DEVELOPMENT AND DESIGN OF AN EXPERIMENTAL FACILITY FOR COST EFFECTIVE THERMAL ROCK BED STORAGE SYSTEMS

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Abstract

Thermal energy storage (TES) is an integral driver for low cost concentrated solar power (CSP). The developing and testing methodology of a cost effective TES system is covered in this study. The heat transfer fluid (HTF) is air and the storage material is a conical shaped packed bed of rocks stacked at the natural angle of repose. Design of an experimental setup for testing the proposed concept is done in this study. Focusing on cost reduction by design for simple manufacturing methods and local materials makes the concept under consideration the best locally developed concept for cost effective thermal energy storage. Prediction of the heat transfer characteristics in the packed bed based on parameters obtained in previous characterizations of the system is considered and the feasibility of an industrial ready system is investigated.

Keywords: Packed bed; storage material; natural angle of repose

1. Introduction

The goal of decreasing the cost of thermal energy storage in CSP is to decrease the levelized cost of electricity (LCOE) and to enable the supply of electricity to meet demand. The concept tested and developed in this study was proposed by Gauché [1]. Since the storage segment in a power plant can contribute up to 11% of the LCOE [2], lower-cost TES methods can have a significant influence in the cost at which electricity can be produced. With the potential to produce cheaper base load electricity from renewable energies, the decision makers in the solar industry can create new feed-in schemes.

When considering cost reduction of any large scale (100 MWh_{th}) TES system, the insulation of the media at high temperatures makes up approximately 33% of the total cost of the TES capital expense [3]. Because the concept under consideration does not require any insulation, the potential cost reduction for an industrial scale thermal storage system can bring the cost of TES down to a range of 5-8 USD/kWh_{th} installed [3]. This can be contrasted to the cost of two tank molten salt storage which is in the order of 22-30 USD/kWh_{th} [4]. A computational fluid dynamics model for calculating the heat transfer to and from the packed rock bed is developed using ANSYS Fluent (CFD). The temperature profile prediction can be illustrated by making use of Effectiveness-NTU method of Hughes (1975) [5], Duffie and Beckmann (1991) [6].

2. Experimental Setup Design

2.1. Experimental Layout Description

The experimental design for a thermal energy storage test facility on the Helio100 site (property of Stellenbosch University) is done during this study. A pile of locally available rocks is used to form the bulk of the storage material. Table 1 shows a summary of the physical rock properties and other parameters of the physical layout.

Rock Properties	Value	Symbol
Density	2650 kg/m^3	ρ
Thermal Conductivity	1.5 W/mK	k
Heat Capacity	820 J/kgK	C_p
Void Fraction	0.45	%
Equivalent Particle Diameter	40 mm	D_v
Natural Angle of repose	38°	θ
Average rock size	53 mm	--

Table 1: Physical properties of the Rocks

2.2 Illustration of Experimental Setup

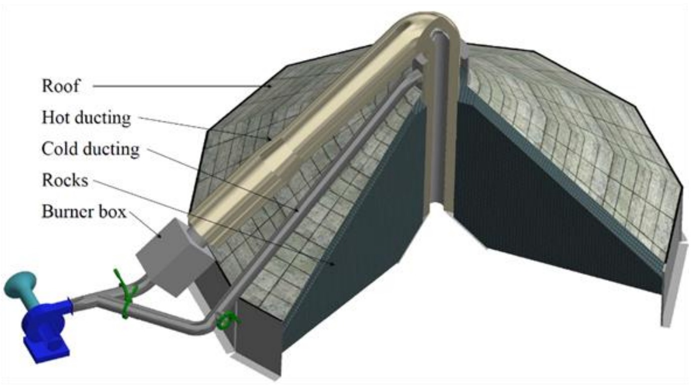

Fig 1: Cut out drawing of the experimental design

A layout drawing of the experimental rig is shown in Fig 1. A cut out of the internal structure is displayed to indicate where the air flow would go during operation of the experimental rig. The whole containment structure must be airtight to enable the fan to run on the cold air side in both charging and discharging modes.

2.3 Design for Installation/ Maintenance

Design of a structure to minimize the cost, but not compromise the potential life-cycle of the system requires careful consideration. The phenomenon that occurs when the rocks are put in a closed constraining structure and thermally cycled is called ratcheting. To minimize the effect of ratcheting, the pile of rocks is stacked at the natural angle of repose with only minimum structure to keep the roof in place. In the case of a large scale packed bed of rocks, there exist a possibility that the storage material (crushed rock) needs to be replaced in 5 or 10 years if the material breaks down over time under the huge mechanical loading of the of the material above.

