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Research Article

Review - Optimization and Property Enhancement Methods of Sand based Energy Storage

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ABSTRACT

Increasing environmental concern around the world makes researchers to work for the development of cost effective storage systems for storing excess or waste energy available in industry and nature. Most of the commercialized electrochemical storage systems are using harmful chemical compounds, which are creating hazard to environment and mankind during their disposal. Moreover, those systems are economically expensive and having limited operation time. Hence, it is necessary to develop energy storage system operates on eco-friendly and cost effective storage material. In this review article, usage of sand in energy sector has been analyzed from its properties, applications, limitations, performance enhancement methods and scope of future research.

Keywords: Sand based Energy Storage

1. Introduction

The extensive use of fossil fuels causing harmful impacts to the earth by global warming and climatic changes which diverts the entire world to use eco-friendly power generation methods[1][57]. Recent adoption of renewable energy power generation technologies has been limited mainly by the intermittence nature of sources with respect to availability [2] [3] [24]. So, the development of effective energy storage system has been mandatory for mitigating the barriers of utilizing environmental friendly renewable energy sources [4]. Even though the innovations of researchers are helping to implement zero emission energy in to commercialization, which are uncompetitive with fossil fuels utilization in terms of its all-time availability, cost and performance [5]. Sometimes, the cost of energy storages used for overcoming the limitations of nature source are expensive which makes the cost of green energy higher than the conventional power.

Among the available energy storage methods, Thermal energy storage (TES) provides reliable, environmental and economical friendly solutions for energy storage [6] [7] [8]. The cost of TES are inexpensive because of the usage of natural materials as storage media, those materials are abundant in nature, less maintenance and provides long life span [9][10][11][12][26][47]. TES stores thermal energy in the forms of Sensible heat, Latent heat and Thermo-chemical [47].

Conventionally, solid materials are preferred to use in sensible heat energy storage method because of easy handling, low cost and stability [47]. The natural silica in the form of sand has a chances to use in TES by sensible heat storage concept. Sand has been found on 6% of earth's land surface and have constituents of silica, feldspar, micas, carbonates and pyroxenes [31] [32]. Generally, the specific heat capacity of the sand ranges between 750 to

1200J/kg°C [41] and has high thermal conductivity of 7.7W/m.K(quartz) [50]. Sands are classified in to four categories as silver sand, medium sand, filter sand and coarse sand based on its gain size [37].

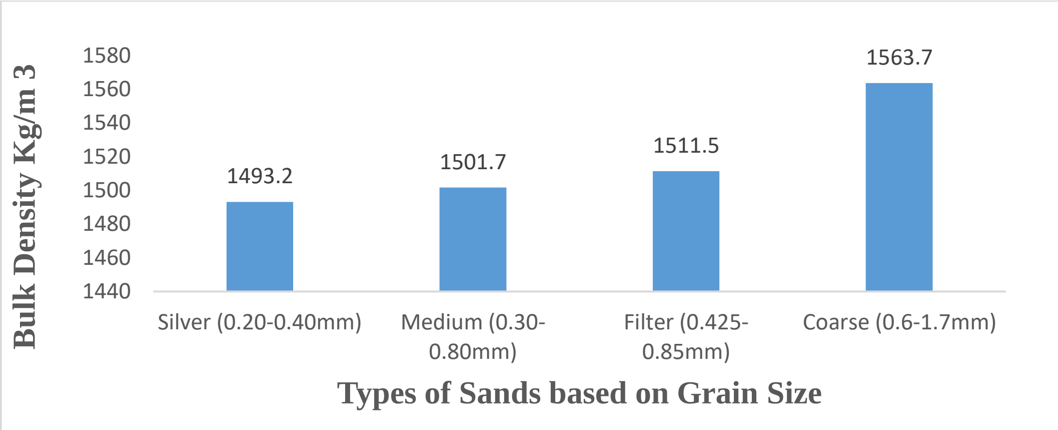

Figure 1 – Bulk density kg/m3 of sands [37]

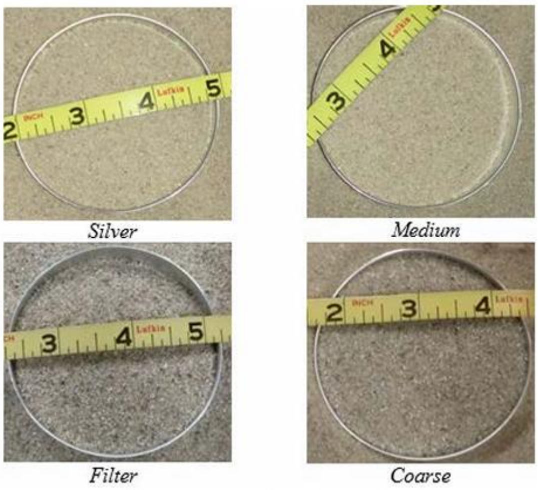

Figure 2 – Types of Sand [37]

