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Metal hydride thermal heat storage prototype for concentrating solar thermal power

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ABSTRACT

CSP (concentrating solar thermal power) is emerging as a viable and cost effective solution to renewable energy generation. Molten salts are currently used as heat storage media to enable power generation during the night-cycle. Metal hydrides offer the possibility of storing energy with an order of magnitude less raw material than molten salts due to their impressive energy densities. To test the viability of hydrogen storage materials for CSP applications we have designed and constructed a prototype scale apparatus for screening materials under dynamic conditions with active heat extraction. The apparatus is tested with 19 g of well-known MgH_2 to assess the viability of the design for screening purposes. The metal hydride is thermally cycled up to 420 °C more than 20 times with a minimal loss in hydrogen capacity. Issues relating to testing on a prototype scale are discussed, where problems with environmental heat loss and powder compaction dominate the performance of the metal hydride in the prototype. Problems with heat loss are inherently minimised on scale-up, leading to thermal behaviour more representative of a full-scale CSP energy storage system.

1. Introduction

It is inevitable that humanity will need to transition to cleaner renewable energy sources from the dominant fossil fuels used today. It is admirable that many countries around the world are striving to increase their energy income from renewable sources. A range of renewable sources allows for energy diversity, where a particular source may be more easily tapped depending on location. Typical sources include solar, wind, hydro-electric, tidal, geothermal and biomass. Solar thermal technology (with suitable storage) is able to provide centralised base-load power from renewable sources and will be a dominant technology in the long-term [1–3].

CSP (concentrating solar thermal power) plants are becoming more common with over 80 operational plants around the world, where 40% are able to store thermal energy to generate electricity on demand [4]. Some of these plants are able to provide base-load power 24/7 at very competitive cost, but most often at $<$ 100% load over the night cycle. In fact, the 110 MW Crescent Dunes plant in Nevada, USA, is scheduled to provide power at 13.5 US¢/kWh [5], with 10 h of energy storage at full-load, when it becomes fully operational in 2015. This is an indication that CSP technology is becoming cost competitive with fossil fuel power generation, especially in remote locations.

There are many options available for thermal energy storage where a chosen storage materials specific heat, latent heat or thermochemical heat of reaction can be utilised [6]. The most common method of storing thermal energy in CSP applications is by utilising the specific heat of molten $NaNO_3/KNO_3$ salts. These nitrate salts have a maximum operating temperature (~565 °C) due to their significant decomposition at 600 °C [7]. This means that alternative materials will have to be utilised for higher temperature, higher efficiency thermal storage applications. A recent review on TES (thermochemical energy storage) [2] provides a comprehensive overview of the state-of-the-art energy storage technologies. Many different classes of materials are suited to high temperature TES including hydrides, carbonates, hydroxides and oxides.

Molten salts are a capable and successful heat storage technology for CSP. However, the quantity of molten salt required to store energy for a night-cycle is very large. The 110 MW Crescent Dunes CSP plant will utilise 31,800 tonnes of molten salt [8], which,

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despite its low raw cost ($US 720/tonne [9]), comes at a significant cost (≈ 10–15 % of the $US 1 billion project cost [10]). The primary advantage of using a metal hydride as a heat storage material instead of molten salts is due to the high energy density of metal hydrides (Fig. 1), which means that up to a factor of 10 times less raw material is required [4,6,12,13]. This means there are potentially significant cost savings to the energy storage system, even when considering the additional cost of heat exchangers within the hydride bed [12]. This recent study provided a techno-economic assessment of proposed metal hydride energy storage systems for CSP plants, where a preliminary cost of $50–60 per $\text{kWh}_{\text{thermal}}$ was derived. Subsequent analysis, that instead used $NaAlH_4$ as the low-temperature hydrogen storage material, further decreased this cost to $28–48 per $\text{kWh}_{\text{thermal}}$ [14]. These cost analyses have room for further reduction, particularly through optimisation of the heat exchangers within the hydride beds. In comparison, the cost for existing molten salt technologies is $30–80 per $\text{kWh}_{\text{thermal}}$ [12].

A metal hydride energy store for CSP operates through the highly endothermic and exothermic processes of hydrogen desorption and absorption, respectively. The metal hydride in question (designated as the HT (high temperature) hydride) will be heated during a day-cycle from solar energy and will release hydrogen. This hydrogen gas must then be stored. The hydrogen can either be stored in a volumetric gas tank or another metal hydride that operates at LT (low temperature). In this case the low temperature hydride would have a much smaller enthalpy of reaction when compared to the high temperature hydride. Both methods of hydrogen storage have their advantages and disadvantages, but most LT hydrides are costly meaning that a volumetric store may be more cost effective, even though it would have to be very large. A further benefit of a volumetric store is in the fact that there is no chemical enthalpy of absorption and desorption in the gas storage system. These enthalpies act as a parasitic energy loss in the system, as the heat is low grade and difficult to utilise. A disadvantage to volumetric gas storage is that the system gas pressure is not constant as it would be if an LT hydride store was used. The variability in the system gas pressure impacts the temperature of the HT hydride as it must change temperature to match the HT hydride equilibrium pressure to the system pressure.

