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Ultra-high temperature thermal energy storage. Part 2: Engineering and operation

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ABSTRACT

The storage of energy at ultra-high temperatures offers many benefits including high energy density and efficient conversion to and from electricity that can be further enhanced by cogeneration. In addition to this, an Ultra-High Temperate thermal energy Storage (UHTS) system would be clean, closed, and reversible and could be built with abundant low cost materials. However, operation at ultra-high temperature is challenging due to the reduced strength and increased reactivity of materials. This paper discusses how a storage system with useful performance can be engineered. In many cases UHTS components and systems can be created by using existing techniques, but in some areas there are engineering challenges that need to be solved before UHTS can become operational. Once the technical and practical feasibility is investigated, there is a brief assessment of the likely capital cost of implementing the storage system at grid scale. As a compact and closed system, UHTS would be inherently suitable for supplying heat at the point of demand. This offers an opportunity to increase the effective roundtrip efficiency to 95%, which far exceeds most other storage methods Beyond this UHTS could be used to aid the transition of a national energy system to all electric renewable operation. The paper closes with a discussion of the complexities and opportunities brought about by the flexibility of configuration and the transient thermal nature of UHTS.

1. Introduction

This paper describes how an Ultra-High Temperature Thermal Energy Storage system could be engineered and is written to support a paper titled “Ultra-High Temperature Thermal Energy Storage. Part 1: Concepts” which will be referred to here as Paper 1. In Paper 1 the Ultra-High Temperature thermal energy Storage (UHTS) concept is described. UHTS offers many benefits over other storage techniques. However to harness the advantages of the UHTS concept it must be practical for real world deployment. This paper demonstrates the feasibility of UHTS whilst outlining the engineering questions that still need to be resolved before the technology can be operational. The configuration of the structures used to store and collect energy is discussed in Section 2.1. Section 2.2 describes the engineering of the heat pump used to recover lost energy. This section will include a thermal analysis that shows how a heat exchanger capable of transferring the required amount of energy can remain within the space and power loss limits necessary for a practical storage system. Section 2.3 will highlight the construction of the charging and extraction equipment. In Section 2.4, an attempt is made to assess the likely capital cost of a UHTS plant relative to other energy storage technologies.

The usefulness of UHTS as an electric-to-electric storage method is demonstrated in Paper 1; however, this usefulness can be further enhanced by the inherent suitability of UHTS to supply heat at the point of consumption. In Section 3.1 there is a discussion of how UHTS, integrated with cogeneration, could not only form the centrepiece of a renewable energy system providing electricity, heat and fuel, but could also help a national grid transition from one energy economy to another. The complexities of designing and operating a UHTS plant are discussed in Section 3.2. A summary of the findings of this paper are given in Section 4.

2. Engineering an ultra-high temperature thermal energy storage system

This section will demonstrate how a UHTS plant with a useful level of performance can be engineered whilst remaining both geometrically and financially feasible.

2.1. Storage system engineering

The first engineering consideration for an energy storage system is

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the medium used to hold the energy and how it is contained. For thermal storage, there is also a requirement to configure this vessel to minimise thermal losses. The standard container material for molten aluminium is alumina (Al_2O_3), which is chemically inert with aluminium [1]. The containment of liquid metal at the temperature and scale required for UHTS is already common in the ore smelting industry, where 20,000 ton furnaces are in use [2]. The outer collector stages for the plant described here will be at lower temperatures and can therefore use lower-cost materials such as crushed rock for the storage medium, and steel for the containment structure.

Conductive losses from the storage vessel can be minimised using medium vacuums. Vacuum insulated panels that can maintain a medium vacuum for decades are in common use at lower temperature ranges [3]. These panels achieve a thermal conductivity of 0.008 W/mK with a vacuum of 20 Pa whilst supported by a silica medium with an average pore diameter of 0.3 mm [3]. Conductive losses for a planar surface is given by Eq. (1), where k is the thermal conductivity, A is the surface area, d is the thickness, T_1 is the lower temperature, and T_2 is the higher temperature.

$$P_c = \frac{kA(T_2 - T_1)}{d} \tag{1}$$

From a 24 m spherical UHTS storage core, operating at 1800 K with an external temperature of 300 k with a 0.1 m thickness of conductive insulation, the power loss is 0.21 MW compared to the radiative loss of 39.4 MW calculated in Paper 1. This calculation is made using the thermal conductivity value for a panel discussed earlier. Alumina at 1800 K has a conductivity four times higher than a silica filler material at 300 K. However, even if this increased heat transfer by an order of magnitude conductive losses would still be small compared to radiative emissions.