2. Properties of Sand

2.1 Thermal Conductivity

Thermal conductivity of sand has been low in nature due to its physical availability in granular form and point of contact between the grains [24]. Poor thermal conductivity of sand makes it useful as an insulation material to prevent heat loss from any thermal system. However, researchers developed innovations for using sand as a material for storing energy by sand coating, inclusion of granite powder, mixing waste metal chips, mixing water and adding waste rubber tyres material [27][28][48]. Change in physical properties of sand during the process of drying and wetting because of the seasonal variations also affect thermal conductivity of the soil [57][59][60]. Soil having air presence in between of particles gaps shows less thermal conductivity compared to soil grains bonded together by using clay or other binding materials[57][58]. Zhang et al [61] concluded from investigation that raise of density of soil by increasing its moisture content does not have significant impact on improvement of thermal conductivity.

Nikiforova et al [49] conducted thermal conductivity experiment on Sand, Clay and Loam using Russian thermal conductivity measuring instrument “MIT-1.0”. Author experimented the type’s soil with variable humidity conditions to study the behaviour of thermal conductivity. The conductivity of sand has been increasing with varying humidity and density combinations as shown in below figure. Results of the experiment confirmed that addition of moisture in to the sand increases the density which causes raise in the conductivity of the sand remarkably [57]. The below figure shows variation in conductivity with respect to change in density. Thermal conductivity of any type of soil in dry state varies from 0.23-0.35 W/Mk because of the non-uniform contact between the particles. Adding water in to dry soil to the particular limit helps to raise thermal conductivity, beyond the limit addition of water makes soil to dissolve in water.

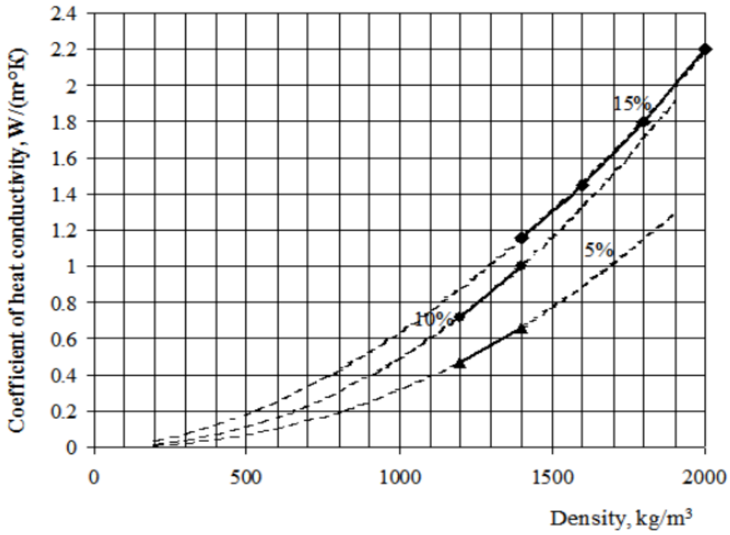

Figure 3 – Change of Sand Density with Change in Humidity [49]

It has been observed that presence of moisture in soil bonds the particles together causes thermal conductivity to raise by increasing surface area of the soil. Clay sands are having high surface area compared to sandy soils due to the presence of fine particles which make them to absorb water in it. Absorption of excess water in to clay reduces thermal conductivity [58].

2.2 Grain Size

Grain size of sand particles are having great influence on Thermal performance by varying conductivity, porosity, permeability, mineralogy and specific surface area [50]. Ahn et al [51] conducted experiment on silica sand of different porosities and particle size to study its impacts on thermal conductivity using ASTM D5334-14. Author experimented three samples of silica sands having mean particle sizes 0.84, 0.33 and 0.16mm and found that thermal conductivity has been decreased with particles having high porosity and low proportions of fine particles. Although thermal conductivity has been decreased with particles having low porosity and high proportions of fine particles mixtures [52] [53] [54] [55] [56]. Farzi et al [63] conducted experiment to study the effect of grain size by using four different sands as energy storage in conventional solar stills to produce water during night time. Author constructed four conventional solar still and sand grains of sizes 6.9, 2.8, 1.1 and 0.7 mm for energy storage. Results of the experiment concluded that 2.8mm grain size enabled high efficiency and productivity of water during night time compared to the other sands. Farzi confirmed that optimization of sand has been mandatory for the balance of porosity and heat transfer property of sand.

3. Applications of Sand in Energy sector

Sand has been used in energy sector for various applications including usage of sand as an energy storage media, Additive for phase change material, Heat transfer medium, and as Anode in electrochemical batteries.

3.1 Sand as Energy storage material

Usage of sand as an energy storage material has been increasing in concentrated solar thermal power plant (CSP) because of its sensible heat storing capacity and high melting point of 1700℃ [13][14]. Generally, molten salts are preferred to use in CSP for the temperature ranges of 260℃ and 565℃, but after frequent cycle of operations use of these materials causes damage to the flow pipes and storage container [16][39][40]. To overcome these issues high quality materials are required for the construction which makes the system to be costlier further [10] [17].

