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Experimental characterization of siliceous rocks to be used as filler materials for air-rock packed beds thermal energy storage systems in concentrated solar power plants

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ABSTRACT

Due to the intermittency of solar radiation, the integration of a thermal energy storage system is a key solution to ensure the dispatchability and enhance the cost-effectiveness of concentrated solar power plants (CSP). Recently, the use of rocks as sensible heat storage materials in packed bed systems has been the main object of several research studies. Nevertheless, limited knowledge is available on the thermal behavior of rocks at high temperatures and their suitability is yet to be deeply studied. The present paper aims to investigate the potential of quartzite and flint rocks to be used as filler materials in a packed bed storage system with air as the heat transfer fluid (HTF). These siliceous rocks have been subjected to an experimental characterization in terms of the properties required in a sensible heat storage material. In fact, the geochemistry and structure of these rocks were identified and some mechanical characteristics were measured. The influence of temperature variation on thermal capacity, thermal diffusivity and thermal conductivity was also analyzed. Besides, thermogravimetric analysis was performed up to 1000 °C, in order to check the thermal stability of rocks. In addition, 110 thermal cycles were achieved in a furnace up to 550 °C. Characterization experiments demonstrated the potential of silica rocks as storage materials. However, the preliminary results of accelerated thermal cycling tests indicate that performing a thermal treatment of these rocks could be of great interest, especially when used at temperatures higher than 250 °C, in order to enhance their lifetime.

1. Introduction

Recent years have witnessed a dramatic increase in energy demand and consumption as a result of population growth and industrialization. Thus, conventional energy resources (oil, natural gas and coal) used to produce heat or electricity are on their way to depletion; furthermore, global warming caused by greenhouse gases (GHG), released by the combustion of fossil fuel, is the nightmare threatening life in our planet. Therefore, the use of renewable energies becomes more crucial and can be considered as the key solution to meet the world's energy demand without increasing GHG emissions. Concentrated solar power (CSP) generation is a very promising and unique technology among other renewable energies, as it has a better dispatchability due to the possibility and ease to integrate thermal energy storage (TES) systems [1].

Because of the intermittency of the solar energy input, the incorporation of a storage system in CSP plants is essential in order to correct the mismatch between the supply and the demand of energy [2]. In fact, the storage option increases the capacity factor and the economic viability of the CSP plant. For instance, adding 6-h of TES in a parabolic trough power plant can double the capacity factor to reach about 50%, whereas it can be as high as 80% by integrating a 15-h storage system in solar tower power plants [3]. In the other hand, TES can decrease the levelized cost of electricity (LCOE) [3], and thus make CSP technologies more competitive with fossil fuel power plants as well as with other technologies based on renewable energies.

Depending on the storage material used, TES can be classified into three types: sensible, latent and thermochemical [4]. So far, sensible heat storage is the most widely used and developed storage mechanism, compared with latent and thermochemical storage. In a sensible heat storage medium, energy is stored/extracted by increasing/lowering the material temperature without changing its phase, while the process of latent heat storage is almost isothermal since the maximum energy is absorbed or released when the storage medium reaches its phase transition temperature [5]. In the case of thermochemical storage, the concept is based on a reversible endothermic/exothermic chemical reactions [5]. It is the least developed method, although it can achieve a

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Nomenclature

C_p	specific heat capacity (J/kg K)
ρ	bulk density (kg/m^3)
λ	thermal conductivity (W/m K)
α	thermal diffusivity (m^2/s)
P	apparent porosity (%)
W_a	water absorption (%)
m_s	saturated mass (kg)
m_d	dry mass (kg)
m_h	humid mass (kg)

Acronyms

CSP	concentrated solar power
TES	thermal energy storage
HTF	heat transfer fluid
LCOE	levelized cost of electricity
LOI	loss on ignition
XRF	X-ray fluorescence
XRD	X-ray diffraction
FTIR	fourier transform infrared
DSC	differential scanning calorimeter
TGA	thermogravimetric analysis
LFA	laser flash analysis

