DESIGN AND DEVELOPMENT OF A NEXT GENERATION THERMAL ROCK BED STORAGE EXPERIMENTAL FACILITY

Stephanus J Erasmus[1], Theodor W von Backström[2], Matti Lubkoll[3] and Frank Dinter[4]

[1] Solar Thermal Energy Research Group (STERG), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa; 16946618@sun.ac.za

[2] Solar Thermal Energy Research Group (STERG), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa; twvb@sun.ac.za

[3] Solar Thermal Energy Research Group (STERG), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa; matti@sun.ac.za

[4] Solar Thermal Energy Research Group (STERG), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, South Africa; frankdinter@sun.ac.za

Abstract

The value of concentrating solar power (CSP) plants lies in dispatchability, which is provided through an integrated cost effective thermal energy storage system (TESS). A TESS consisting of a rock bed has the potential to reduce storage capital costs significantly, compared to current state of the art molten salt TESS.

Further improvement of the Stellenbosch second generation rock bed design, for significant cost reduction, has previously been developed and built at Stellenbosch University (SU). This project focuses on improving the performance of the second-generation rock bed TESS, through partial re-design, predominantly aiming at maximizing the usable rock mass.

The purpose of rock bed TESS is to find an alternative, low cost thermal energy storage system that is as effective and efficient as other conventional storage systems that are being used in the CSP industry. This paper presents an improved design contributing to cost reduction by the increase of usable rock mass, based on a previous SU design.

Keywords: Rock Bed; Thermal Energy Storage; TESS; Low Cost, Concentrating Solar Power, CSP

1. Introduction

Currently, molten salt is primarily used for the purpose of thermal energy storage in CSP Plants. By making use of a rock bed TESS, storage costs can be reduced.

Thermal rock bed storage forms part of seasonal sensible thermal energy storage systems. These systems include hot-water thermal energy storage, aquifer thermal energy storage, borehole thermal energy storage and gravel-water thermal energy storage [1]. This project will focus on thermal rock bed storage and build on previously completed projects [2].

1.1. *Motivation*

Molten salt is primarily used as the heat transfer fluid for TESS in the industry. It is regarded as a state of the art method of thermal energy storage and works on the principle of sensible heat.

The motivation is to generate and build a thermal energy storage concept that is more cost effective than molten salt storage, without decreasing the efficiency of the system [3]. It can be concluded that, after the completion of the previous project, there is still progress to be made regarding the research of thermal rock bed storage.

By taking the current facility and improving on the design, the facility is expected to reach better efficiencies regarding thermal storage and volumetric efficiency, defined as the percentage of the total rock mass that is active storage material, with the capital expenditure and levelized cost of electricity (LCOE) being reduced.

1.2. *Objectives*

The objectives of the project are to:

- Minimize the thermal loss of the current facility.
- Improve the facility in such a way that it operates as a storage facility with an idle period.
- Improve the heat recovery efficiency.
- Improve the volumetric efficiency.
- Maintain an economic feasible TES facility.

2. Literature Review

2.1. Rock Bed TESS

The first commercial high temperature rock bed TESS was built in Morocco, with air as a heat transfer fluid. The facility was commissioned in 2014, with test results concluded that air can successfully be used as heat transfer fluid [4]. The facility design is illustrated in Figure 1.

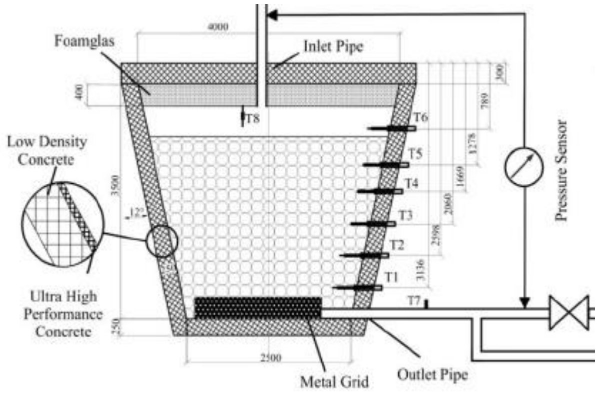


Fig. 1. Design of the first rock bed TESS [4]

The search for a more economical solution regarding storage has been ongoing at the University of Stellenbosch since the year 2010 [3]. This includes detail studies on various elements of thermal storage that include the pressure drop over a packed rock bed for various shapes, formations, void fractions and sizes [5].

