Applied Thermal Engineering 117 (2017) 591–608

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Identification of suitable storage materials for solar thermal power plant using selection methodology

Rachid Tiskatine [a,*], Ahmed Aharoune [a], Lahcen Bouirden [a], Ahmed Ihlal [b]

[a] Thermodynamics and Energetics Laboratory, Faculty of Science, IbnZohr University, BP8106, 80006 Agadir, Morocco
[b] Materials and Renewable Energies Laboratory, Faculty of Science, IbnZohr University, BP8106, 80006 Agadir, Morocco

HIGHLIGHTS

- Paper proposes selection methodology to select the most suitable material for TES applications.
- The most relevant properties of rock samples collected from different Moroccan regions have been characterized.
- An experimental device has been made for thermal conductivity measurement.
- Rocks have great potential as SHS materials up to 650 °C.
- Gabbro rock is potentially suited for packed bed storage system with air as the HTF.

ARTICLE INFO

Article history:
Received 16 October 2016
Revised 7 January 2017
Accepted 29 January 2017
Available online 1 February 2017

Keywords:
High temperature SHS
Rock bed
CSP plants
Experimental characterization
Thermal conductivity measurement
Selection methodology

ABSTRACT

Due to the intermittent nature of solar energy, there is a need to store heat to meet the needs when solar light is not available. Rock bed using air as heat transfer fluid (HTF) is being now used for thermal energy storage (TES) in concentrated solar power (CSP) plants. It is considered as a cost effective storage system. However, no detailed works have been published on selection and identification of rocks for high temperature storage applications. The scope of the present study is to choose the most suitable rocks for high temperature sensible heat storage (SHS) using a methodology based on laboratory measurements. Thus, experimental characterization of several rock types has been performed. An experimental device has been made for thermal conductivity measurement at room temperature. The obtained results show that the gabbro rock is the best candidate material for CSP plants. Comparative study with some other conventional materials found in literature indicates that rock is an efficient filler material for high temperature TES. From the obtained results and correlations, a second selection methodology has been proposed in order to minimize the steps of selection using simple and few tests.

1. Introduction

Solar energy is the most important source of renewable energy available today. It is the most abundant, and Morocco has one of the best direct normal irradiation (DNI) conditions world-wide. However, solar energy, as well as most other renewable sources, is known for its intermittent nature. It is available only in daylight and depends to weather conditions. High temperature thermal energy storage (TES) is starting to play an important role in industrial field and solar applications. It is a key technology for regularization and correction of mismatch between supply and energy demand as well as optimization of Concentrated Solar Power (CSP) [1,2] that has became the most important technologies to produce electricity from renewable energy resources. Furthermore, thermal storage has lower capital costs as compared to other storage technologies and has very high operating efficiencies. TES systems would be charged in the day-time, and the stored heat would be released when there is no sunlight.

There are three kinds of TES systems: sensible heat storage (SHS), latent heat storage (LHS) and thermo-chemical storage [3–6]. Combination of the first two types is considered as well [1,7,8]. In SHS systems, energy is stored by heating or cooling a liquid or solid storage medium without change the phase. Some advantages of SHS systems compared to other alternatives are simplicity of design, operation and construction, ease of control, economy and lower cost, and maturity for seasonal energy storage [3,4,9]. Kumar and Shukla [8] and Singh et al. [4] reported that SHS is the most common method of TES. In this context, water appears to be the best SHS liquid because it is inexpensive and

* Corresponding author.
E-mail address: tiskatinerachid@gmail.com (R. Tiskatine).

http://dx.doi.org/10.1016/j.applthermaleng.2017.01.107

Nomenclature

Latin characters

m	mass [kg]
V	volume [m^3]
n	porosity [%]
F	force [N]
S	surface [m^2]
d	diagonal [m]
P	pressure [N/m^2]
HV	hardness Vickers [–]
T	temperature [°C]
e	thickness [m]
h	heat transfer coefficient [W/m^2 K]
Q	thermal energy stored [J]
c_p	specific heat [J/kg K]

Greek characters

ρ	density [kg/m^3]
Φ	heat flux [W]
λ	thermal conductivity [W/m K]
α	thermal diffusivity [m^2/s]