Inexpensive energy storage has been developed by choosing naturally and easily available material as storage media. Sand has been used as a storage material for energy storage but low thermal conductivity property of sand has been a limiting factor for its wide usage in energy sector [7]. Pure Quartz are one type of sand having high specific heat, thermal conductivity and capable to operate above 1000°C without any change in its properties [15]. Silica sand naturally available on earth are mainly constitutes of silica and oxygen and remains in solid state till 1800°C of operating temperature [18]. Impure sands are the mixtures of sand, clay, organic matter and other impurities created by nature and manmade. These materials operated up to the temperature range of 500°C because of its mixed thermos-physical properties [19].

Haggag et al [39] conducted experiment on heat storing capacity of desert sand by considering charging, storage and discharge of energy from the storage system. Results indicated that storage efficiency of the system as 62.4% and discharge efficiency of the system 61% for the operating temperature ranges of 1000°C.

3.2 Waste Foundry Sand as Composite Phase change material

Anagnostopoulos et al [38] suggested a methods of recycling Waste Foundry Sand (WFS) by creating a Composite Phase Change Material (CPCM) using additives sodium nitrate ($NaNo_3$). Presently, USA and china are the leading generators of WFS with quantity of 70 million tonnes. Out of which only a small quantity has been recycled remaining were disposed in landfills that has been a one of the major issue for the safety of environment. Method of developing CPCM using WFS with additives creates a chance for using them back in energy storage applications. Developed CPCM exhibits thermal and physical stability till the operation temperature of 400°C.

3.3 Solar Thermal Energy Storage (STES)

Mahfoudi et al [35], conducted experiment on solar thermal energy storage system by using dune sand of Algeria. Quartz, Fe_2O_3, $CaCo_3$, Al_2O_3 and heavy materials are major constitutes of dune sand. Grain size of the sand has been an important parameter to influence the heat storage capacity of the sand [36]. The results of experiment conducted by author [35] concluded that the number of tubes employed in charging storage material plays major role in energy storage of the system. Optimization of tubes will enhance the performance of storage system further to improve heat transfer both in charging and discharging.

3.4 Air – Sand Heat Exchanger (ASHE)

ASHE generally used to store heat energy in sand and to utilize it when air heating or water heating is needed. Warerkar et al [20] conducted experimental and analytical research to develop cost effective energy storage system using coarse sand. Results of the experiment concluded that effectiveness of heat exchanger (HE) raises for smaller grain size of less than 3mm. Grain size of sand further limited to 1mm for fluidized bed flow in heat exchanger. Al-Ansary et al [21] conducted experimental work on ASHE for raising temperature of compressed air to operate gas turbine. Results indicated that the grain size of silica or olivine sand never had influence on the heat transfer rate but raise in sand velocity greatly impact the heat transfer rate.

Cárdenas et al [23] investigated the integration of sand based heat exchanger with compressed air energy storage (CAES). Author considered delivery pressure of 250bar, which was achieved through multi stage compression process. Generally, Intercoolers are used in between the compressors to remove heat energy from air by maintaining constant pressure for the reduction of work consumption of next compressor because of the expansion of air due to additional heat addition by the compression process. Cardenas planned to store that removed heat energy in sand to utilize it for preheating the incoming ambient air to remove moisture for the assurance of long system operation by avoiding corrosion. Indirectly, preheating of ambient air helps to improve the efficiency by reduction of electricity involved in the compression process. As a result of this research, Authors concluded that remarkable change in efficiency observed at low cost investment by coupling CAES and Sand heat exchanger using sand silica.

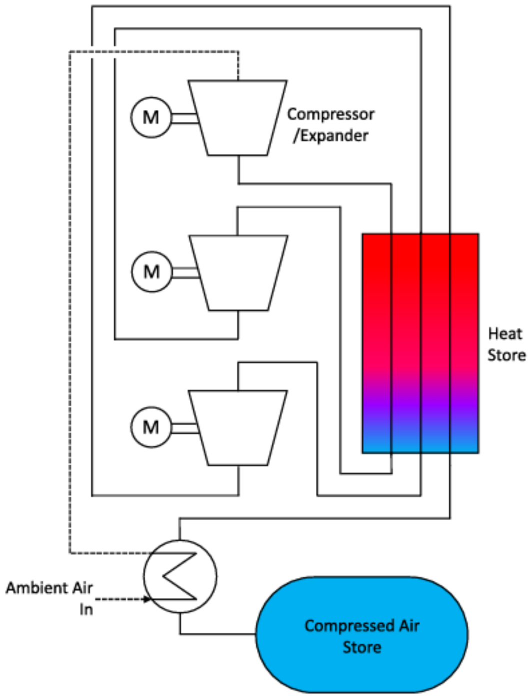

Figure 4 – Multistage compression with sand based storage system [23]

3.5 Sand based energy generation

Poulose et al [22] suggested the method of using sand as a replacement material in pumped hydro energy storage. Author proposed to use small balls made from bulk density materials of sand (1602 kg/m^3) or other waste engineering materials (2427 kg/m^3). These materials are kept to elevated position above the turbine using excess solar power produced. When need arises to meet peak energy demand, the balls are allowed to come down from elevated place towards turbine setup. Balls coming from elevation make a high impact on turbine shaft by hitting which makes the turbine shaft to rotate to produce electricity using generator.