In 2013, the concept illustrated in Figure 2 was proposed [6]. This concept was patented on the design and layout of a thermal rock bed storage system. Hot air is introduced into the top of the rock bed, with cold air leaving the rock bed at the bottom, forming a thermocline with the hot air section at the top and the cold section at the bottom of the rock bed. The rock bed is covered with a solid containment structure, insulating the rock bed from ambient conditions.

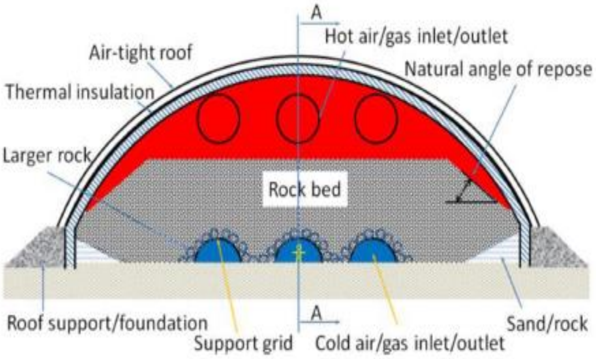


Fig. 2. Rock bed concept with a solid containment structure [6]

A second concept was developed, illustrated in Figure 3 [7]. The concept entailed simplifying the previous concept to make it a more economical option. This entailed removing the insulation from the concept, cutting a large portion of the costs. Another change sees the hot air being introduced to the center bottom of the rock pile. This affects the development of the thermocline: the hot section of the thermocline is now on the inside of the rock bed, with the cold section on the outside. The temperature thus decreases from the center of the rock bed to near ambient temperature on the outside layer of the rock bed. This allows for the absence of insulation, since the outside layer that is part of the cold section would act as the insulation of the hot section. The concept also contains an optional cover over the rock pile to protect it from outside elements such as rain and wind.

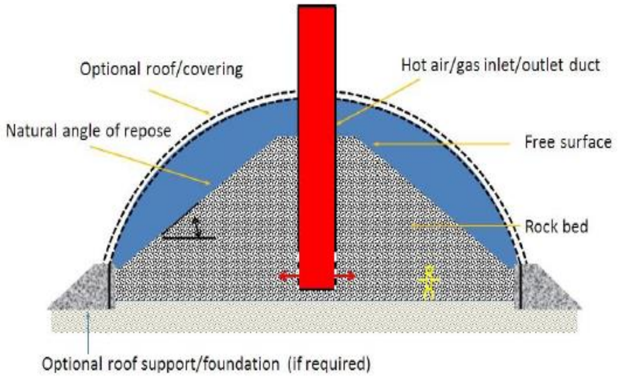


Fig. 3. Rock bed concept [7]

The drawback identified with this concept is that buoyancy causes the hot air administered to rise and dissipate into the atmosphere in the event of long-term thermal energy storage. Discharging of the hot air would entail reversing the flow direction of the air, sucking the air back into the duct and out into the pipe that previously supplied the hot air into the rock bed.

In [2] this concept is described in detail and predictions regarding the distribution of the hot air within the rock pile are made: due to increased pump power, heat would potentially move to areas within the rock pile that would make the heat irretrievable, allowing dead zones to form within the packed rock bed [2].

2.2. Existing Facility

The existing facility, based on the concept in Figure 3, was successfully developed, built and commissioned at the Stellenbosch University Renewable Energy (SUNREC) site outside of Stellenbosch, Western Cape, South Africa and is illustrated in Figure 4.

Fig. 4. SU rock bed TESS

After commissioning of the facility, it was recommended that more accurate CFD modeling needed to be done on an adaptation of the concept. An adaptation must ensure a more efficient heat recovery as well as a more stable thermocline at a charged state. Another recommendation was to add insulation to the concept. The insulation would increase the capital cost of the concept, but with the correct design and better heat recovery, the concept would still be cost effective. With the old concept, long-term storage is impossible. The above recommendations are expected to make long-term storage possible [2].

3. Concept Re-Design

3.1. Concept

A new concept was developed on the recommendations made in section 2.2. Figure 5 illustrates the concept.

