispensed with altogether.

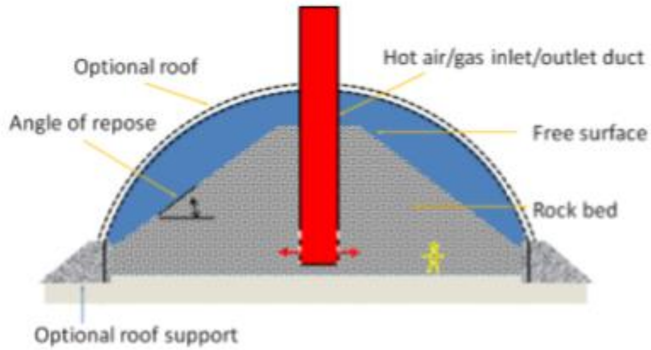

Fig. 2. TES rock bed concept [4,5]

The main advantage of this system is that the thermal energy is stored at the centre of the bed. Consequently, the containment dome needs no insulation. However, there are difficulties that need to be considered and overcome: Destratification of the rock bed may occur, especially over longer periods of time, because hot air tends to rise within the rock bed due to buoyancy effects. The distance from the duct at the base of the bed to the surface is not constant. This will result in uneven airflow distribution, leading to sub-optimal use of the rock. This will be exacerbated by rock particle orientation.

Despite these problems, it is well-worth considering the concept because it almost eliminates the need for thermal insulation, which is more expensive than rock fill. [4,5]

2.1 Experimental TES Rig at STERG

A packed rock bed thermal energy storage (TES) basic test facility was built at STERG, Stellenbosch university to perform different thermal charging-discharging cycles on 2.5 tonnes of rocks. The rig is shown in figures 3. A diesel burner is used for the tests with an automatic controller. Dolerite rocks of average size 75 mm are used in the packed rock bed.

Fig. 3. Packed rock bed test facility, STERG, Stellenbosch University.

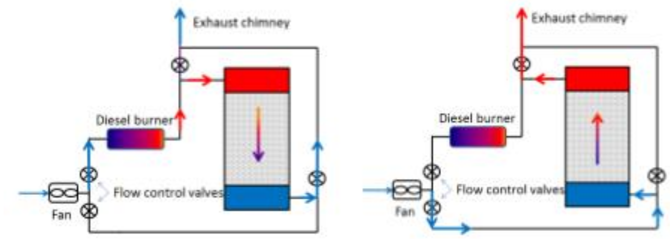

Fig. 4. Schematic of air flow direction in the TES test rig.

The air flow direction through the bed is fully reversible, as illustrated in Figure 4. To reduce capital and operating costs same blower is used for charging and discharging, and the blower is on the cold air side. Typical storage temperatures are of the order of 500-600 °C.

2.2 Packed rock bed technical challenges

The rock storage material faces multiple technical challenges to sustain the different thermal and mechanical loads imposed by the thermal charge-discharge cycles.

- First Challenge: The rocks must sustain hundreds of thermal cycles without significant cracking or disintegration, and to ensure their stability a number of tests were performed to test their stability upon different heating rates and temperatures. Also different types of rocks including dolerite, sandstone, and Gneiss were tested to select the most suitable rocks for this application. Dolerite was chosen as it showed superior resistance to disintegration upon thermal cycling. built at STERG, Stellenbosch university to perform different thermal charging.
- Second challenge is the chosen rock type must sustain a high level of mechanical load imposed by the huge rock stack in a $MW_{thermal}$ scale TES concept. The rock integrity must be sustained under combined thermal and continuous mechanical load imposed by the weight of at least 15-25m stack of rocks on the bottom rock layers. The rock needs to have sufficiently high compressive strength so that the bottommost layer does not crush under the load of the rock above it.

  For a packed bed 25 m high, the average load at the bottom would bein order of ~ 1 MPa for a rock density of 3000 kg/m3. However, the point loads between individual rock particles could exceed the average load significantly, and additional loads could arise from thermal expansion of the rock increasing the risk of rock de-fragmentation and disintegration.

With an average density of 3000 kg/m3 and stack density of 1600 Kg/m3 the point to point stress on bottom stack rocks is a major concern fo the rock integrity to prevent their defragmentation and disintegration causing major pressure drop.

