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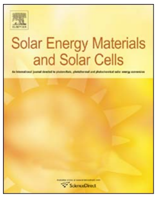

Thermal properties and friction behaviors of slag as energy storage material in concentrate solar power plants

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ABSTRACT

Thermal energy storage (TES) system is greatly used in concentrated solar power (CSP) plants to collect energy for later need. It is proposed that slag is suitable for energy storage in CSP plants, however, little has been studied in this field. In this paper, the thermal stability, specific heat capacity, thermal conductivity and microstructures of two electric arc furnace (EAF) slag samples were studied. In TES system, as heat storage material, slag will meet with high temperature and low temperature environment. The wear resulted from heat expansion and cold contraction of slag with storaging and releasing energy process was addressed. The results revealed that slag is a good candidate to be used as heat storage material for TES system. Revalorization of slag into TES material is a cost-effective solution to the CSP plants and the industry waste recovery.

1. Introduction

The International Energy Outlook 2013 (IEO2013) predicted the world energy consumption will grow by 56 percent between 2020 and 2040 [1]. An important challenge society must face is the limitation of fossil fuel. In this frame, renewable energy is a key factor to solve energy problem. Among the different renewable energies, electricity generation in CSP plants presents several advantages when compared with modern biomass, hydroelectricity and wind electricity [2,3]. One of the most attractive one is the use of heat storage, which will improve efficiency of the CSP plants [4]. With a TES system, an electrical power generator can work after sunset. In addition, CSP plants can help reducing the air pollutants linked with electricity generation and lowering the costs of climate change mitigation.

Parabolic trough collectors (PTC) and solar power towers (SPT) are the most used technologies for CSP plants. The work temperature range of PTC and SPT technologies is 20–400 °C. [5] In commercial CSP plants, the widely used TES solution is a molten nitrate salts mixture called “Solar salt” [6] in a double-tank arrangement. The arrangement requires a large number of “Solar salt” for each power plant (e.g. 28,500 t in the ANDASOL 1 (50MWe) plant in Granada, Spain) [7]. Except the large demand of the material, another disadvantage of using solar salt is the high freezing point of most salts which would require more piping and insulation materials [8]. These features made it cost a lot to use “Solar salt” in TES system. Overall, it's necessary to find a cost-effective and efficient storage material.

In sensible heat storage applications, heat storage requires: high specific heat capacity, high thermal conductivity, good mechanical stability, cheap and abundant materials [8]. In this frame, the valorization of industrial waste or by-product as heat storage material can reduce the cost of the TES system [9]. Some waste materials have been studied, such as ceramics coming from asbestos containing waste [10–12], municipal solid waste incinerator fly ashes [13], concrete [14] and slag from steelmaking industry [7,15–18].

In this work, EAF slags from steelmaking industry were characterized. Steel slag is produced in the melting process of the iron ore and about 10–20% of slag is generated per ton of steel [3]. Steel slag is mostly consist of oxides of aluminum, calcium, iron, magnesium and silicon [7,19,20]. Some researchers have proposed the revalorization of steel slag in different fields, such as concrete aggregate [21–24], road construction [25,26], waste water treatment [27], cement production [28,29] and others. In Europe, about 76% of slag is reused, however the residual 24% is landfilled (13%) or stored in the steelmaking plants [30]. Revalorization of the remaining slag into TES material can lead to a cost-effective solution to the CSP plants and the industry waste recovery. The use of slag as TES material can reduce the landfilled account, reduce the air pollution during electricity generation process and low the cost of climate change mitigation. The implementation of slag based packed-bed storage solution could be successful [31]. A complete characterization of slag is need to prove the feasibility of slag as heat storage material.

Different authors studied the thermophysical properties of slag.

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Ortega et al. [7] presented thermophysical and structure characterization of two different slag samples from two steelmakers in Spain. Calvet et al. [12,15] presented an experimental characterization of as received slag and re-melt slag. Gil A et al. [7] competed the characterization of Calvet, the values of heat capacity, density and thermal conductivity up to 1000 ℃ of two type of slag were studied. But, there are still some characteristics need to be investigated. In a packed bed arrangement, as heat storage material, slag will meet with high temperature and low temperature environment. The wear resulted from the heat-expansion and cold-contraction of the slag with storaging and releasing process, which may cause decomposition, can't be ignored [32].

The main aim of this work is to study the feasibility of slag as a heat storage material in PTC and SPT system for CSP plants. In this paper, the microstructures, thermal properties, wear resulted from the heat expansion and cold contraction of the slag with storaging and releasing process of two EAF slag samples were addressed. The results revealed that slag is a potential heat storage material.