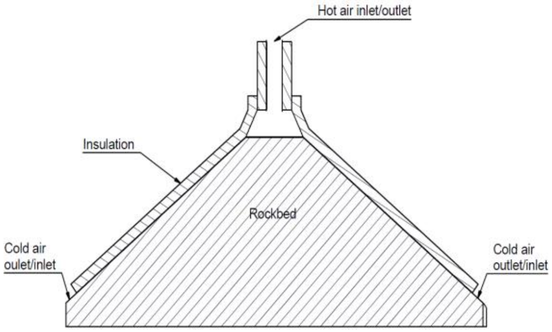


Fig. 5. Re-designed concept, depicting the charge cycle

The evaluation process is based on:

- Whether the concept will be able to achieve the objectives.
- Can the concept be implemented onto the existing facility?
- Ease of construction.
- Does the concept provide suitable heat transfer characteristics?

The concept differs from [7] in two major aspects. Firstly, the hot air is introduced at the top of the rock bed with the cold air exiting at the bottom, which is expected to relatively evenly distribute the heat through the rock bed, causing the thermocline to progress linearly downwards. Secondly, insulation is added to the rock bed to reduce thermal losses. To extract the thermal energy from the rock bed, air is sucked into the rock bed through the cold air inlet, with hot air exiting through the hot air outlet. The concept is designed to be able to use more of the rock mass, increasing the volumetric efficiency of the TESS.

The insulation will be installed as illustrated in Figure 6. From the right-hand side of the figure the mesh is illustrated, followed by 3 layers of insulation which will be stacked on each other to better insulate the rock bed. By adding cladding to the outside of the third layer, the insulation is protected from ambient elements.

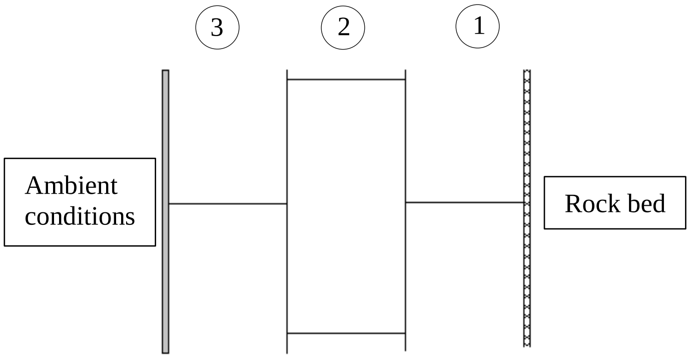


Fig. 6. Insulation layers

3.2. Adaption for Experimental Setup

Implementation of the concept on the existing facility means an adaption of the concept is necessary. The existing facility possesses a tarpaulin cover, seen in Figure 4, that protects the rock bed from ambient conditions such as rain and wind. The facility makes use of a fan that blows air, while the concept makes use of a fan that both blows and sucks air. The concept is adapted to allow for the use of both the tarpaulin cover and blower, with the final concept shown in Figure 7. The figure illustrates the charge cycle, with the discharge cycle being the reverse thereof.

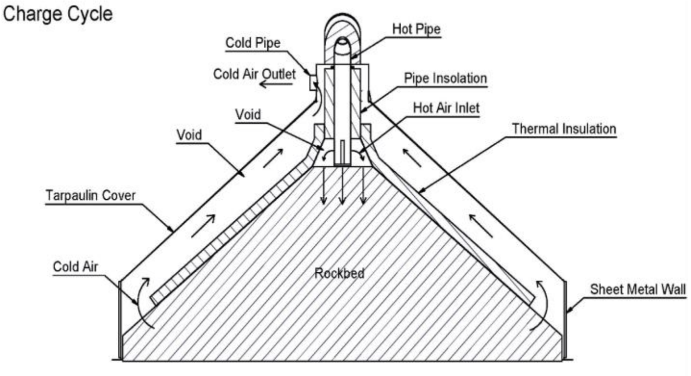


Fig. 7. Final concept [8]

4. Construction

The construction, followed by the experimental testing, was done in parallel with the development of an analytical model for the experimental facility, which is discussed in section 6.

4.1. Construction

The main construction procedures are depicted in an array of figures with an explanation following each figure.

Fig. 8. Modification of hot air inlet pipe

The hot air inlet pipe is modified to ensure that the hot air is introduced into the top of the rock bed. Slots are cut into the pipe and bent, to ensure that there is material left to seal the slots, if needed, in the future. The pipe is also sealed just below the slots to prevent any air from flowing into the pipe and into the bottom of the rock bed.