3.6 Sand in Electro-Chemical Batteries

Wang et al [45] conducted experiment by using desert sand – carbon composite as anode by connecting sand particles through carbon framework derived from polystyrene. Authors concluded that application of sand-carbon anode in Lithium batteries performed over 200 cycles with high stability and reversible capacity of 555mAh. Deng et al [46] developed a novel electrolyte of “Soggy sand” for Zinc-Ion batteries by combining the advantages of solid-liquid electrolyte to overcome the limitations of traditional aqueous Zinc-ion batteries. Application of Soggy Sand exhibits stabilized operation after 500 cycles of operation.

4. Limitations

Though the sand has been providing environmental friendly solutions to the environment, it has not been commercialized because of its technology and infrastructure lagging and high investment costs. Sand does not exhibit high density energy storage compared to lithium-ion batteries, which makes less attraction towards it. Also, high time consumption for charging and large land requirement for construction of sand battery are not favorable for widespread usage [42]. Sand properties has been subject to variations based on the working atmosphere and its moisture conditions. Since, the hazards of electrochemical storage methods are over shadowed by its advantages which doesn’t allow investors to take risk on developing high scale energy storage using sand. Moreover, the main sources of energy for charging sands are from waste heat or solar energy are intermittent in nature. Implementations of optimization and enhancement techniques are mandatory to overcome the above mentioned limitations.

5. Enhancement of Thermo-Physical Properties of Sand

Researchers among the world are conducting research for the widespread usage of sand in energy generation, usage and storage application to create energy and economic efficient systems by enhancing properties of sand. Thermal conductivity has been an important factor for selecting the material for heat transfer applications [26]. Thermal conductivity of sand increases with decrease in porosity which creates close contact between sand granular [33]. Further thermal conductivity raises with increment in grain size and quartz content. Sand has poor thermal conductivity because of its size and form which are limiting the wide usage of sand in energy storage applications. In order to enhance sand conductivity further, sand coating process are adopted in few applications but not suitable for mass quantity and longtime requirement. Chung et al [27] suggested coating for quartz sand to improve its thermal absorptivity in solar applications. García-Plaza et al [28] conducted experiment on sand coating process and observed improvement in efficiency from 60% to 80%. Creation of composite sand by mixing other heat conductive material with sand has been considered as an advantageous method, but the additive material should not be costlier and no value for it in terms of usage and money.

Karell et al [29] suggested a method of creating composite sand by using waste scrap mixtures collected from metal workshops as an inexpensive solution. Tetteh, S et al [30] conducted an experiment to investigate the improvement in conductivity of brown silica sand by adding aluminum, brass and mixed metal chips by layered and uniform methods of arrangement in a rectangular container of size 380x230x380 mm. Author compared COSMOL simulation results with real time experimental results and found 5% deviations in between them. Also, authors concluded that the addition of metal chips of 20% with sand exhibits effective improvement in thermal conductivity compared with 5% and 10% addition.

Han et al [37] conducted an experiment to develop novel thermal energy storage using sand by improvising its property and efficiency through saturation of sand with high conductive fluid (XCELTHERM® 600 hot oil). Results of the experiment concluded that improvement in thermal conductivity of the sand by 2 to 3 times and enhancement in efficiency by 18% compared with sand based storage system.

Davenport et al [41] conducted thermal stability test on silica sand by heating it to 1200℃ for 500 hour under air and hydrated air atmospheric conditions in /Blue MTM box furnace. Results of the experiment and XRD analysis confirmed that no significant changes observed in the properties of silica and ensure the usage of sand as a stable form storage media for thermal energy.

6. Prediction and Optimization of Sand properties

Researchers conducted thermal conductivity predictions of soil using theoretical and empirical models. Compared to Theoretical Models(TM), Empirical Models (EM) are easy to predict based on the actual results of experiment. Theoretical model uses mathematical relations of thermal properties [57]. Prediction using TM are requires more accurate data and sometimes it has been a complex process to predict because of the use of complex formulas. Also, possibility of error in prediction with respect to the actual operation data with respect to changes in soil properties due to environment, climate and operational factors. EM models are easy to predict, but the results are not taken as a benchmark to compare the performance of other types of soils.

