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Concrete as a thermal energy storage medium for thermocline solar energy storage systems

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Abstract

Rising energy costs and the adverse effect on the environment caused by the burning of fossil fuels have triggered extensive research into alternative sources of energy. Harnessing the abundance of solar energy has been one of the most attractive energy alternatives. However, the development of an efficient and economical solar energy storage system is of major concern. According to the Department of Energy (DOE), the cost per kilowatt hour electric from current technologies which utilize solar energy is high, estimated at approximately \$0.15–\$0.20/kW $h_{electric}$, while the unit cost to store the thermal energy is approximately \$30.00/kW $h_{thermal}$. Based on traditional means of producing electricity (through burning fossil fuels), the unit cost of electricity is \$0.05–\$0.06/kW h. Clearly, current solar energy technologies cannot compete with traditional forms of electricity generation. In response, the DOE has established a goal of reducing the cost of solar generated electricity to \$0.05–\$0.07/kW $h_{electric}$ and achieving thermal storage costs below \$15.00/kW $h_{thermal}$. Reduction in the cost of the storage medium is one step in achieving the stated goal. In this research program economical concrete mixtures were developed that resisted temperatures up to 600 °C. This temperature level represents a 50% increase over the operating temperature of current systems, which is approximately 400 °C. However, long-term testing of concrete is required to validate its use. At this temperature, the unit cost of energy stored in concrete (the thermal energy storage medium) is estimated at \$0.88–\$1.00/kW $h_{thermal}$. These concrete mixtures, used as a thermal energy storage medium, can potentially change solar electric power output allowing production through periods of low to no insolation at lower unit costs.

Keywords: Solar energy; Energy storage; Thermocline; Concrete; Molten salt

1. Introduction

At the turn of the millennium, discussions around solar energy systems focused extensively on thermal energy storage (TES), its cost and suitable storage media. Early discussions on sensible heat storage media identified concrete, bricks, sodium chloride, cast iron and steel as possible candidates for the application (Hermann and Kearney, 2002). Based on the relatively low cost and high heat capacity of concrete, it was given priority for research as a thermal energy storage medium (Hermann and Kearney, 2002).

The literature (Hermann and Kearney, 2002; Laing et al., 2006, 2002; John et al., 2010, 2011; Skinner et al., 2011; Pacheco et al., 2001; Yang and Garimella, 2010; Faas et al., 1983) identifies two concepts that uses concrete or has the potential to use concrete as a thermal energy storage medium for solar power electric generation. One concept uses a concrete-heat exchanger (steel) medium Laing et al., 2006, 2002; John et al., 2010, 2011; Skinner et al., 2011, and the other employs a combination of rock and sand, as the thermal energy storage medium, in a single

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tank that is charged and discharged by the direct flow of a heat transfer fluid through the medium (Pacheco et al., 2001; Yang and Garimella, 2010; Faas et al., 1983; Kolb and Hassani, 2006; John et al., 2011). This paper focuses on the latter option for energy storage. This option of energy storage is referred to as a thermocline system. The system received its named based on the concept of housing a thermally stratified fluid in a single tank, the hotter portion of the fluid, being less dense, sits on top of the colder fluid creating a distinct zone between hot and cold known as a thermocline. This system was proposed as an option to replace the conventional two-tank system because it reduces the storage volume resulting in a cheaper option for energy storage (Pacheco et al., 2001; Yang and Garimella, 2010).

In the thermocline option, high temperature heat transfer fluids (HTF) such as thermal oil or molten salt are used as the storage medium. However, due to the high cost of the HTF ($0.484/kg), Pacheco et al. (2001) proposed replacing the fluid with a packed bed of quartzite rock and silica sand. The system functions by having the HTF enter the top of the tank charging the storage medium and pushing the thermocline towards the bottom of the tank. During discharge, colder fluid enters the bottom of the tank extracting the heat energy from the storage medium as it exits the top of the tank. The discharge process is complete when the thermocline moves to the top of the tank and the fluid exiting the tank is at a temperature that is insufficient for the operation of the mechanical system, the steam generator/Rankine cycle (Laing et al., 2006, 2002).

However, a major technical issue with this system is thermal ratcheting. Repeated thermal cycles result in the settlement of the aggregate filler which occupy the increased tank volume during the charging phase. During the discharging phase, the compacted filler material prevents the contraction of the tank walls, thus generating high lateral stresses on the lower tank wall (Yang and Garimella, 2010; Faas et al., 1983). This phenomenon, referred to as thermal ratcheting, can potentially lead to yielding of the tank walls. This paper seeks to address this concern by proposing the use of packed concrete bricks in place of the aggregate filler as the storage medium and using molten (solar) salt as the heat transfer fluid.

2. Objective

The paper's goal is to investigate the resistance of concrete at temperatures up to 600 °C, with the ultimate objective of identifying a concrete mixture or mixtures that are suitable for use as a thermal energy storage medium in the thermocline energy storage option. The mechanical and thermal properties of various concrete mixtures and their compatibility with molten salt, a eutectic mixture of 40% by weight potassium nitrate (KNO_3) and 60% by weight sodium nitrate ($NaNO_3$), at elevated temperatures is assessed.

3. Concrete

Concrete is a construction material comprised of cementitious materials (portland cement (PC) and/or calcium aluminate cement (CAC)), coarse and fine aggregates, water and possibly chemical admixtures which are used to improve the fresh and hardened properties. In addition to PC, the concrete may contain other cementitious materials such as fly ash, slag cement and/or silica fume. After mixing, the mass solidifies and hardens due to a chemical process known as hydration. The main hydration product, which determines the strength of the concrete, is calcium silicate hydrate (CSH). The most critical physical trait of concrete is its porosity. Pores of different sizes and shapes present in the various phases of concrete influence its behavior more than the properties of the individual solids of which concrete consists (Skalny and Roberts, 1987).

4. Assessment of concrete developed for thermocline thermal energy storage (TES)

Thermal energy storage system cost is one of the key variables in determining its viability. A thermocline TES is more economical than a two-tank option (Pacheco et al., 2001; Yang and Garimella, 2010; Faas et al., 1983; Kolb and Hassani, 2006). As researchers push the frontier of the operating temperatures from 400 °C to temperatures in excess of 500 °C, there is an equivalent need to employ a HTF that remains stable (no phase change) within this temperature range. One such fluid is molten salt. Molten salt can potentially withstand temperatures up to 600 °C.

Current thermocline systems use combinations of rock and sand or a HTF as the main storage medium. These systems operate at a maximum temperature of 500 °C. This research investigated the use of concrete bricks as the storage medium at operating temperatures up to 600 °C. The use of concrete bricks/plates can eliminate thermal ratcheting and at this temperature more energy can be stored for a given volume of material.

5. Concrete mixtures

Twenty-six concrete mixtures, shown in Tables 1–4 were batched and tested in a bath of molten salt at 585 °C for 500 h. The specimens were also subjected to 30 thermal cycles between 300 °C and 585 °C when submerged in molten salt. Specimens were also cycled (30 times) in air between 300 °C and 600 °C.

The coarse aggregates used in the mixtures varied. Mixtures 5–14, 18, and 21–23 contained sandstone with nominal maximum size of 12.7 mm. Mixtures 1–4, 15, and 16 contained no coarse aggregates. All mixtures employed washed river sand (siliceous sand) as the fine aggregates. Limestone was used as the coarse aggregate in Mixtures 17, 19, and 25, whereas, Mixtures 20 and 24 contained syenite of a single particle size of 4.7 mm. The results of work published by Pacheco et al. (2001); Kolb and Hassani