Fig. 9. Frame installation

After manufacturing the frame sections, which serves as a support structure for the mesh, the sections are installed onto the rock bed. The frame contains nails that are used to fix the insulation onto the mesh. The frame also offers a structure to move up and down the rock bed during fitment of the insulation.

Fig. 10. Rock preparation

To limit air flow between the mesh and the rock bed, the rocks were manually shifted into any gaps situated in this area.

Fig. 11. Fitment of insulation

Insulation layers are fixed onto the mesh by making use of the nails. The insulation is cut into shape prior to fitment, to ensure that the layers are stacked as illustrated in Figure 6.

4.2. Leak Testing

To ensure that the insulation is working effectively, a leak test was done. The leak test entailed charging the rock bed and then monitoring the outside of the insulation to look for any thermal losses. Figures 12 and 13 illustrate two spots that were identified. These spots were fixed.

Fig. 12. Hot spot 1

Fig. 13. Hot spot 2

5. Experimental Test Results

Insight into a test campaign is provided here. The experimental conditions can be found in Table 2. The experiment was conducted on the completed rock bed TESS facility.

Parameter	Experimental	Units
Average charge mass flow rate	0.53	kg/s
Average discharge mass flow rate	0.3	kg/s
Charge time	8	hours
Discharge time	28	hours

Table 2. Experimental conditions

The test entailed a charge cycle followed by an immediate discharge cycle. The information in Table 2 gives the durations of each stage, as well as the flow rate for both the charge and discharge cycles. The flow rate was closely monitored and kept constant by measuring the pressure drop over the bell mouth at fan inlet. Heat is supplied by a burner, using liquid petroleum gas (LPG). Dolerite with an average particle diameter of 50mm is used during experimental testing.

The temperature was measured at 50 different points throughout the rock bed, using a stainless steel pipe frame setup of 25 thermocouples at two different locations in the rock bed. Figure 14 illustrates the points of each thermocouple on a grid. The average of the data collected is then used for analysis.

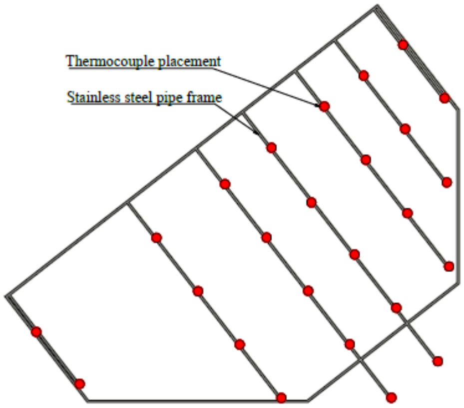
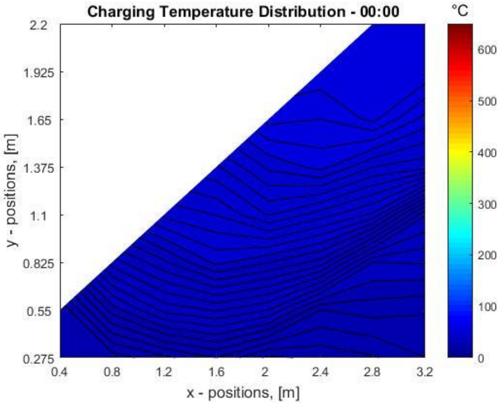


Fig. 14. Thermocouple layout

Figure 15 illustrates the rock bed temperature distribution before the charge cycle commenced. The rock bed temperature was at 60 °C.



f

Fig. 15. Rock bed at charge cycle start

The charge cycle lasted a total of 8 hours, however 20 minutes before the end of the cycle, the gas bottles emptied out, cold air got blown into the rock bed and as a result the rock bed temperature distribution changed as illustrated in Figures 16 and 17. The average air inlet temperature was 618 °C during the 8 hours.