Vyas et al [42] suggested to optimize the property of sand utilized in the storage system for the effective and enhanced operation of the system. Also, author compared sand storage system with other methods and concluded that this system has been a cheaper option compared to other storage system for the operation temperature of 1000°C. Rizvi et al [43] reviewed the method of optimizing thermal conductivity of sand using hard and soft computational methods. Author mentioned that Effective Thermal Conductivity (ETC) depends on water content, mineral composition, density, particles size and environmental factor of the sand. Soft computational methods includes Deep Neural Networks (DNN) using machine learning concept provided faster and reliable optimization with limited datasets. Hard computing uses Thermal Lattice Element Method (TLEM) using numerical methods provides accurate predictions even with complex datasets. Abera et al [44] optimized efficiency of sand based solar thermal energy storage using COMSOL analysis and concluded that charging efficiency of the system improvised to 13.7% compared to the non-optimized systems efficiency.

Fei et al [62] optimized Effective Thermal Conductivity (ETC) of sand using a novel methods of combining advanced imaging techniques and machine learning concept of Artificial Neural Networks (ANN). Author optimized thermal conductivity of four types of sand by considering changes in porosity, size, shape, connectivity and mineral content of sand particles. Results of the analysis indicated that inclusion of particles physics helps to optimize the ETC more effectively compared to other methods which are focusing only few parameters related to thermal conductivity. In this method, author used weighted coordination number (WCN) to include the impact of particle connectivity and contact area to predict effective thermal conductivity (ETC).

7. Conclusions

Sand has good physical properties for high temperature operating conditions around 1000-1500°C without causing any damages to the equipment's of CSP compared to the molten salt limitations. Adoption of sand in energy storage applications helps to develop cost effective and eco-friendly storage for solar as well as waste heat recovery utilities. The natural properties of sand provides opportunities to use it for different applications in energy sector as an insulator, energy generator, heat exchanger, additive for phase change material, anode material in electrochemical batteries. Thermal conductivity and Grain size of sand are very important factors for the performance of sand in energy storage, these properties need to be selected and optimized with respect to application and operating conditions. Further enhancement in sand properties by thermos-physical treatment and addition of external agents make it to use it further in power industry to develop cost effective systems. Addition of waste metal chips with sand shows consistency in efficiency of energy storage compared to other methods, the external metal agents are unusable for other expensive applications. Optimization has been used as an effective tool to ensure the development of effective sand based energy storage system to meet long durability and large scale installation. It has been observed that prediction and optimization using modern software's are essential in choosing sand, mixing agents, porosity levels, moisture conditions necessary for Sand based energy storage to achieve the world's target of Zero Emission by 2050 by harvesting and storing green energy.

References

[1] Ellabban, O., Abu-Rub, H., & Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews, 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.

[2] U. Nations, 'Renewable energy – powering a safer future', United Nations. [Online]. Available: https://www.un.org/en/climatechange/raising-ambition/re newable-energy.

[3] U. Nations, 'ClimateChange', United Nations. [Online]. Available: https://www. un.org/en/climatechange.

[4] Mitali, J., Dhinakaran, S., & Mohamad, A. (2022). Energy storage systems: a review. Energy Storage and Saving, 1(3), 166–216. https://doi.org/10.1016/j.enss.2022.07.002

[5] Xu, B., Han, J., Kumar, A., Li, P., & Yang, Y. (2017). Thermal storage using sand saturated by thermal-conductive fluid and comparison with the use of concrete. Journal of Energy Storage, 13, 85–95. https://doi.org/10.1016/j.est.2017.06.010

[6] Prasad, J. S., Muthukumar, P., Desai, F., Basu, D. N., & Rahman, M. M. (2019). A critical review of high-temperature reversible thermochemical energy storage systems. Applied Energy, 254, 113733. https://doi.org/10.1016/j.apenergy.2019.113733

[7] Tetteh, S., Yazdani, M. R., & Santasalo-Aarnio, A. (2021). Cost-effective Electro-Thermal Energy Storage to balance small scale renewable energy systems. Journal of Energy Storage, 41, 102829. https://doi.org/10.1016/j.est.2021.102829

[8] Thermal Energy Storage could save the EU over 500Mt CO2 per year. (2022, December 15). Coordinating Energy Research for a Low Carbon Europe | EERA. https://www.eera-set.eu/news-resources/3850:thermal-energy-storage-could-save-the-eu-over-500mt-co2-per-year.html

[9] Villasmil, W., Fischer, L. J., & Worlitschek, J. (2018). A review and evaluation of thermal insulation materials and methods for thermal energy storage systems. Renewable and Sustainable Energy Reviews, 103, 71–84. https://doi.org/10.1016/j.rser.2018.12.040

[10] Alva, G., Liu, L., Huang, X., & Fang, G. (2016). Thermal energy storage materials and systems for solar energy applications. Renewable and Sustainable Energy Reviews, 68, 693–706. https://doi.org/10.1016/j.rser.2016.10.021

[11] Lou, W., Luo, L., Hua, Y., Fan, Y., & Du, Z. (2021). A review on the performance indicators and influencing factors for the thermocline thermal energy storage systems. Energies, 14(24), 8384. https://doi.org/10.3390/en14248384

