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Thermophysical and chemical analysis of gneiss rock as low cost candidate material for thermal energy storage in concentrated solar power plants

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ABSTRACT

A packed bed of rocks with air as heat transfer fluid can be considered as a cost effective storage system, as it enhances the dispatchability of the concentrated solar power plant at lower costs. However, the identification of suitable rocks to be used as a storage medium requires a prior experimental characterization, since the studies published about the behaviour of rocks at high temperatures are scarce in literature. This work aims to investigate the potential of gneiss rock as a candidate storage material in solar power plants. Thus, thermal stability of two varieties of gneiss rock has been studied at temperatures up to 1000 °C during heating and cooling by thermogravimetric and differential thermal analyzer (TG/DTA). The influence of temperature on specific heat capacity, thermal diffusivity and thermal conductivity has been analyzed. Furthermore, the chemical composition and crystalline phases have been identified by X-ray fluorescence and X-ray diffraction, respectively. The obtained results proved the potential of this type of rocks in terms of high thermal capacities, high density and good thermal stability up to 550 °C.

1. Introduction

One of the most promising ways to use solar energy is concentrated solar power (CSP) [1]. It is considered as a commercially available renewable energy technology, which is capable of harnessing the immense solar resource in countries with high direct normal irradiance (DNI). Indeed, CSP plants can be considered as a promising technology which helps reducing greenhouse gas emissions linked with electricity generation. However, due to the intermittency of solar energy, the incorporation of a storage system becomes mandatory, in order to ensure the dispatchability of the power plants, reduces the levelized cost of electricity (LCOE) and thus, make this technology competitive with conventional power plants.

At present, the most commercially available storage option is based on the concept of liquid sensible heat storage in a two tanks of molten salts [2]. Nevertheless, the current formulations of molten salts are not stable at temperatures higher than 565 °C [3]. Besides, the major challenge of the currently used molten salts is their high freezing point (120–220 °C). This latter requires innovative protection methods which generate high costs [2]. Thus, in order to reduce the cost of the thermal energy storage (TES) section, an air-rock packed bed storage system can be considered as a cost effective storage option and a promising alternative to the state of the art TES technology. In this concept, hot air is ducted into a single tank filled with rocks in order to store energy, which is recovered by reversing the flux of the air. In fact, this system presents several advantages, it is environmentally friendly due to the use of air as heat transfer fluid (HTF) and natural rocks as low cost storage material; the direct contact between the HTF and filler materials allows good heat transfer characteristics and eliminates the use of heat exchangers. Moreover, using a unique tank instead of two reduces costs linked with the storage option (up to 35%) [4]. Therefore, packed beds systems are economically attractive due to their lower capital cost [5]. This system can ensure the dispatchability of the CSP plant and potentially reduces the LCOE by increasing the capacity factor of the plant.

A wide body of publications is available on numerical modeling of the air-rock packed bed storage system to investigate its performance up to 600 °C, based on calculated or average

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thermophysical properties of rocks, such as the studies presented by zanganeh et al. [6] and Hänchen et al. [7]. However, only few studies have been conducted to explore the potential and durability of natural rocks as material storage whether with air or other HTFs. In 1991, Fricker [8] identified five varieties of rocks which withstood thermal cycling tests, between 20 °C and 600 °C, without disintegration or excessive mass loss. These rocks are: granite, basalt, gneiss, peridotite and diabase. In the same context, Allen et al. [9] identified some suitable rocks by performing thermal cycling tests 950 times between 350 °C and 500–530 °C. As a result, the variety which resisted to the process of thermal cycling included: dolerite, unweathered granite, hornfels, and some gneisses survived the process while some others did not. Another experimental study conducted by Pacheco et al. [10] lead into the selection of a mixture of quartzite rock and silica sand as the most suitable filler materials in a thermocline storage system with molten salts as the HTF.

The most relevant thermophysical characteristics required in rocks as any other sensible heat storage material are: high density (**ρ**), high specific heat capacity (C_p) and high thermal conductivity (**λ**) [11]. In this perspective, a parametric study conducted by Aly and El-sharkawy [12] about the effect of the thermophysical properties on the packed bed performance, showed that the higher are the specific heat capacity and density, the higher will be the amount of energy stored in the system as well as the rate of charging. Besides, a high thermal conductivity is required to enhance the thermal dynamic of the system, as when this property increases it improves considerably the rate of charging as well as increases the amount of energy stored for a specific charging period [12]. Furthermore, thermomechanical and chemical stability of the storage material are also required, since the rock should survive thermal cycling without disintegration or chemical decomposition.