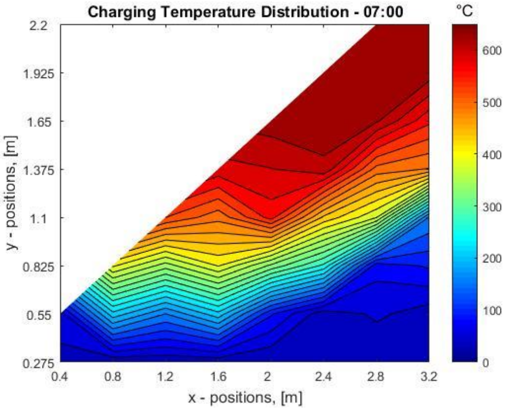


Fig. 16. Charge cycle – 7 hours

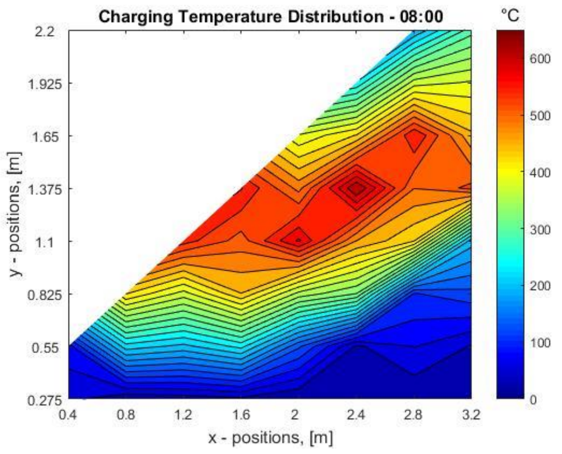


Fig. 17. Charge cycle – 8 hours

The temperature distribution of the rock bed at the start of the discharge cycle is the same as in Figure 17. Figures 18 and 19 illustrate the progression of the temperature distribution during discharge.

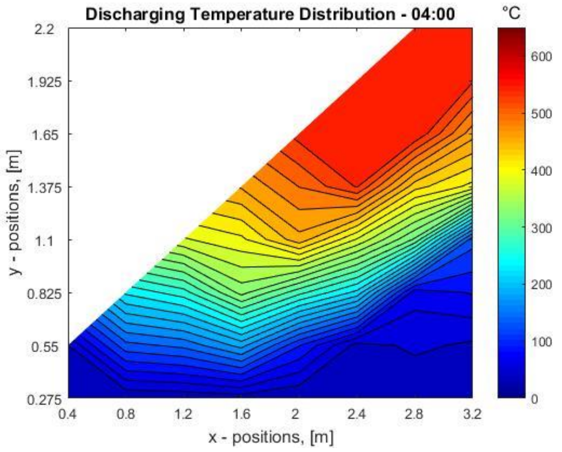


Fig. 18. Discharge cycle – 4 hours

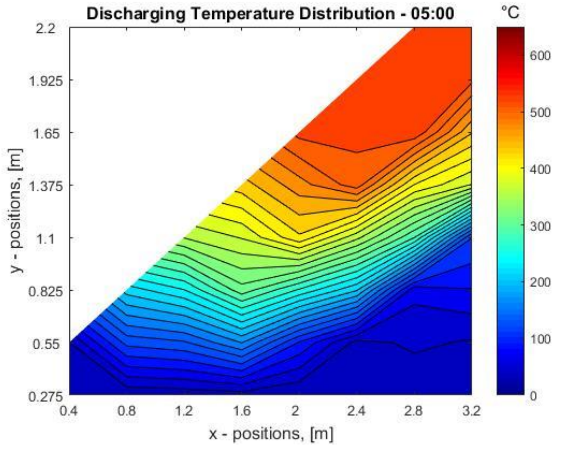


Fig. 19. Discharge cycle – 5 hours

From the figures it can be deducted that the heat is extracted from the rock bed in the same profile as the heat distributes during the charge cycle.

Figure 20 shows the air outlet temperature at the discharge outlet over time. Here it is illustrated that the outlet temperature exceeds 500 °C and remains above 400 °C for 10 hours. The total discharge time of 28 hours is due to a lower mas flow rate than the charging mass flow rate. Discharge stops once the rock bed reaches the same temperature as before testing started.

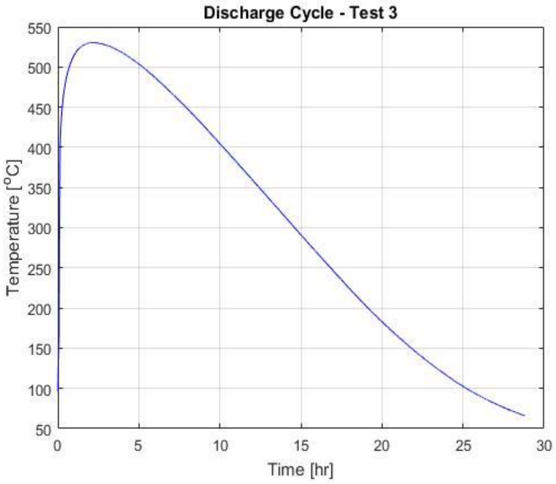


Fig. 20. Discharge temperature over time

Table 3 contains a summation of the charge cycle results from the experiment.