[12] Zadeh, A. A., Peng, Y., Puffer, S. M., & Garvey, M. D. (2022). Sustainable sand substitutes in the construction industry in the United States and Canada: Assessing stakeholder awareness. Sustainability, 14(13), 7674. https://doi.org/10.3390/su14137674

[13] Wang, Z., Wang, Q., Pan, S., Jia, C., Bai, J., & Cui, D. (2021). The chemical structure and thermal evolution of oil Sands bitumen: Experimental and molecular simulation study. Journal of Analytical and Applied Pyrolysis, 158, 105271. https://doi.org/10.1016/j.jaap.2021.105271

[14] Kamińska, J., Puzio, S., & Angrecki, M. (2019). Effect of bentonite clay addition on the thermal and mechanical properties of conventional moulding sands. Archives of Foundry Engineering, 111–116. https://doi.org/10.24425/afe.2020.131291

[15] Radwan, O. and Humphrey, J.: Sand as a thermal energy storage material for solar thermal technologies, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-2421, https://doi.org/10.5194/egusphere-egu24-2421, 2024.

[16] Makhanya, N., Oboirien, B., Ren, J., Musyoka, N., & Sciacovelli, A. (2020). Recent advances on thermal energy storage using metal-organic frameworks (MOFs). Journal of Energy Storage, 34, 102179. https://doi.org/10.1016/j.est.2020.102179

[17] Wang, Z., Wang, Q., Pan, S., Jia, C., Bai, J., & Cui, D. (2021b). The chemical structure and thermal evolution of oil Sands bitumen: Experimental and molecular simulation study. Journal of Analytical and Applied Pyrolysis, 158, 105271. https://doi.org/10.1016/j.jaap.2021.105271

[18] Hinkelman, K., Milner, D., & Zuo, W. (2023). Open-Source models for Sand-Based thermal energy storage in heating applications. Linköping Electronic Conference Proceedings. https://doi.org/10.3384/ecp204627

[19] John, E. E., Hale, W. M., & Selvam, R. P. (2011). Development of a High-Performance concrete to store thermal energy for concentrating solar power plants. ASME 2011 5th International Conference on Energy Sustainability, Parts a, B, and C. https://doi.org/10.1115/es2011-54177

[20] Warerkar, S., Schmitz, S., Göttsche, J., and Hoffschmidt, B. (2011). "Air-Sand Heat Exchanger for Solar Tower Power Stations." Journal of Solar Energy Engineering, 133(2), 021010. DOI

[21] Al-Ansary, H., Jeter, S., Sadowski, D., Alrished, A., Golob, M., El-Leathy, A., & Al-Suhaibani, Z. (2012). Experimental Study of a Sand-Air Heat Exchanger for Use With a High Temperature Solar Gas Turbine System. Journal of Solar Energy Engineering, 134(4), 041017. DOI: 10.1115/1.4007772

[22] Poulose, T., Kumar, S., & Torell, G. (2022). Power storage using sand and engineered materials as an alternative for existing energy storage technologies. Journal of Energy Storage, 51, 104381. https://doi.org/10.1016/j.est.2022.104381

[23] Cárdenas, B., & Garvey, S. (2023). A directly charged thermal store for compressed air energy storage systems. Journal of Energy Storage, 71, 108183. https://doi.org/10.1016/j.est.2023.108183

[24] Tetteh, S., Juul, G., Järvinen, M., & Santasalo-Aarnio, A. (2024). Improved effective thermal conductivity of sand bed in thermal energy storage systems. Journal of Energy Storage, 86, 111350. https://doi.org/10.1016/j.est.2024.111350

[25] W. Lou, L. Luo, Y. Hua, Y. Fan, and Z. Du, 'A review on the performance indicators and influencing factors for the thermocline thermal energy storage systems', Energies, vol. 14, no. 24, Art. no. 24, Jan. 2021, doi:https://doi.org/10.3390/e n14248384.

[26] Zhang, L., Zhou, K., Wei, Q., Ma, L., Ye, W., Li, H., Zhou, B., Yu, Z., Lin, C., Luo, J., & Gan, X. (2018). Thermal conductivity enhancement of phase change materials with 3D porous diamond foam for thermal energy storage. Applied Energy, 233–234, 208–219. https://doi.org/10.1016/j.apenergy.2018.10.036

[27] Chung, K. M., & Chen, R. (2022). Black coating of quartz sand towards low-cost solar-absorbing and thermal energy storage material for concentrating solar power. Solar Energy, 249, 98–106. https://doi.org/10.1016/j.solener.2022.11.028

[28] García-Plaza, J., Díaz-Heras, M., Mondragón, R., Hernández, L., Calderón, A., Barreneche, C., Canales-Vázquez, J., Fernández, A., & Almendros-Ibáñez, J. (2022). Experimental study of different coatings on silica sand in a directly irradiated fluidised bed: Thermal behaviour and cycling analysis. Applied Thermal Engineering, 217, 119169. https://doi.org/10.1016/j.applthermaleng.2022.119169

