Tanzania Journal of Engineering and Technology 2025, **44**(2):265-273
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Websites: https://ajol.org/tjet; https://tjet.udsm.ac.tz

ISSN 1821-536X (**print**); ISSN 2619-8789 (**electronic**)
https://doi.org/10.52339/tjet.v44i2.1304

Special Issue – 8th International Conference on Mechanical and Industrial Engineering, October 24 – 25, 2024 at The Nelson Mandela African Institute of Science and Technology, Arusha - Tanzania

Thermal Energy Storage System Using Silica Sand as Heat Storage Medium: Simulation of Geita Gold Mine

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ABSTRACT

Currently, Geita Gold Mine (GGM) relies on electrical energy from the national grid and diesel power generators to generate electricity for various industrial applications. The plant currently spends a large amount of money on generating power from diesel generators. The total annual cost of power generation from diesel generators including lubricants is USD 56,057,990. The total annual fuel cost is USD 53,531,805 for a total of 54,985,473 liters per year. Most of the power generated by the generators is consumed in the industrial thermal processes. Thermal energy applications at the plant are thermal drying of the extracted ores to remove moisture content before further processes, thermal treatment of minerals and in gold refining and smelting which require over 1000°C temperatures. However, this thermal energy can be obtained from thermal energy storage system. This study was initiated to investigate the potential of silica sand as thermal energy storage medium for GGM. In the assessment of the potential of silica sand, three (3) different samples were collected at the GGM site from three different locations and the samples were analyzed to determine their chemical compositions using energy-dispersive x-ray fluorescence (EDXRF) and later purified using coke to obtain the 95% desired purity. Thereafter, silica sand thermal energy storage model was developed using the chemical compositions and thermal properties of the analysed silica sand. The model performance assessment used heat transfer in the solids interface in COMSOL Multiphysics. The silica content of the three samples were 87.32%, 78.25%, and 75.59% silica content. The model results show capacity to be charged for two hours and discharging for twelve hours.

ARTICLE INFO

Submitted: **Apr. 23, 2024**

Presented: **Oct. 25, 2024**

Revised: **Nov. 26, 2024**

Accepted: **Jan. 30, 2025**

Published: **June, 2025**

Keywords: *Simulation of thermal industrial applications, Modelling thermal energy storage, Silica sand.*

INTRODUCTION

Fast population growth puts pressure on increased energy demands. Besides the limitations of conventional energy sources like coal, oil, or gas, their use causes emissions of CO_2 and other greenhouse gases (GHG) (Adedeji, 2014). The emissions are claimed to have negative effect on climatic changes such as global warming and ozone layer deterioration (Nema et al., 2012). To maintain the standard of living in industrialized countries and to improve the situation in developing countries, energy consumption cannot be avoided. Rather, energy can be used much more efficiently with a higher share of renewable sources (Mountjoy, 2007; Zhang et al. 2021).

Past recent studies have demonstrated that the primary energy consumption will rise by 48% in 2040 (Tira et al., 2016). Renewable energies such as solar radiation, ocean waves, wind, and biogas have been playing a major role in reforming the natural balance and providing the needs for the growing population (Josue and Mushi, 2022; Twidell, 2021). The rapid demand has necessitated the need for alternative storage systems from renewables (Iten et al., 2016). This has led to the need to develop efficient and sustainable methods of storing energy (Baver et al., 2012). Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications; and power generation (Sarbu and Sebarchievici, 2016). TES systems are particularly used in buildings and industrial processes which lead to increased overall efficiency and better reliability, and can lead to better economics, reductions in investment and running costs, and less pollution of the environment, i.e., fewer CO_2 emissions (Dincer and Rosen, 2021). TES is particularly important for electricity storage in combination with concentrated solar power (CSP) plants where solar heat can be stored for electricity production during absence of sunlight (Ayyappan et al., 2016; Xu et al., 2015). For example, new materials were selected, characterized, and enhanced in their thermo-physical properties to serve the purpose of a 24 hour operation that gave an efficient TES system (Sarbu and Sebarchievici, 2018). Current TES systems allow for higher capacity factors although at the cost of increasing the power plant cost. Balghouthi et al. (2016), suggested that the incremental cost can be justified economically. Furthermore, without exceeding a specific storage size, the levelized cost of electricity reduces as the available hours of storage increase (Balghouthi et al., 2016). The heaters used to heat the TES may either be powered by solar photovoltaic (PV) plant; wind power plant; or an integration of the renewable power plant and national grid.