2.4 Design Description of Airflow

For this experimental setup crushed rock that is available in a standard size is used. The average void fraction of the rocks as given in Table 1 is 0.45 and is used as the design value for the air inlet at the bottom of the cone. Inlet air velocity need to be kept under a certain threshold to minimize the pressure losses of the airflow. The largest fraction of the pressure drop occurs at the centre of the conical pile of rocks, therefore the inlet velocity is designed to be under 1 m/second.

2.5 Design Parameters of the System

Parameters that quantify the design objectives of the TES system are summarised in Table 2.

Design Parameter	Value
Heating capacity	400 kW$_{th}$
Storage time	(5-8) hours
Total Energy Storage	1.5 MWh$_{th}$ - 2.5 MWh$_{th}$
Fan Power	5.5 kW
Rocks Weight	70 000 kg
Max Charging Temperature	550 °C – 600 °C
Max Outlet Temperature	40 °C – 60 °C
Rock bed Footprint Size	7 m Ø

Table 2: Design Values of the Experimental System

3. Numerical Calculation

3.1 Mathematical Correlations

Mathematical correlations used to calculate the distribution of the temperature as well as the pressure drop over a porous medium have been investigated to a great extent in previous studies. Special correlations formulated for this specific particle size, geometry and void fraction are covered in the above mentioned studies [2]. Due to the poor heat transfer characteristics between air and rock, the particle size should be chosen to have the best ratio between convective heat transfer on the surface of the particles and the internal heat conduction through each particle. The Biot number, *Bi*, is used to quantify the heat transfer on the surface of the particles relative to the internal conduction coefficient of the particle in the porous media.

The Biot number is a function of the equivalent volumetric diameter, D_v, of the particles and also the overall surface-area heat transfer coefficient, h and the particle conductivity, k_p.

$$Bi_v = \frac{hD_v}{2k_p}$$

Heat transfer and flow calculations in a packed bed of rocks have been investigated and studied in previous work done by Allen *et al* [2]. The Effectiveness-NTU (E-NTU) method as developed by Hughes [5], Duffie and Beckmann [6] proves to be a simple and effective method of predicting the temperature profile. See Fig 2 for the predicted temperature profile, with the fully charged state of the heat transfer fluid and also the storage medium illustrated.

$$Nu_v = \frac{hD_v}{k} = Re_{pv}^{0.6}$$

$$Re_{pv} = GD_v/\mu$$

3.2 Numerical Results

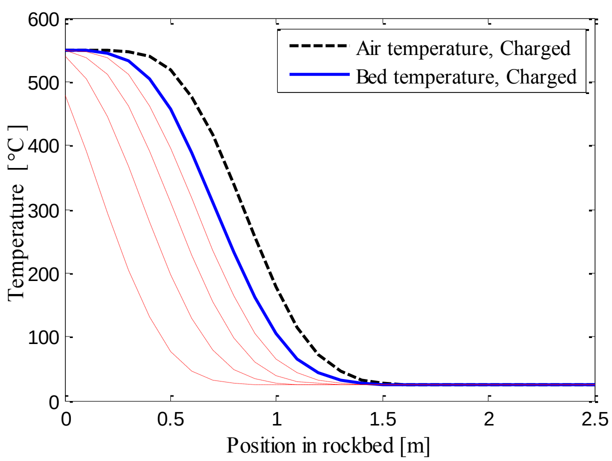

Fig 2: Temperature distribution prediction over packed bed showing the hourly progression lines of the charging

4. Cost reduction Potential: Packed Rock Beds

The potential cost reduction of thermal energy storage can be illustrated in the graph in Fig 3. State of the art two tank molten salt systems used in industry have an average price of 22 USD/kWh$_{th}$ - 30 USD/kW$_{th}$ for installed capacity [4]. The cost of three different concepts of packed rock bed TES is compared with the installation cost of molten salt TES. Cost analysis on these three concepts has been done in previous studies and has been documented in an internal report at the Mechanical and Mechatronic Engineering department of Stellenbosch University. The concept that is being developed in this project is the concept 2a. At a smaller scale of thermal storage capacity (smaller than 100 MWh$_{th}$), the packed bed of rocks is predicted to be more expensive than conventional molten salt systems. For utility scale TES, the potential cost for installed thermal storage capacity with using a packed bed of rocks as storage medium is much lower in comparison with the molten salt TES.