2. Materials and testing methods

2.1. Rough materials

EAF slag is generated in the steelmaking plants using EAF technology production method. During the steelmaking process, ferrous steel scrap and fluxing agent (alumina, silica and lime) are put to furnace and melted using EAF technology. When the process is finished, the liquid steel slag is floating over steel because of density difference. The steel slag is tilted into a ladle to cool down. Steel slag can be identified as a mixture of metal oxides [3]. The slag samples studied in this work were gathered from steelmakers in two different regions, one from China Steel called c slag, another from Spain called s slag. They were both cold in air (Fig. 1).

2.2. Thermal stability and XRD (X-ray power diffraction)

The thermal stability of both slag samples were assessed by Netzsch Simultaneous Thermal Analyzer (STA) 499 F3 Jupiter, a combined thermogravimetric analysis (TGA). The test run was heating from room temperature (RT) to 1000 °C with heat rate of 10 °C/min, under a flowing nitrogen atmosphere. This test run was applied on a sample mass of 10 mg ± 1 mg. Three times thermal cycles between 100 °C and 1000 °C have been done to determine the material thermal stability.

The structural analysis of both slag samples before and after the TGA test were characterized by XRD in a Philips X'Pert PRO diffractometer using CuK$_{\alpha1,2}$ ($\lambda_1 = 1.540598$ A, $\lambda_2 = 1.054446$) radiation. The data were recorded in the range $10° < 2\theta < 80°$, with a step size of $\Delta 2\theta = 0.026°$ and counting time of 96.39 s per step.

Fig. 1. Picture of raw EAF slags, s slag on the left and c slag on the right.

2.3. Specific heat (C_p), thermal diffusivity (α) and thermal conductivity (λ)

The specific heat capacity and thermal diffusivity of the slag samples were measured by laser flash analysis (LFA) 467 from Netzsch in RT-500 °C. The LFA467 offered high precision of the heat capacity (experimental error around 3%) and thermal diffusivity (experimental error around 5%). The instrument used Pyroceram 9606 as a reference material. The samples were prepared in square forms with a side length of 10 mm and a thickness of 2 mm. The samples surfaces were parallel and smooth. A graphite film was covered over samples surfaces to minimize the experimental error. Data were averaged of three measurements for each sample to assure the accuracy of the result. The thermal conductivity was calculated according to the following equation:

$$\lambda = \alpha \cdot \rho \cdot C_p \tag{1}$$

With α the thermal diffusivity, ρ the density and C_p the specific heat.

2.4. Wear test

Wear test were conducted by sliding dry pin slag ($\phi 5 \times 10$) against rotating disc slag ($20 \times 20 \times 4$) using a GHT-1000E high-temperature vacuum pin-on-disc rotation tribometer under vacuum (approximate 1×10^{-1}P$_a$) (Fig. 2) [33]. The pin and disc were both made of the same slag. A series of tests were carried out to evaluate the effect of temperature on the tribological properties of slag samples. During the series of tests, the temperature value of RT, 100, 200, 300 and 400 °C were selected with a sliding speed of 17 m/min under 10 N, for duration of

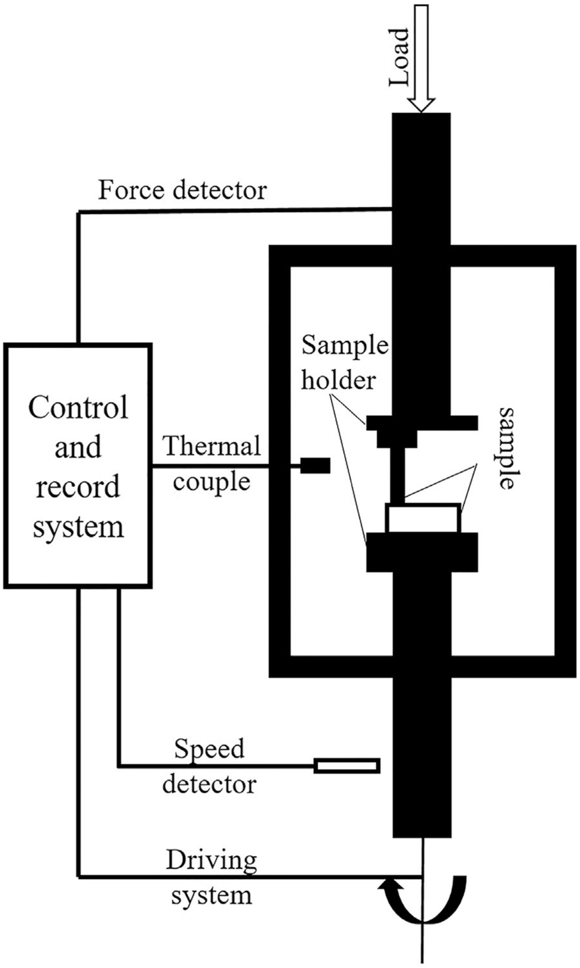

Fig. 2. Schematic diagram of the high-temperature friction and wear test.

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