higher energy density than sensible and latent storage systems [2], due to its high cost and complexity [6]. In addition to the storage mechanisms, two TES concepts can be distinguished: the active storage, where the storage material is a fluid and can flow between the tanks; and the passive storage, where the storage medium is a solid and during the process of charging/discharging, the heat transfer fluid (HTF) passes through the storage material [7]. An active storage can also be called “active-direct” when the HTF is also used as the storage medium; in the case of an “active-indirect” storage, heat exchangers are needed to separate the storage material and the HTF [8]. Among the available TES technologies, sensible heat storage in the two tanks of molten salts is the most widely used option in commercial CSP plants, mainly parabolic trough and central receivers [9]. While short term storage (less than 1-h) can be achieved by a steam accumulator, which is integrated in CSP plants using water as the HTF such as linear Fresnel systems [2]. In fact, molten salt has proven its efficiency by allowing up to 15-h of storage at the Gemasolar solar tower power plant in Spain [10]. Nevertheless, this technology induces high costs [11] due to the high freezing point (120–220 °C) of the storage media which requires protective methods to prevent its solidification [5]. In addition to the corrosive character of molten salts toward the storage container, a large amount (28,000 t for Andasol) of the material is used, which increases the investment costs of the storage unit [12]. In this regard, extensive studies are being conducted to identify and/or develop more efficient and low cost storage systems. Recently, the thermocline concept has been suggested as a possible alternative to the two reservoirs of molten salts [2]. This technology is based on the use of a single tank where the hot fluid (synthetic oil or molten salts) is at the top of tank and the cold at the bottom, their separation is ensured by thermal stratification [5]. This concept can achieve up to 35% of cost reduction compared with the state of the art storage systems, which results in decreasing the LCOE [13]. However, the insertion of solid filler materials in the tank is of great importance to reduce the convection through the liquid phase, maintain the thermal gradient [2] as well as to reduce the amount of the liquid used [14]. This innovation is called dual-media thermocline storage system where the energy is stored in both liquid and solid phases [9]. The direct contact between both materials allows higher heat transfer efficiencies and the use of inexpensive filler materials makes the concept more attractive technically and economically [15].

Today, a great attention is paid to solid storage mediums in order to enhance the storage system efficiency and make it more cost effective. In this regard, several studies were carried out with the aim to investigate the potential of some material candidates such as: ceramics, concrete, asbestos and rocks. Zunft et al. [16]conducted a test campaign at the Solar Power Tower Jülich, to evaluate the performance of the storage system using a honeycomb made of ceramics (alumina porcelain C130) as the storage medium and air as the HTF. The obtained results confirmed the functionality of the storage system through many thermal cycles up to 680 °C.The German Aerospace Center (DLR) has developed a high temperature concrete, which is able to be used in storage applications up to 500 °C. A series of tests were conducted and confirmed the feasibility of this option [2]. In addition, some research works focused on the valorization of industrial wastes as TES materials such as asbestos containing wastes, fly ashes and wastes from recycling steel [17]. However, all the previously mentioned materials have a common drawback which is their development cost. In this perspective, natural rocks have been suggested as cheap and available materials, especially when used in a direct contact with air at low velocities [18]. So far, an air-rock bed storage system is considered as promising and cost effective system [8]. The direct contact between air and rocks allows higher heat transfer efficiencies and eliminates costs generated by the use of heat exchangers to separate the HTF and the storage medium.

A great number of research works on air-rock packed beds are available in the literature, however, most of them are concerned with the modeling and simulation of the TES systems, but only few studies include experimental work. Among these studies, Zanganeh et al. [19] focused on the prediction of the thermal performance of an air-rock packed bed system using a developed and experimentally validated model. While Allen et al. [20] conducted a series of thermal cycling tests (up to 530 °C) to evaluate the durability of many types of rocks. They identified several suitable rocks such as hornfels, some types of gneisses, unweathered granite and dolerite. In addition, Pacheco et al. [21] demonstrated the potential of using a mixture of quartzite rock and silica sand as filler materials due to their low cost and compatibility with molten salts, among other material candidate. In the same context, Brosseau et al. [14] performed a series of isothermal (1-year) and thermal cycling tests (10,000 cycles) to demonstrate the durability of quartzite rock and silica sand up to 500 °C. No significant degradation of the filler material was detected. Other studies such as Yang and Garimella [22] simulated the performance of a thermocline system filled with quartzite and molten salts during charging and discharging. The results showed a severe decrease in the air outlet temperature at small Reynolds number and non-adiabatic boundary conditions [22].

According to our knowledge, thermophysical properties of rocks used in simulation works found in literature are whether measured at room temperature, or calculated using correlations to predict the temperature dependence of these properties. Only few research work conducted experimental characterization of some rocks candidates to obtain more reliable values, such as Grirate et al. [23], Tiskatine et al. [24] and Jemmal et al. [25]. Indeed, quartzite rock has been selected as a potential filler material with molten salt up to 500 °C [14] and with synthetic oil up to 300 °C [23]. In this context, and since limited data are available on the effect of temperature related behavior of rocks, this study suggests the investigation of the potential of two different types of siliceous rocks, namely quartzite and flint rocks, to be used as storage material in a packed bed system using air as the HTF. The present work

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