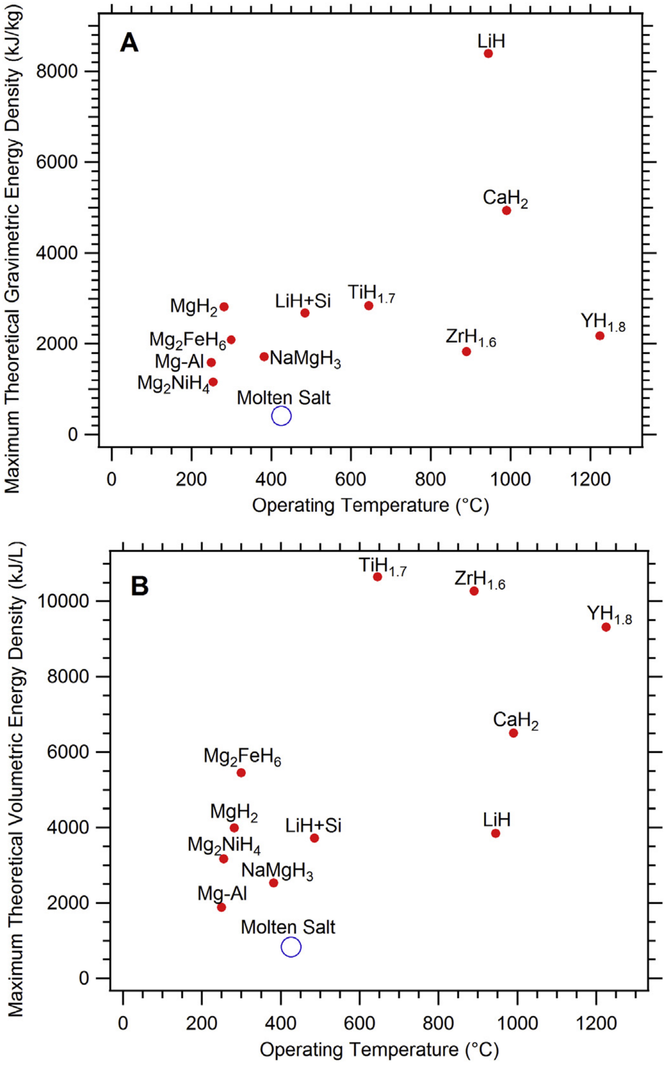

Fig. 1. Maximum theoretical A) gravimetric and B) volumetric energy storage densities of select metal hydrides compared to existing molten salt technology [11]. Operating temperatures are given as the 1 bar hydrogen equilibrium pressure temperature. The molten salt energy densities are based on the specific heat of a eutectic nitrate salt mixture over the entire operating temperature range, 288–565 °C.

In a CSP application, the heat from the HT metal hydride must be extracted so that it can be used to generate electricity through a heat engine or steam turbine. There are a wide range of HTF (heat transfer fluids) that have been identified or utilised in solar thermal or conventional power plants. Synthetic oils are typically used in parabolic trough CSP plants where the maximum operating temperature is quite low (<400 °C) [15]. In solar power tower plants with higher operating temperatures (<600 °C) molten salts are typically used as the HTF. Liquid metals such as sodium (m.p. 98 °C, b.p. 883 °C) or lead–bismuth alloys (m.p. 125 °C, b.p. 1670 °C) appear promising as high temperature HTFs due to their low melting points and high boiling points, given suitable containment materials can be utilised [16]. Sodium can react violently with water, however its use in the nuclear industry is well established in large quantities (i.e. >1500 tonnes at the prototype fast reactor in Dounreay, UK from 1974 to 1994 [17]).

Supercritical water has been suggested as a HTF for CSP [18] and the concept allows for higher temperatures in the TES system than thermal oil allows. The technology has also been used in conventional power plants for decades [19]. Supercritical water possesses advantageous properties for use as a moderate temperature HTF, however its use at high temperatures may be restricted by the cost of high pressure tubing capable of high temperature operation. Fig. S1 illustrates the thermal conductivity of water as a function of temperature and pressure. It is clear that the thermal conductivity is much higher in supercritical water, especially in comparison to low pressure steam. The corrosion of steel tubing can be a problem in long term supercritical water use [20], however the 316L alloy shows improved resistance over other alloys [21]. In this prototype supercritical water is utilised as an HTF due to its favourable properties over the examined temperature range (<420 °C). Supercritical water/steam is also compatible with existing power generation turbines. This is particularly relevant as supercritical steam generation from a CSP test plant has recently been demonstrated (235 bar, 570 °C) [22]. Thus, optimisation of the prototype system using supercritical water and a well-known hydride, MgH_2, means that the configuration can easily be applied to higher temperature hydrides that are compatible with producing supercritical water/steam at the temperatures of commercial steam turbines. Higher temperature operation will likely require molten salt/metal HTFs due to the costs and difficulties associated with high pressure water containment at very high temperature >600 °C.

Using metal hydrides as heat storage materials is not a new concept, but can also be applied to CSP applications. For example, 6.27 kg of Mg_2Ni was used in a prototype heat storage system in 1983 with a maximum operating temperature of 350 °C [23]. This