At present, nitrate salts (molten salts) are most used storage materials in conventional commercial TES systems such for CSP plants (Alva et al., 2017). However, one of the drawbacks of molten salts is that they are oxidizing agents and very corrosive, therefore to contain them at high temperatures is problematic. Also, their thermal conductivity is low. Hence, conventional thermal energy storage systems have limitations in terms of their efficiency, cost–effectiveness, and stability. So, there is a need to explore alternative approaches to TES that can overcome these limitations, by using a promising material with high specific capacity and thermal stability. These alternatives are graphite, concrete, and silica sand, to name a few (Magaldi, 2022). In this study silica sand is proposed to be used as the heat storage material at Geita Gold Mine (GGM) so as to overcome the limitations of molten salts. Silica sand is one of the extracts obtained during mining extraction processes at the GGM, which is currently not in use, and is among the TES alternatives. The plant incurs a high generation cost of electricity for industrial thermal processes. Therefore, there is a possibility of using these extracted silica sand as a heat storage medium in the TES for thermal industrial applications. Therefore, this study seeks to investigate the effectiveness of using silica sand as the TES system development for industrial thermal applications and develop a comprehensive understanding of the factors affecting its performance.

Wavelength – dispersive X–ray fluorescence spectrometry (XRF) – is a nondestructive analytical technique used to identify and determine the concentrations of elements present in solid, powdered and liquid samples. XRF is capable of measuring all elements from beryllium to uranium and beyond. Wide application in industry and research derives from the ability to carry out accurate, reproducible analyses at very high speed. With modern, computer–controlled systems, the operation is fully automatic and results are typically delivered within minutes or even seconds.

MATERIALS AND METHODS

Description of Study Area

Geita Gold Mine one of AngloGold Ashanti's flagship mines with an open pit, is located in north-western Tanzania (2.8676° S, 32.1865° E), in the Lake Victoria gold fields of Geita region. It is about 120 km from Mwanza and 4 km west of the township of Geita (Lange, 2011). It has been in operation as a large–scale mine since the 1930s (Emel et al., 2014). The maximum power demand of the plant is 32 MW (Munisi et al., 2024). The industry has two electricity sources that is – Tanzania National Electricity Supply Company (TANESCO) supply, and diesel generators power plant (DG). These are used for lighting, heating processes, and other mining activities, for instance, ore extraction, crushing, and grinding. TANESCO only feeds 15 MW, and the remaining 17 MW is generated from the of DG that has 40 MW capacity (Munisi et al., 2024).

Availability of Silica Sand at the Geita Gold Mine

Preliminary survey was done at GGM on the sand available at the site after ore extraction that was dumped near the mining pits. Sand samples were randomly selected from three (3) different positions and one kilogram of each sample was collected for further analyzation of sand chemical composition to determine the quantity of silica content present in each sample.

X-Ray Fluorescent Spectrometry Procedures

Three (3) samples of sand from three (3) different locations around GGM were collected and sent to the laboratory. The samples were coded appropriately as 1, 2, and 3 for proper identification and to avoid contamination in the next stages of analysis. This experiment was conducted at African Minerals and Geosciences Centre (AMGC) specifically the Analytical laboratory located at Kinduchi in Dar es Salaam. The samples were crushed using a roll crusher, split using a rotary riffle technique, and pulverized using a vibratory ring mill that incorporates an integral three phase vibratory duty electric motor drive. Then they were pelleted and loaded onto the Rigaku NEX CG Energy Destructive X-Ray Fluorescence (EDXRF) spectrometer machine for analysis.

