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Characterization of desert sand to be used as a high-temperature thermal energy storage medium in particle solar receiver technology

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HIGHLIGHTS

- Desert dune sand is evaluated as thermal energy storage, heat transfer, and direct solar absorber material.
- Comprehensive characterization of seven sand samples from the desert of the United Arab Emirates.
- Operation up to 1000 °C demonstrated possible.

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ABSTRACT

Desert dune sand is considered as a potential sensible heat thermal energy storage (TES) material. Several samples are collected from different locations of the desert in the United Arab Emirates (UAE), and relevant thermophysical and mechanical properties are measured. In addition, the optical properties of desert sand are investigated to evaluate its performance as a direct solar absorber. Thermogravimetric analyses show that the samples appear to be thermally stable between approximately 650 °C to 1000 °C following an initial mass loss occurring during the first heating cycle. The transformation of calcium carbonate into calcium oxide at higher temperature during the first heating process has a negative impact on the solar absorption of the sand. In addition, the high calcium content leads to sand agglomeration which has significant implications on receiver design and operation. It is therefore critical to locate sand collection points with low carbonate content.

1. Introduction

Concentrated solar power (CSP) plants can extend production beyond sunlight hours with the use of thermal energy storage (TES) [1]. The two-tank molten salt system is currently the only proven technology in commercial CSP plants to sustain power production beyond sunshine hours. The temperatures in the molten salts typically fluctuate from 290 °C to 565 °C (e.g., Solar Two [2], Gemasolar [3]) as thermal energy is charged and discharged from the well-established "Solar Salt" formulation. This temperature range imposes substantial limitations on the system. To maintain the salts above their freezing temperature, adequate pipe insulation and electrical tracing are necessary, and the upper operating limit of 565 °C bounds the maximum efficiency of the power block. Despite ongoing research to develop new formulations with wider operating temperatures [4–6], higher temperatures remain inaccessible due to the onset of thermal decomposition in the salts [7]. Alternative TES approaches have been proposed such as phase change materials (PCM) which reach significantly higher energy densities and are capable of exchanging heat within narrow temperature ranges [8]. Research remains active on developing candidate materials [9–11] and enhanced heat transfer techniques [12–14] for PCM's. Thermochemical energy storage concepts are also potential alternative TES solutions, however the technology is still in early development [15]. Finally, extensive research has been carried out on solid sensible heat TES designs, including thermal storage in solid blocks of material [16–19], as well as in packed beds [20,21].

Heat storage in solid particles is a TES approach which allows to store and dispatch thermal energy from ambient temperature to an excess of 1000 °C. The higher temperatures lead to higher heat engine efficiencies, which in turn allow to reduce overall costs of LCOE [22] and TES sub-systems [23]. Moreover, direct solar absorption on solid particles requires much simpler technology than molten salts [24,25] and reduces system exergy losses [26]. A comprehensive review of recent developments in solid particle receivers has been published by Ho

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[27]. Several solid particle solar projects are in development, including demonstrated prototypes such as the "falling particle" receiver at the Sandia National Laboratories in development since the early 1980s [28]. Commercial ceramic particles have been successfully heated above 700 °C under concentrated solar flux [29–31], and several supporting material characterization studies have been carried out [32–35]. A class of proppants from the oil industry has been identified to have promising optical and mechanical properties. Furthermore, PROMES-CNRS independently demonstrated a solar receiver capable of heating silicon carbide particles above 700 °C [36,37]. DLR presented a 15 kW_{th} centrifugal receiver with bauxite particles heated to 900 °C [38]. Zhejiang University has tested a spiral solid particle receiver where a stream of alumina particles was heated to 650 °C [39,40]. Finally, this work is presented within the scope of the SandStock project, which consists in a gravity-fed hopper-like solar receiver. The concept has been demonstrated in a 2 kW solar furnace using desert sand samples [41,42].