[29] Karell, E., & Niinimäki, K. (2019). Addressing the Dialogue between Design, Sorting and Recycling in a Circular Economy. The Design Journal, 22(sup1), 997–1013. https://doi.org/10.1080/14606925.2019.1595413

[30] Radwan, O. A., & Humphrey, J. D. (2023). Uses of sands in solar thermal technologies. Solar Energy Materials and Solar Cells, 261, 112533. https://doi.org/10.1016/j.solmat.2023.112533

[31] Miall, A. D. (2007). Sands, gravels, and their lithified equivalents. In Springer eBooks (pp. 960–966). https://doi.org/10.1007/978-1-4020-3609-5_176

[32] Pye, K., & Tsoar, H. (2008). The formation of sand seas and dune fields. In Springer eBooks (pp. 141–173). https://doi.org/10.1007/978-3-540-85910-9_5

[33] Díaz-Heras, M., Calderón, A., Navarro, M., Almendros-Ibáñez, J., Fernández, A. I., & Barreneche, C. (2020). Characterization and testing of solid particles to be used in CSP plants: Aging and fluidization tests. Solar Energy Materials and Solar Cells, 219, 110793. https://doi.org/10.1016/j.solmat.2020.110793

[34] Haemmerle, M., Haider, M., Willinger, R., Schwaiger, K., Eisl, R., & Schenzel, K. (2016). Saline Cavern Adiabatic Compressed Air energy Storage using sand as heat storage material. Journal of Sustainable Development of Energy Water and Environment Systems, 5(1), 32–45. https://doi.org/10.13044/j.sdewes.d5.0131

[35] Mahfoudi, N., Khachkouch, A., Moummi, A., Benhaoua, B., & Ganaoui, M. E. (2015). Design and characterization of a portable heat storage facility. *Mechanics & Industry*, *16*(4), 411. https://doi.org/10.1051/meca/2015021

[36] A. Bouaziz, R. Hamzaoui, S. Rezigue, A. Bennabi, Valorisation du sable de dune dans les formulations des mortiers et des b´etons, 31` emes Rencontres de l'AUGC, E.N.S. Cachan, 29 au 31 mai, 2013

[37] Han, J., Xu, B., Li, P., Kumar, A., & Yang, Y. (2014). *Experimental Study of a Novel Thermal Storage System using Sands with High-Conductive Fluids*. Proceedings of the ASME 2014 International Mechanical Engineering Congress and Exposition, IMECE2014, Montreal, Quebec, Canada. DOI: 10.1115/IMECE2014-38999 1.

[38] Anagnostopoulos, A., Navarro, M. E., Sharma, S., Ahmad, A., & Ding, Y. (2024). From waste to value: Utilising waste foundry sand in thermal energy storage as a matrix material in composites. *Solar Energy*, 268, 112294. Available online: https://doi.org/10.1016/j.solener.2023.112294 1.

[39] Haggag, S., Ibrahim, G., Katsikogiannis, A., Tesh, A., Kamal, H., Menezes, N., & Al Nuaimi, R. (Year). *Experimental Study of Solar Thermal Energy Storage in Sand System*. Department of Mechanical Engineering, American University in Dubai, Dubai, United Arab Emirates.

[40] Miguel Diago, Alberto Crespo Iniesta, Thomas Delclos, Tariq Shamim, Nicolas Calve, "Characterization of desert sand for its feasible use as thermal energy storage medium", the ICAE2015, pp 2113 – 2118, 2015

[41] Davenport, P., Ma, Z., Nation, W., Schirck, J., Morris, A., & Lambert, M. (2022). Thermal stability of silica for application in thermal energy storage. AIP Conference Proceedings. https://doi.org/10.1063/5.0085641

[42] A. M. Vyas and G. S. Kushwah, "Sand Battery: An Innovative Solution for Renewable Energy Storage (A Review)," *2023 IEEE Renewable Energy and Sustainable E-Mobility Conference (RESEM)*, Bhopal, India, 2023, pp. 1-5, doi: 10.1109/RESEM57584.2023.10236319.

[43] Rizvi, Z. H., Zaidi, H. H., Akhtar, S. J., Sattari, A. S., & Wuttke, F. (2020). Soft and hard computation methods for estimation of the effective thermal conductivity of sands. Heat and Mass Transfer, 56(6), 1947–1959. https://doi.org/10.1007/s00231-020-02833-w

[44] Abera, M. M., Ancha, V. R., Amare, B., Sundar, L. S., Mouli, K. V. V. C., & Sangaraju, S. (2024). Simulation and optimization of energy efficiency and total enthalpy analysis of sand based packed bed solar thermal energy storage. Frontiers in Heat and Mass Transfer, 0(0), 1–10. https://doi.org/10.32604/fhmt.2024.049525

[45] Wang, Y., Zhou, L., Chu, C., Zhang, J., Huang, H., Gan, Y., Xia, Y., Tao, X., & Zhang, W. (2019). Sand/carbon composites as low-cost lithium storage materials with superior electrochemical performance. *New Journal of Chemistry*. DOI: 10.1039/C9NJ00424F6.