Calibration of the EDXRF

The Rigaku NEX CG EDXRF machine was first calibrated using an MCA calibration sample and the standard results Fe = 663, Ba = 470 and K = 356 were obtained. Then the library calibration, which is a peak profile calibration of the spectrometer, and the intensity library calibration through the intensity drifty calibration, was conducted using standard samples. The order of MCA was, Sn, Cu, and SiO_2. Afterwards, sample pellets were loaded and analyzed on the EDXRF machine. The obtained sample results were evaluated using a NEX program, normalized, and finally printed for reporting. The processes and results are displayed in Figures 1 – 6.

Figure 1: Calibration of EDXRF machine using MCA calibration samples.

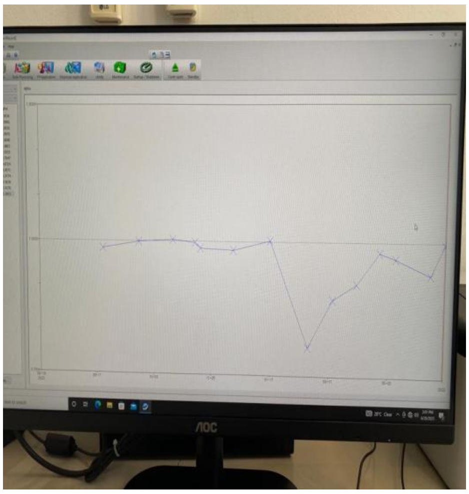

Figure 2: Calibration results.

Figure 3: Placing the samples in the EDXRF machine.

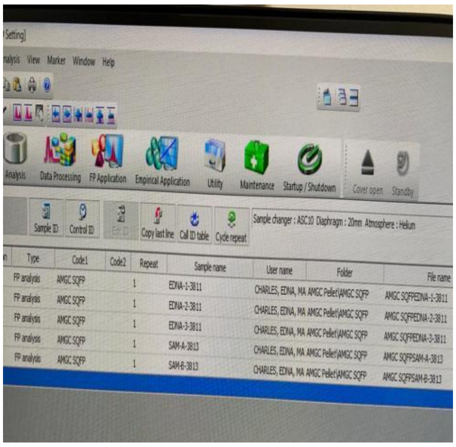

Figure 4: Registering each sample using NEX software.

Figure 5: Assuring that each sample is placed in its respective position in the EDXRF machine.

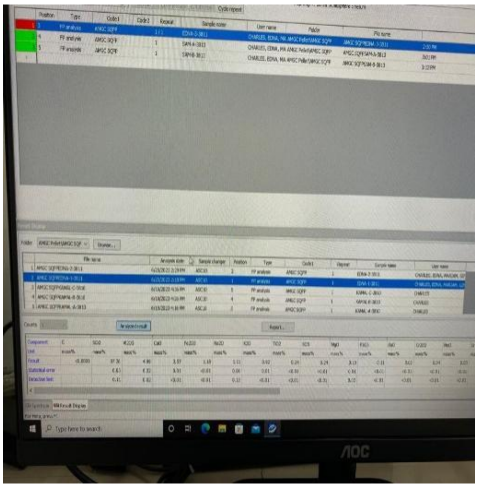

Figure 6: Starting the analysis process using NEX CG Software.

Experiment

The EDXRF machine took 10 minutes to complete analyzing each sand sample. The raw data were extracted in PDF format and downloaded for evaluation on Excel sheet. Material must contain at least 95% SiO_2 and less than 0.6% iron oxide to be categorized as silica sand. Sand will be considered "regular sand" if it does not match these requirements (Magaldi, 2022).