So far, there is a lack in literature concerning the thermophysical characteristics and temperature related behaviour of rocks. These data are necessary in order to well predict the performance of the packed bed storage system and select rocks with the highest potential for each range of temperature. In this regard, the present paper aims to investigate the thermophysical properties and the geochemical and mineralogical composition of two varieties of gneiss rock collected from two different Moroccan regions. An experimental characterization has been performed to identify the chemical composition and the crystalline components of these rocks, as well as to study the influence of temperature variation on their thermal properties.

2. Experimental

2.1. Materials

Gneiss rock studied in this work have been gathered from two different Moroccan regions (Ourika and Benibousera), where this kind of rock is present in copious quantities. Indeed, Gneiss is a high grade metamorphic rock characterized by medium to coarse grain size due to the crystallization under high temperature and high pressure. Table 1 presents thermophysical properties of gneiss in comparison with molten salts, the state of the art storage material. These data found in literature at ambient temperature encourage the investigation of the potential of gneiss as a candidate material to be used in a packed bed storage system.

2.2. Characterization techniques

Experimental characterization of the studied rocks requires a prior preparation. Thus, gneiss samples gathered in their natural state were crushed and ground to be transformed into a fine powder, while other samples were cut and polished to obtain square shapes of $10\times10\times2$ mm. The prepared samples were characterized in term of the properties required in a sensible heat storage material:

Table 1
Thermophysical properties of gneiss and molten salts [13–15].

	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal capacity (MJ/m^{3}K)	Thermal conductivity (W/m K)
Gneiss	2700	770–979	2.08–2.64	2.7–3.1
MoltenSalts	900–2600	1500	1.35–3.9	0.15–2

The chemical composition of powder samples were identified by the X-ray fluorescence, Axios XRF by PANalytical. An X-ray diffractometer D8 Discover (BRUKER Company) was used to define the crystalline phases present in the analyzed samples, at room temperature. The data were collected between 1 and 90 in 2θ, with a scanning speed of 4.5° (2θ)/min.

Concerning the thermophysical properties, the density of the gneiss samples was obtained using a Helium pycnometer Accupic 1330. A series of five measurements have been performed in this device to assure the accuracy of the results. A differential scanning calorimeter (DSC instrument model Q100) was used to measure the specific heat capacity, upon heating the sample in a temperature range of 20–370 °C. DSC was performed in the modulated heat only method under nitrogen atmosphere with a flow of 60 ml/min. For each measurement a mass of 15 mg to 20 mg was used and the heating rate was 10 °C/min. The tests were conducted on three different samples of each type of gneiss and the average values are presented in the results. In order to study the thermal stability of the gneiss varieties, a thermal cycle was performed by a thermogravimetric and differential analyzer (TG-DTA Setaram Setsys evolution 1750). The powder samples were heated in a platinum crucible from room temperature up to 1000 °C with heating and cooling rates of 10 °C/min, under a flowing air atmosphere. The test has been performed using a sample mass of 30 mg ± 1 mg. Square samples ($10\times10\times2$ mm) were used in a laser flash apparatus (LFA 447 NanoFlash) in order to measure the thermal diffusivity of the studied rocks. These samples were heated from room temperature to 1000 °C with a heating rate of 2 °C/min, under argon atmosphere. The thermal conductivity of the studied rocks was calculated by multiplying the volumetric heat capacity ($\rho\times C_p$) and the thermal diffusivity (d) of the rock (see Eq. (1)); assuming that density of rocks remains constant while temperature increases, since this parameter undergoes only a small change under heating [16].

$$\lambda=\rho\times C_p\times d \tag{1}$$

3. Results and discussion

3.1. Geochemical composition and structural analysis

The chemical composition of both varieties of gneiss was examined by X-ray fluorescence. The obtained results were compared with average data reported in the literature [17], as shown in Table 2. It can be revealed that the most predominant element is silicon, followed by aluminum, as expected from literature. The rock contains also a reasonable amount of sodium. In fact, it has been found that the larger the amount of SiO_2 present in a rock, the higher is its strength characteristics and microhardness [18], these latter are very required in the storage material, since a high