Property	Value	Units
Heating capacity	319.91	kW_{th}
Total energy input	2.552	MWh_{th}

Table 3. Charge cycle results

A total of 40 tons of rock were charged, giving a volumetric efficiency of 61.5 %. The heat recovery efficiency is yet to be determined, with data analysis still in progress.

6. Analytical Model

An analytical model of the TESS is done to validate the results obtained from the experiments. By predetermining the heat distribution throughout the rock bed through experiments, the accuracy of the analytical model can be improved. A comparison of the two will allow for error determination between theory and experimental testing. This will enable the concept to be simulated to accurately predict the outcome of an industrial size concept. The theory used to build the model is developed for heat transfer between air and rocks [8].

The rock bed is represented by a conical shape within the computation domain of the model. Due to this shape, the cross-sectional area differs from top to bottom. Figure 21 illustrates the approximation of the heat progression through the rock bed. The cross-sectional area increases from the top of the rock bed to the bottom as progression takes place. From the experimental results, it is observed in Figure 16 that the thermocline progresses in the shape as illustrated in Figure 21. L represents the direction of progression, while β is the angle of the rock bed surface. The progression of the thermocline is due to a larger void fraction between the rock bed free surface and the mesh, causing a preferential flow path around the edges. As the flow moves downwards into the rock bed, the flow experiences more resistance and then only moves into the rock bed.

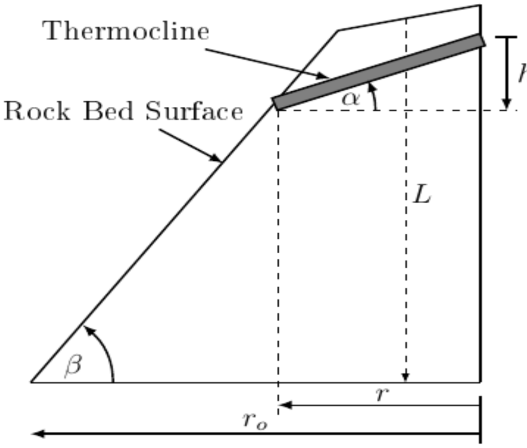


Fig. 21. Computational domain of the thermocline progression

The cross-sectional area is a function of the radius and height of each progression segment. The vertical progression is determined by the approximate diameter of a typical rock within the rock bed, with the horizontal progression following the same procedure. The ratio between the height and radius of the progression is defined by α and determined from the experimental results. From here the height and area of each progression segment is determined by the equations below:

$$h = r\tan(\alpha)$$

$$A_{cs} = \pi\, r\sqrt{r^2 + h^2}$$

Forced convection is the dominant type of heat transfer that takes place during the charging and discharging cycles, with radiation and conduction negligible small compared to convection. The heat transfer throughout the rock bed is thus calculated by making use of the effectiveness number of transfer units (e-NTU) method. The e-NTU method is also a good method for predicting heat transfer in a one-dimensional model. [8]

The following equations are applied to determine the temperature of the rocks and air at each step of the heat progression through the rock bed. A detailed discussion on the equations can be found in [8]:

$$G = \frac{\dot{m}}{A_{cs}}$$

$$NTU = \frac{h_v L}{G c_{p,a}}$$

$$h_v = \frac{h_s(1 - \varepsilon)6}{D_v}$$

$$h_s = \frac{Nu}{\frac{D_v}{k_a G}}$$

$$\tau = \rho(1 - \varepsilon)\frac{A_{Cs} L c_{p,r}}{\dot{m} c_{p,a}}$$

Simplified equations of both the Reynolds and Nusselt numbers are non-dimensional numbers used in the e-NTU method:

$$Re_{pv} = \frac{G D_v}{\mu}$$

$$Nu = {Re_{pv}}^{0.6}$$

The efficiency of the heat transfer is calculated by:

$$\eta = 1 - e^{\left(\frac{-NTU\,\Delta r}{r_o - r_i}\right)}$$

Finally, the temperature of each progression segment is determined for the air and rocks respectively by:

$$T_{a(i+1)} = T_{a(i+1)} - \eta(T_{a(i)} - T_{r(i)})$$

$$T^{+}{}_{r(i)} = \frac{T_{a(i)}\left(1 - \frac{\Delta t}{2\tau}\frac{L}{\Delta x}\eta\right) + T_{a(i)}\left(\frac{\Delta t}{\tau}\frac{L}{\Delta x}\eta\right)}{1 + \frac{\Delta t}{2\tau}\frac{L}{\Delta x}}$$

These equations loop through the rock bed from top to bottom for each progression segment as calculated by A_{cs}. The model is transient, with the amount of time steps defined by the user.