Simulation of the TES Model in COMSOL Multiphysics

TES model titled "silica sand (solid, true value) block coated with a structural steel model" was built in COMSOL Multiphysics. The source chosen in this study for the TES system is National grid that currently is available at GGM. The National grid will be used to power the electric heaters that will be integrated with the TES model. The output temperature from electric heaters is used as the input for the TES model. The developed model from COMSOL Multiphysics was evaluated by setting margins (hot and cold) since the software does not include electrical connection studies but heat transfer studies and others. Therefore, the hot margin side is assumed output temperature from the electric heaters. The model operated in two (2) phases which are charging and discharging.

RESULTS AND DISCUSSIONS

Experimental Results

Table 1 and 2 show the normalized data from the EDXRF machine, as done by Excel software.

Table 1: Final EDXRF results for the three samples

Sample ID	SiO_2 [%]	Al_2O_3 [%]	CaO [%]	Fe_2O_3 [%]	Na_2O [%]	K_2O [%]	TiO_2 [%]	SO_3 [%]
1	87.32	4.99	3.57	1.18	1.11	0.92	0.24	0.24
2	78.25	12.68	1.46	1.68	1.85	2.30	0.31	0.36
3	75.59	7.24	12.17	1.20	1.01	1.18	0.19	0.42

Table 2: Final EDXRF results for the three samples

Sample ID	MgO [%]	P_2O_5 [%]	BaO [%]	Cr_2O_3 [%]	MnO [%]	SrO [%]	Cl [%]
1	0.19	0.11	0.05	0.04	0.03	<0.01	<0.01
2	0.52	0.31	0.18	0.03	0.03	0.03	<0.01
3	0.35	0.42	0.08	0.03	0.05	<0.01	0.06

Key: For Table 1 and 2, ID means identity and < 0.01% means the parameter reading is less than the lowest detection limit which is 0.01%.

For all three (3) samples of sand analyzed, silica content is the highest of all other components of sand. Sample 1 has 4.366 g (87.32%) out of 5 g of sand sample, sample 2 has 3.9125 g (78.25%) out of 5 g of sand sample, and sample 3 has 3.7795 g (75.59%) out of 5 g of sand sample. During mining extraction processes, more than 50,000 tons per day of sand is obtained as one of the by-products of mining activities. From sand sample 1, the quantity of silica content of 43,660 tons was calculated to be extracted per day.

Simulation Results

The model built in COMSOL Multiphysics is depicted in Figures 7, 8, and 9, by building a rectangular block and set material specifications for silica sand. The model is charged by setting the hot margin on one side of the block and cold margin on the other side of the module in (Figure 8), which shows heat transfer from the hot margin side to the cold margin side, whereby the highest temperature achieved is 900 K for about a quarter of the silica sand model. The rest of the silica model was below 900 K. This sand model then is assumed to retains this heat for applications when needed. Thereafter, Figure 9 shows the discharging phase that is heat transfer of the sand block from the right-hand side that attained higher temperature of 900K during charging to the left-hand side where the temperature was below 900K after assuming the heating source is turned off.