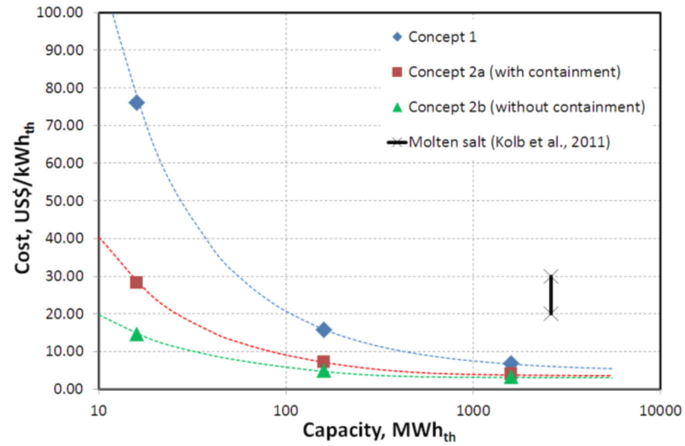

Fig 3: Cost comparison of different thermal energy storage concepts. Concepts 1 and 2 are both for a packed rock bed as the storage medium [7].

5. Measurements for numerical Validation

5.1 Measurements

The experimental setup would be used for gathering experimental data to use as validation of the results produced by numerical simulation. The volumetric flow rate of the heat transfer fluid (air) through the porous media would be monitored and recorded. The volumetric measurement along with the temperature of the air at the point of measurement would be used to calculate the mass flow rate of the air. The energy put into the storage media (rocks) would be calculated by the enthalpy transferred to the rocks. Hot air with the characteristics of an ideal gas is used to calculate the energy flux transferred into the rocks. Measured air temperature at the outlet side of the rocks would be logged to calculate the enthalpy of the air again and the difference in the enthalpy of the air would be the enthalpy that was transferred to the rocks.

The cycle efficiency is defined as the efficiency of the heat recovery on a round-the-clock basis. The energy stored in the storage media and the energy recovered from the storage would be used to calculate the cycle efficiency of the TES.

The thermocline in the storage media would be measured with type-K thermo couples. Two vertical planes in the conical pile would be measured to check for symmetry of the temperature distribution and to have two sets of thermocline data

5.2 Symmetry: Numerical Model Simplification

In designing a system that should be potentially industry ready, there are various cases where symmetry can be implemented in the modelling or the of the system operation. Measurements of temperatures are expected to be similar around the centre axis of the conical pile of rocks. A recent CFD simulation shows that the temperature distribution inside the thermal energy storage approaches symmetric behaviour around the centre vertical axis of the conical pile. Fig 4 shows a qualitative temperature distribution in the packed bed of rocks, which is predicted by CFD simulation. Real measured temperature values will be shown in a following publication, when the CFD model is verified with the measured experimental data.

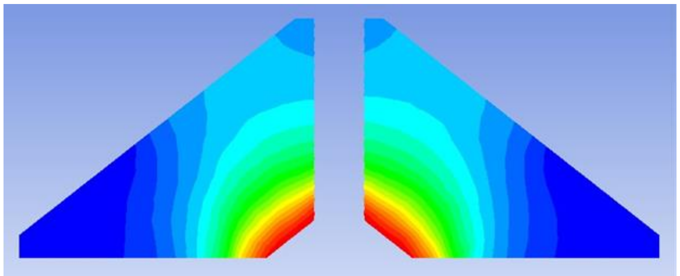

Fig 4: Qualitative temperature distribution in the packed rock bed, results produced with ANSYS Fluent

5. Conclusion

Experimental design and construction of an experimental setup is a huge investment in future projects of the research group. In the research environment, experimental data are something concrete that can be used to validate simulated data or data obtained from analytical calculations. Test preparation for the thermal energy storage facility is in process and cost reduction of the material choices and also the manufacturing processes are taken into account to make the design as cost effective as possible.

Packed rock bed thermal energy storage has the potential to significantly decrease the LCOE in CSP, provided that the heat recovery of the experimental setup is adequate. An experimental design and development of the proposed concept, to store thermal energy, in a packed bed of rocks is a result of this study. The viability of the proposed concept is validated via results of an experimental setup as well as CFD simulation. At this stage, only simulated and predicted results are available. At the end of the study it would be clear if this concept is economically viable on an industrial scale.

Acknowledgements

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