A vacuum insulated panel consists of a medium vacuum contained within a metallic sealing envelope supported by a microporous filler medium [3]. In the context of UHTS the sealing envelope would need to be made from a film of a temperature resistant metal or alloy like platinum-iridium to have the necessary mechanical properties at UHTS temperatures [4]. The filler could be made using an alumina ceramic microporous medium which is available with average pore diameters below 0.3 mm [5]. It has been observed that metallic oxides have an oxygen dissociation pressure which can cause a vacuum to be broken at elevated temperatures [6]. If alumina is used as a filler medium oxygen dissociation will not occur as the associated oxygen dissociation pressure is 1.01325×10^{-7} Pa at 1800 K [7]. Carbon foams [8] are also a candidate for a filler material at elevated temperatures. The metallic envelope can also be used to provide a radiative barrier as discussed below.

Only a relatively small area of solid material is required to support the structure, resulting in negligible conduction losses as demonstrated in Paper 1. The radiative losses can be minimised by reducing the surface area and emissivity of the storage vessel. This dictates that the container should be as close to spherical as possible with a low emissivity outer surface material. A cylindrical vessel is the common shape used in existing furnaces [9] and may reduce the difficulty and cost of engineering the UHTS plant. The disadvantage of a cylindrical shape over a sphere would be to increase radiative losses by approximately 15%.

Alumina offers a relatively low emissivity of 0.69 at 600 K and 0.41 at 1400 K [10]. However, it may be possible to coat the alumina containment vessel in a low emissivity metal such as platinum, gold or tungsten.

Platinum is the most suitable material to coat the storage core as it has an emissivity of 0.047 at 373.15 K and 0.191 at 1773 K [11]. It is common to splutter coat platinum onto an alumina substrate [12]. With only a 300 nm thickness coating of platinum required to lower the emissivity [13] of the storage core, the cost of this small amount of rare metal (1.5 kg for coating a 24.3 m sphere) is negligible compared to the energy savings the coating confers. If vacuum insulating panels were used as a combined radiative and conductive barrier a metallic film with a thickness of 100 μm would be required to resist mechanical loading [3]. If this barrier was made of platinum the cost would be approximately $US 14.7 million.

The platinum coating will be protected by the medium vacuums put in place to minimise conductive losses.

The construction of the storage vessel and its support structure can be achieved with conventional furnace building techniques. It should be possible to create the spherical storage container required for UHTS using shaped monolithic bricks and existing construction methods [9]. Molten metal is contained by lining the inner surface of the monolithic brick vessel with a refractory mastic to provide a seal [9].

UHTS is a closed system where pure aluminium can be used; therefore, all the following factors that reduce furnace life span can be eliminated:

- Mechanical damage during the loading process.
- Damage to the lining due to impurities in the molten metal.
- Erosion caused by the flow of molten metal during unloading.

Without these causes of damage the usual ten years of use a large furnace gets between relining [14] could be extended almost indefinitely for a UHTS vessel. Creep could be a limiting factor on UHTS core container lifespan; however, as creep in ceramics is well understood [15] it can be minimised by design. Thermal shock and differential expansion may limit the charge and discharge rate of the UHTS plant, but again thermal shock resistance of ceramics is predictable and well understood [15], and methods to allow differential expansion in furnaces without damage have been developed [9,16].

Whilst the metal storage medium is solid it will expand and contract as it is heated and cooled. If the medium remained solid during the complete temperature range of the storage system then appropriate spacing could be left to account for expansion. However, when the metal is liquid at some stage during operation this is not possible. In this scenario, when the medium is reheated material expansion may lead to damage of the UHTS vessel. To avoid this damage a controlled melting process must be implemented for use during the charging cycle. Vacuum remelting furnaces [17] remove impurities by reheating metals solidified within a container. This is accomplished through a controlled melting process, which avoids the expansion that would lead to vessel damage during reheating. If a controlled melting process cannot be adapted for use within a UHTS plant, it will be necessary to operate with a material that remains solid through the full temperature range, which will have implications for plant size and thermal loss rates.

2.2. Storage cycle heat pump engineering

The heat pump that is described in the first paper is a non-essential system that could be added to the UHTS plant to recover energy during the storage and charge cycle. The alternative method of energy recovery discussed in paper 1, which may be simpler to implement, is the use of storage stages to collect lost heat that can then be used for gas heating during the extraction cycle. The use of a heat pump within the UHTS charging cycle makes the operation of the UHTS plant similar to existing pumped heat systems like those described by McTigue et al. [18], Desrues et al. [19], morandin et al. [20] and Thess [21]. These pumped heat concepts share the components seen in the UHTS heat pump like the heat exchangers, compressor and turbine but are intended to operate within a temperature range from 123 K to 1268 K. Therefore, previous authors have not addressed the engineering difficulties introduced by ultra-high temperature operation.

The critical components of the heat pump used to return escaped heat to the storage core include the compressor, turbine and the heat exchangers. The multi-stage compressor of the heat pump operates with a total pressure rise and flow rate seen within a portion of a