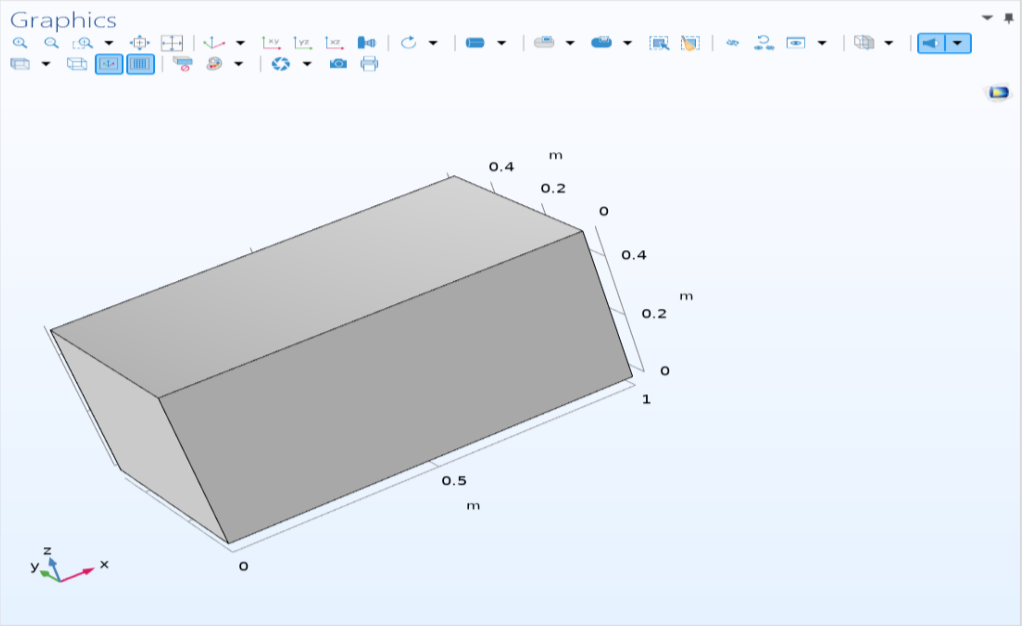

Figure 7: Developed model of silica sand block coated with structural steel, in COMSOL Multiphysics.

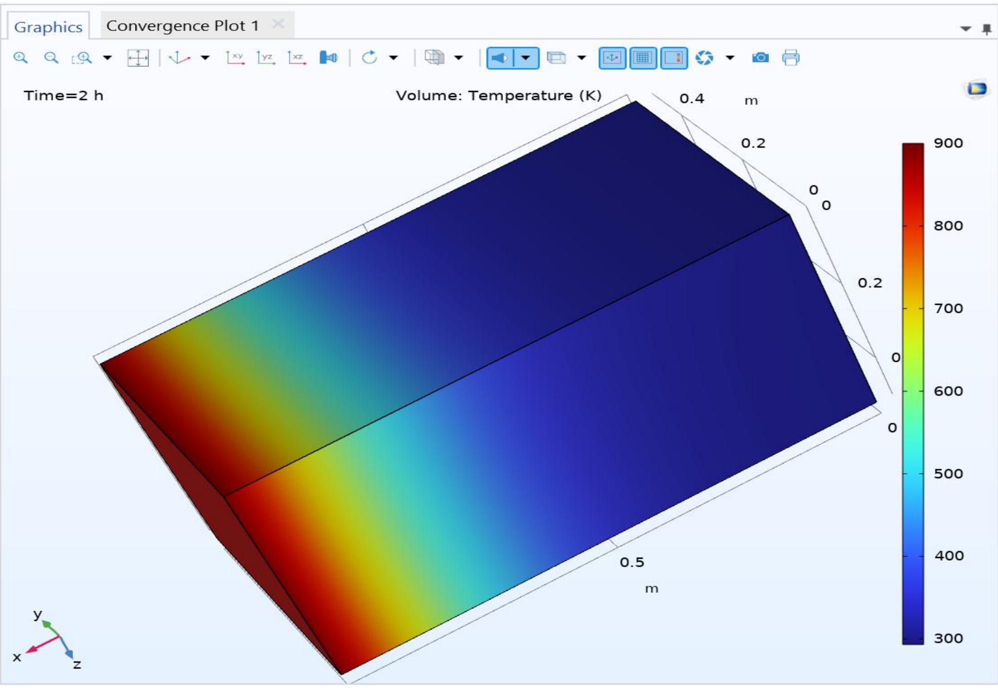

Figure 8: Left hand side of the module set as the hot margin (indicating charging side) and right-hand side set as the cold margin (indicating discharging side).