7. Results Comparison

After completion of both the experimental testing and the analytical model, the results are compared to validate the facility and the model with one another. Table 4 compares the results of the charge cycle. The analytical model of the discharge cycle is yet to be completed.

Property	Analytical	Experimental	Units
Heating capacity	299.71	319.91	kW
Total energy input	2.50	2.56	MWh_{th}
Volumetric efficiency	65.1	61.5	%

Table 4. Analytical compared to experimental results - charge

A difference of the heating capacity evaluated in the model and the experimental result is 6.3 %, while the total energy input difference is 2.3 %. The volumetric efficiency difference equates to 5.5 %.

8. Conclusion

The re-design, construction and experimental testing of SU's rock bed thermal energy storage pilot plant is completed.

The re-design of the rocked storage system met the criteria set in section 3.1.

Experimental testing took 7 days in total. The experimental test results show a volumetric efficiency of 61.5 %. The stored energy in the rock bed equates to 2.56 MWh_{th}.

An analytical model was developed in parallel to the construction and experimental testing phases of the project. Comparison between the experimental and the analytical results yields a heating capacity difference of 6.3 %, a total energy input difference of 2.3 % and a volumetric efficiency difference of 5.5 %.

The objectives of improving the volumetric efficiency, minimizing heat loss and improving the facility to act as a long-term storage facility are met. The remaining objectives, as set out in section 1.2, will be answered once the discharge cycle and the economic analysis is completed.

The new design of the rock bed storage system seems to be a promising technology for cheap and effective thermal energy storage systems in the future.

Acknowledgements

T.W. von Backström, M. Lubkoll and F. Dinter for their guidance, expertise, recommendations and project funding. H.F. Laubscher for recommendations as well as the development of the pilot plant. Solar Thermal Energy Research Group (STERG) for project funding.

References

[1] L.G. Socaciu, (2011). Seasonal sensible thermal energy storage solutions, *Leonardo Electronic Journal of Practices and Technologies*, vol. 10, pp. 49-68, ISSN 15831078.

[2] H.F. Laubscher, (2017). 'Developing and Testing a Cost Effective Thermal Rock Bed Storage System', Master's Thesis, Stellenbosch University.

[3] K.G. Allen, (2010). 'Performance characteristics of packed bed thermal energy storage for solar thermal power plants', Master's Thesis, Stellenbosch University.

[4] G. Zanganeh, A. Pedretti, S. Zavatonni, M. Barbato, A. Steinfeld, (2012). Packed-bed thermal storage for concentrated solar power – Pilot-scale demonstration and industrial design, *Solar Energy*, vol. 86, no. 10, pp. 3084-3098, ISBN 4074451360, ISSN 0038092X.

[5] K.G. Allen, T.W. von Backström, D.G. Kröger, (2013). Packed Bed Pressure Drop Dependence on Partical Shape, Size Distribution, Packing Arrangement and Roughness, *Powder Technology*, vol. 246, pp. 590-600.

[6] D.G. Kröger, (2013). *Packed Rockbed Thermal Storage Facility*, SA 2013/03068, Innovus, Stellenbosch University.

[7] P. Gauché, A.D.R. Louw, (2014). *Cone Rock Bed Thermal Energy Storage System*, SA 2014/03555, Innovus, Stellenbosch University.

[8] T.W. von Backström, S.J. Erasmus, H.F. Laubscher (2017). *Rock bed energy storage system*, South African Provisional Patent SU-Disc-2017-0027, Stellenbosch University.

[9] K.G. Allen, T.W. von Backström, D.G. Kröger, (2015), Rock Bed Pressure drop and Heat Transfer: Simple Design Correlations, *Solar Energy*, vol 115, pp. 525-536, ISSN 0038-092X