3. Experimental Test Rig design

In order to simulate the high mechanical load imposed simultaneously with thermal cycling a test rig has been designed and is in the implementation stage to test the integrity of the rocks within thermal cycling to 500C and under a mechanical load of ~240 kN. A schematic of the test rig showing different components is shown in Fig.5

- A grade 316 stainless steel test chamber will be inserted in the existing TES test rig utilizing the existing infrastructure of the rig body, thermal insulation and heating source (diesel burner).
- The test chamber is cubic with 0.95*0.95m and has a volume of 0.86 m3.
- Stainless steel metal grates are used for the top and bottom sections of the chamber to allow unrestricted air flow into the rocks.
- Using the calculated stack density of the dolerite rock bed of 1600 kg/m3 a total mass of 1380 Kg of rocks are encased in the test chamber.
- Mechanical loading is achieved using a linkage mechanism with a movable front loading plate and the load is achieved using 12*20 kN Fmax heavy duty mild steel compression springs to give a total force of 240 kN. The loading is performed externally so as to place the springs outside of the heated section as to protect them and maintain their spring effect as most steel springs have a maximum useful service temperature of 200°C

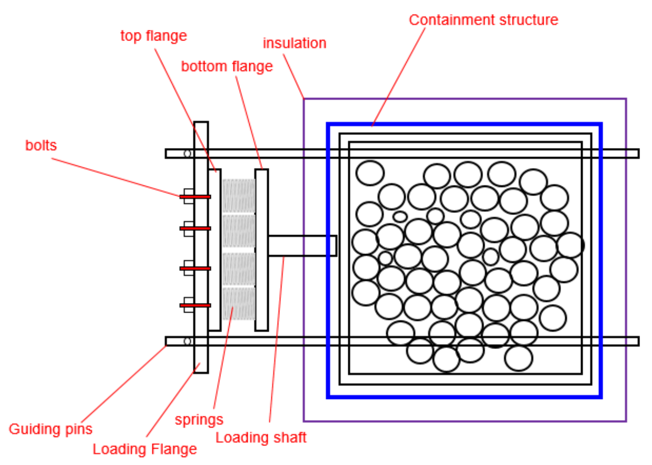

Fig. 5. Test Rig schematic for combined mechanical and thermal loading of packed rock bed.

4. Experimental Findings

The test rig is in final stage of implementation and would be the first time to simulate the actual harsh thermal and mechanical loading conditions for a large MW scale rock bed TES concept.

The mechanical integrity of the rocks will be evaluated by:

- Visual inspection of the rocks after testing
- Weight loss measurements.
- Size retention characterization using sieve sheets (rock cracking and disintegration into smaller pieces will be evaluated using grated metal sieve sheets similar to the technique used in mining industry to classify mean rock sizes). An automated sieve machine is available in civil engineering faculty at Stellenbosch University and will be utilised to characterize the rocks after testing. Sieve machine shown in Fig.6

Fig. 6. Automatic Sieving machine with different sized sieve sheets for size classification of granular materials.

Acknowledgements

The authors would like to thank Mr Cobus Zietsman for the helpful discussions during building the experimental rig.

References

[1] Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011. SANDIA report: *Power tower technology roadmap and cost reduction plan*, SAND2011-2419, Sandia National Laboratories, Albuquerque.

[2] K.G. Allen, T.W.vonBackström, D.G.Kröger, A.F.M.Kisters "*Rock bed storage for solar thermal power plants: Rock characteristics, suitability, and availability*" Solar Energy Materials & Solar Cells 126 (2014) 170-183.

[3] K.G. Allen, T.W. von Backstrom, D.G. Kroger "*Rock bed pressure drop and heat transfer: Simple design correlations*" Solar Energy 115 (2015) 525-536

[4] T.W. von Backström, K.G. Allen, E.C. Joubert, "Rock Bed Thermal Storage" Report 3-"Initial design of a pilot scale thermal storage system"

[5] Gauché, P., 2014. Thermal Energy Storage Facility, South African provisional patent 2014/03555

[6] Kenneth Guy Allen,"Rock bed thermal storage for concentrating solar power plants " PhD thesis, Stellenbosch University 2014