Subscripts

b	bulk
p	particles
amb	ambient
s	surface
w	wall
smp	sample
ref	reference
wsmp	sample wall
wref	reference wall
sref	reference surface
ssmp	sample surface

Abbreviations

DNI	direct normal irradiation
TES	thermal energy storage
CSP	concentrated solar power
SHS	sensible heat storage
HTF	heat transfer fluid
LHS	latent heat storage
XRF	X-ray fluorescence
XRD	X-ray diffraction
TGA	thermogravimetric analysis
DTA	differential thermal analysis
DSC	differential scanning calorimetry
HTC	high temperature concrete

has a high specific heat capacity. However, it has a limit temperature for operation (about 100 °C). From the literature, TES technologies implemented in commercial plants are based on molten salts as storage materials [10]. However, molten salt is not stable at temperatures higher than 565 °C [11] and needs complex equipment [10]. Thermal oil can also be used in CSP applications but it is limited to a maximum temperature of about 400 °C and is not environmentally friendly.

Numerous studies are available on TES. Ismail and Stuginsky [12] compared six possible fixed bed models for TES in packed bed, both for SHS and LHS. They reported that thermal capacity, thermal conductivity and particle size are the relevant thermo-physical properties of a storage material, and found that the void fraction of the bed affects the overall heat capacity of the storage system. Singh et al. [4] discussed a detailed review on packed beds solar energy storage systems with a list of potential filler materials and their corresponding thermo-physical properties. They found that the shape and size of the storage materials and void fraction are important parameters that affect the performance of a storage system. Gil et al. [10] reviewed a list of the materials used in high temperature TES applications and reported that the requirements for a thermal storage system are high storage capacity, mechanical and chemical stability and long lifetime of the storage material, good heat transfer between HTF and the storage material, low thermal losses, ease of control and integration into the power plant. Kuravi et al. [11] published a broad review of the various TES technologies applicable to CSP plants. They pointed out that the cost of the system affects the overall cost of the plant and the energy output.

In order to ensure optimal storage dynamics and longevity, thermo-physical properties, chemical properties, environmental and economic impact, lifetime, as well as availability have to be taken into account [9,12–15]. The use of rock as storage material addresses widely the previous criteria. In addition, rock may reduce the quantity of heat transfer fluid (HTF) used for charging and discharging energy. Zanganeh et al. [7], Fricker [16] and Hänchen et al. [17] reported that rock bed is a simple efficient thermal storage component in many air-based solar heating systems, and does not need an additional heat exchanger between the collector and the heat storage tank [18]. In fact, these systems present several advantages: they are economical and environmentally friendly due to the use of air (HTF) and natural rocks that are clean and inexpensive. Morever, the heat transfer between air and rock is good [18] and it is not necessary to use the heat exchangers.

In literature, few studies have been published on the suitability of rocks for TES. Fricker [16] studied five varieties of rocks for use in TES and showed the great potential of rock beds for high temperature application. Pacheco et al. [19] recorded that quartzite and silica sand are the most suitable filler materials when used with molten salt as working fluid. Same result was obtained by Brosseau et al. [20] who have tested several rock types with the same HTF. Allen et al. [21] thermally cycled a variety of rock samples in order to know which rock types are suitable for thermal storage. They found that granite, shale and gneiss were damaged during thermal cycling, while sandstone, dolerite and greywacke withstood the thermal cycles and can therefore be used in packed bed TES. Recently, in 2016, Tiskatine et al. [22] discussed the thermo-mechanical behavior of rocks during thermal cycling and found that the degree of cracking and the open porosity increase gradually for rocks that are unable to withstand thermal cycles. Jemmal et al. [23] studied the potential of gneiss rock for use in thermal storage and suggested it as a successful storage material up to 550 °C. Concerning the selection of materials for SHS, the studies for high temperature utilization are scarce in literature. Fernandez et al. [24] and Navarro et al. [25] compared some materials with others available in literature using a methodology developed by Prof. Ashby [26] and based on a CES Selector Software [27] which considers various selection criteria such as cost, availability and thermo-physical properties. The first worked in a temperature range 150–200 °C. They indicated that Halite (sodium chloride) is a low cost material having good thermophysical properties. The second worked in temperatures up to 500 °C and demonstrated that Cofalite is among the cost effective materials that have the best performance for CSP industrial TES. Khare et al. [9] used the same