[46] Deng, R., Chen, J., Chu, F., Qian, M., He, Z., Robertson, A. W., Maier, J., & Wu, F. (2023). "Soggy-Sand" chemistry for High-Voltage aqueous Zinc-Ion batteries. Advanced Materials, 36(11). https://doi.org/10.1002/adma.202311153

[47] Prasant, N., Roy, S., Das, B., & Debbarma, S. (2021). Experimental evaluation of Sand-Based sensible energy storage System. In Lecture notes in mechanical engineering (pp. 563–572). https://doi.org/10.1007/978-981-15-7711-6_56

[48] Yi, F., Gao, J., & Qi, X. (2022). Influence of granite powder addition on thermal conductivity of bentonite-based backfill material in ground source heat pump. Geothermics, 107, 102613. https://doi.org/10.1016/j.geothermics.2022.102613

[49] Nikiforova, T., Savytskyi, M., Limam, K., Bosschaerts, W., & Belarbi, R. (2013). Methods and results of experimental researches of thermal conductivity of soils. Energy Procedia, 42, 775–783. https://doi.org/10.1016/j.egypro.2013.12.034

[50] Midttomme, K., & Roaldset, E. (1998). The effect of grain size on thermal conductivity of quartz sands and silts. Petroleum Geoscience, 4(2), 165–172. https://doi.org/10.1144/petgeo.4.2.165

[51] Ahn, J., & Jung, J. (2017b). Effects of fine particles on thermal conductivity of mixed silica sands. Applied Sciences, 7(7), 650. https://doi.org/10.3390/app7070650

[52] Barry-Macaulay, D.; Bouazza, A.; Singh, R.M.; Wang, B.; Ranjith, P.G. Thermal conductivity of soils and rocks from the Melbourne (Australia) region. Eng. Geol. 2013, 164, 131–138. 16.

[53] Côté, J.; Konrad, J.-M. Thermal conductivity of base-course materials. Can. Geotech. J. 2005, 42, 61–78. 17.

[54] Lu, Y.; Lu, S.; Horton, R.; Ren, T. An Empirical Model for Estimating Soil Thermal Conductivity from Texture, Water Content, and Bulk Density. Soil Sci. Soc. Am. J. 2014, 78, 1859–1868.

[55] Kömle, N.; Hütter, E.; Feng, W. Thermal conductivity measurements of coarse-grained gravel materials using a hollow cylindrical sensor. Acta Geotech. 2010, 5, 211–223.

[56] Ochsner, T.E.; Horton, R.; Ren, T. A New Perspective on Soil Thermal Properties. Soil Sci. Soc. Am. J. 2001, 65, 1641–1647.

[57] Zhang, N., & Wang, Z. (2017). Review of soil thermal conductivity and predictive models. International Journal of Thermal Sciences, 117, 172–183. https://doi.org/10.1016/j.ijthermalsci.2017.03.013

[58] Yu, X., Zhang, N., Pradhan, A., & Puppala, A. J. (2016). Thermal conductivity of sand–kaolin clay mixtures. Environmental Geotechnics, 3(4), 190–202. https://doi.org/10.1680/jenge.15.00022

[59] Overduin, P., Kane, D., & Van Loon, W. (2006). Measuring thermal conductivity in freezing and thawing soil using the soil temperature response to heating. Cold Regions Science and Technology, 45(1), 8–22. https://doi.org/10.1016/j.coldregions.2005.12.003

[60] Smits, K. M., Sakaki, T., Limsuwat, A., & Illangasekare, T. H. (2010). Thermal Conductivity of Sands under Varying Moisture and Porosity in Drainage–Wetting Cycles. Vadose Zone Journal, 9(1), 172–180. https://doi.org/10.2136/vzj2009.0095

[61] Zhang, N., Yu, X., Pradhan, A., & Puppala, A. J. (2015). Thermal conductivity of quartz sands by Thermo-Time Domain Reflectometry probe and model prediction. Journal of Materials in Civil Engineering, 27(12). https://doi.org/10.1061/(asce)mt.1943-5533.0001332

[62] Fei, W., Narsilio, G. A., & Disfani, M. M. (2021). Predicting effective thermal conductivity in sands using an artificial neural network with multiscale microstructural parameters. International Journal of Heat and Mass Transfer, 170, 120997. https://doi.org/10.1016/j.ijheatmasstransfer.2021.120997

[63] Farzi, A., Nameni, R., & Yazdi, H. A. (2021). Enhancement of single slope solar still using sand: the effect of sand grain size distribution. Journal of Solar Energy Research, 6(2), 740–750. https://doi.org/10.22059/jser.2021.320642.1194