Herein we propose the use of natural dune desert sand as a solar absorber and TES medium. In contrast with nitrate salts and engineered solid particles, sand is readily available at no cost in attractive locations for the deployment of CSP projects (e.g., Chile, Australia, UAE), and can be used with almost no pre-processing. Solar projects with substantial TES systems may source the material locally from nature, eliminating the cost of importing materials typically required for TES applications. Moreover, dune sand provides the advantages of other engineered solid particles, including the possibility of higher operation temperatures and direct solar absorption. Several samples from the desert of the UAE are identified as potential candidates and shown to be capable of absorbing, storing and delivering sensible heat up to 1000 °C. High calcium contents are shown to have significant implications in practical CSP applications. This work complements and extends geological characterizations previously carried out in the region [43–47], and is based on partial results presented earlier by the authors [41,48,49].

2. Materials and methods

2.1. Material selection

Desert sand samples were collected across several desert regions of the UAE. The exact sampling locations are given in Table 1, and mapped in Fig. 1.

In each case, the sand was collected from an undisturbed region of the site, after the removal of the first layers exposed to the atmosphere. Batches of approximately 8 kg were retrieved and stored in sealed containers.

2.2. Elemental analysis

The elemental analysis was done with a *Thermo Scientific Niton XL3t GOLDD+* portable X-ray fluorescence (XRF) analyzer. The device is equipped with a large area drift detector operating with a resolution below 185 eV, and calibrated with the soil standards provided by the vendor (*Lead high*, *Lead medium* and *Lead low*). The analyzer was mounted on a stationary test stand to facilitate the handling of the samples, and to improve repeatability of the experimental conditions. Each sample was mounted on a holder closed by an XRF polypropylene film. During each measurement, the sample holder was placed inside the test stand in front of the aperture of the XRF gun. The analyses were carried out under the device's *AllGeo* identification routines, using exposure times of 60 s. Other routines were tested, although the results showed no significant differences. All samples were tested a minimum of three times.

Table 1
Coordinates of sample collection points.

Sample name	GPS location
Abu Dhabi	24.427087 N, 54.953474 E
Dubai	24.436554 N, 55.356433 E
Al Ain 1	24.353357 N, 55.401953 E
Al Ain 2	24.215931 N, 55.389515 E
Al Ain 3	24.789423 N, 55.389991 E
Liwa 1	23.123534 N, 53.821159 E
Liwa 2	22.914587 N, 54.269939 E

Fig. 1. Sample collection points placed on the map of the United Arab Emirates.

2.3. Thermal stability

The thermal stability of the sand samples was studied using a combined thermogravimetric analysis-Fourier transform infrared spectroscopy (TGA-FTIR) setup. The technique records the mass variations of each sample with respect to temperature, as well as the infrared spectrum of the gases that emanate during the decomposition. This provides an insight into the temperature-dependent transformations that may occur in the material at different stages during its use as TES media.

All the analyses were done on a TGA device provided by *NETZSCH*, model *TG 449 F3 Jupiter* with a balance resolution of 0.1 µg, linked to an FTIR machine from *Bruker Optics*, model *Vertex 80V*. Before the measurement series, the TGA data processing software was calibrated with an empty crucible using the same temperature program used for the sample evaluation. The signal obtained during this calibration was later subtracted from the raw experimental output to calculate the actual mass loss curve. Prior to each analysis, the sand samples were manually stirred in their containers, and then placed in alumina crucibles for weighing in an analytical balance with a precision of 0.1 mg. The typical mass studied each time was in the vicinity of 70 mg. Each measurement was repeated at least three times for each sample. The experiments were run under a protective atmosphere of nitrogen flowing at 20 mL/min into the TGA furnace. In each experiment, the furnace was first stabilized to 40 °C, and then heated at a constant rate of 10 K/min up to 1100 °C. The samples were analyzed as collected from the desert. In all cases, the materials were free of extraneous elements (i.e., organic matter), and therefore no supplementary preprocessing was performed.

2.4. Specific heat capacity

The sand samples were analyzed using the differential scanning calorimetry (DSC) technique. This provides the evolution of the specific heat capacity of the material as a function of temperature, and allows to detect transformations with a thermal footprint (endo/exothermic