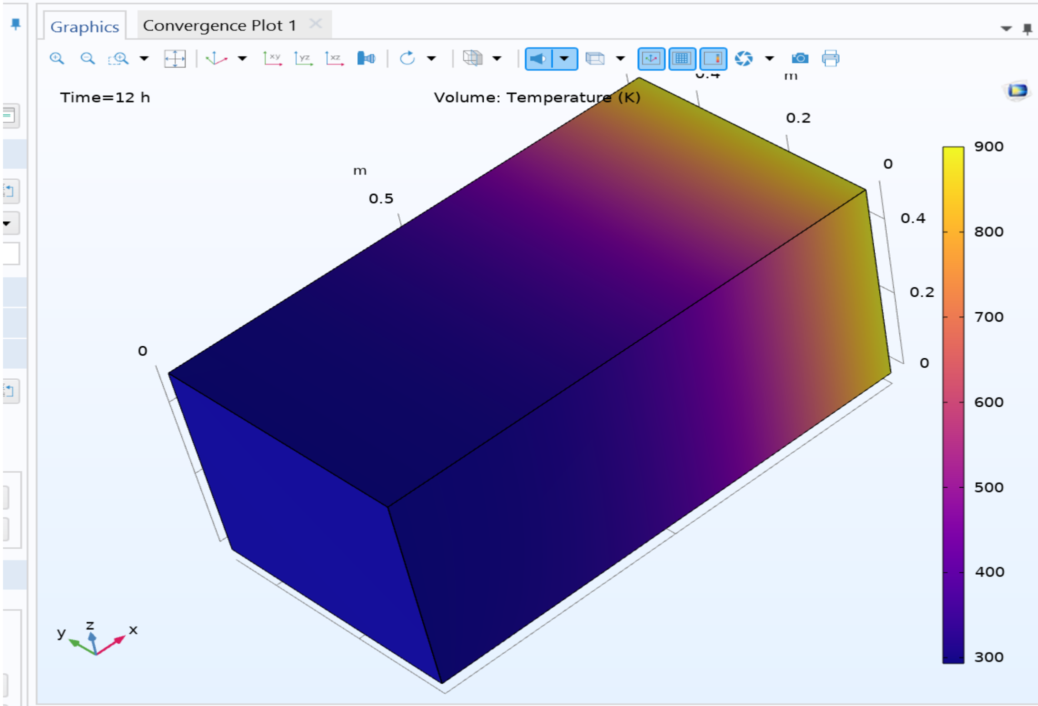

Figure 9: Discharging phase shows this temperature distribution, after the previous charging phase.

Discussions

Based on the experiments conducted all the three sand samples cannot be categorized as pure silica sand as they all have less than 95% silica. Therefore, separating pure silica from other components, involves reducing silica with coke in an electric furnace, followed by refinement of the impure byproduct. By reducing the oxide with aluminum, silicon can be extracted from it on a small scale (Xakalashe and Tangstad, 2012). Data collected from the survey established the total thermal energy demand for the GGM plant in a year to be 92,064,738 kWh. The highest average demand was observed in December to be 12,502,996 kWh. This research revealed that, future expansions of the plant activities will need installation of thermal storage with a capacity of 13,000,000 kWh to meet the increased demand. From the results of Magaldi (2022), the block TES model was designed with 80 MWh capacity. Therefore, it will require 163 such modules to meet the industrial thermal demand for the GGM. This will require 81,150 tons of silica sand for the needed TES modules. The data collected showed that 43,660 tons of silica sand is extracted from the mining pits on a daily basis. Hence, it will take at least two days to collect the required amount of the silica sand.

In this study the national grid has been chosen to power the TES modules so as to serve the costs of installing renewable plant. For instance, it would cost $4 million/MW to install a CSP plant. It would cost $1 million/MW to install a solar PV power plant. These costs are based on the current market trends as researched by the National Renewable Energy Laboratory.

CONCLUSION

This study has investigated the use of plentiful available silica sand at the GGM for possible uses as a TES. Silica content of the collected sand was 87.32%, 78.25%, and 75.59%. Sand purification using coke to achieve the required silica content of 95% purity must be undertaken in the further studies. The COMSOL Multiphysics silica sand TES model was only able to show heat transfer during the charging and discharging phases. Therefore, it is recommended to conduct a Laboratory Experiment, to evaluate the performance based on the duration of silica sand to charge and discharge. The source of energy for this TES could be a combination of the national grid or available renewable energy resources. This would result in green energy use at the GGM site, and therefore preserving the environment.

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