New Concept for High Temperature Thermal Energy Storage Using a Concrete Tank

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Abstract

The use of concrete is showing great potential as thermal energy storage material for concentrating solar power plants (CSP) due to its versatility, relatively low cost, and the possibility to reach a high operating temperature, above 500ºC thus increasing the plant efficiency. However, actual configurations based on concrete show different drawbacks including difficulties during the manufacturing on-site, different thermal expansion coefficients between concrete and pipes, and poor thermal conductivity of concrete. In order to address those challenges, this study proposes a new TES concrete tank concept based on three main pillars: modularity, improved concrete formulation, and direct contact concept. A preliminary assessment of the thermal performances of the new concept was analyzed through simulations showing the temperature distribution of the modules.

Keywords: thermal energy storage; sensible TES; concrete; csp; modular concept;

1. Introduction

Solar energy represents today the main renewable source to produce both thermal and electric power. One of the main large-scale technology to convert solar energy into electricity is represented by concentrating solar power (CSP) plants. According to REN21, in 2020 the total capacity installed worldwide amounts to 6.2 GWe (REN21, 2020). In order to deal with the intermittency of solar radiation at a given location, thermal energy storage (TES) is an essential component. Current CSP technologies mainly rely on the use of molten salts as storage medium. However, the main drawbacks of molten salts are corrosion issues and their limited operating temperature range (up to 565 ºC), which limits CSP in both global performance and cost. Amongst all storage medium alternatives, the use of concrete represents a viable option due to its versatility, relatively low cost, and the possibility to reach a high operating temperature above 565 ºC.

One of the first storage concepts using concrete was developed by DLR and tested at Plataforma Solar de Almeria. Regarding the storage material, blast furnace cement was used with iron oxides, flue ash, and auxiliary materials. The system used thermal oil as HTF flowing through an array of pipes (tube register) embedded in the storage medium (Laing et al., 2009a). Another concept, EnergyNest, developed and tested two modules of 500 kWth thermal energy storage capacity based on a modular design and concrete as a storage medium, named HEATCRETE vp1, able to resist temperatures up to 400 ºC (Hoivik et al., 2019a). The modules of the TES developed by EnergyNest consisted of cylindrically shaped thin-walled (0.4 mm) steel casing closed at one end and open at the other with integrated steel pipe heat exchangers.

Although concrete has a high potential for storage solution, there are still challenges related to this technology that needs to be addressed, which include its fabrication techniques, material formulation, and design, which limit the construction feasibility and thermal performance. In order to improve the currently available configurations, this study proposed a novel concept of thermal energy storage using concrete based on a modular concept, improved concrete formulation, and a direct contact design. Moreover, a preliminary assessment of the thermal performance of the new concept proposed in this study was analyzed using a 3D thermal analysis showing the temperature distribution throughout the modules.

2. Challenges of current concrete tank concepts

Today, concrete tanks concepts show different drawbacks that need to be overcome to ensure concrete TES deployment. Such drawbacks are:

(i) On-site construction

Laing et al. (2009a) pointed out that the first heating of the new concrete TES is crucial in the process. During this first heating, free water and a certain amount of chemically bound water evaporate, which could lead to excessive vapor pressure damaging the storage module. This pressure is higher the larger the TES module; also, in-situ production involves a higher water content in the concrete than production and curing in a controlled environment.

(ii) Different thermal expansion coefficients of steel and concrete

The difference between the thermal expansion coefficients of steel (heat transfer fluid pipes) and concrete can lead to cracks in the concrete, and erosion of the concrete by the friction of both materials, damaging the modules and causing a decrease of the contact surface between the storage material and the heat transfer fluid as the operating cycles of the system increase.

According to Laing et al. (2006), the thermal expansion in the axial direction of one of their concrete modules with a steel heat exchanger was 120 mm, therefore, the modules did expand by approximately 60 mm at the end. During cycling at operating temperatures, the temperature difference should only be about 40 K, so the movement would be less than 10 mm at each end. In this prototype, this was compensated using two metal sheets that acted as sliding planes.

Hoivik et al. (2019a) also mentioned the fact that different thermal expansion coefficients have to be taken into account, without giving further details, and investigated improvements to the materials to match their thermal expansion values. However, even if the concrete and metal pipes have similar thermal expansion coefficients, the thermal conductivity of the two materials is different, so during the cycle, the steel will reach temperature before the concrete, which will generate differential expansions.

(iii) Poor thermal conductivity of concrete

According to Asadi et al. (2018), concrete has a thermal conductivity between 0.4 W m^{-1} K^{-1} and 1.01 W m^{-1} K^{-1}. The addition of some components such as copper wires or phase change materials (PCM) may bring this thermal conductivity up to 3.84 W m^{-1} K^{-1}, but it can also decrease to 0.21 W m^{-1} K^{-1} .

Efforts to increase the thermal conductivity of concrete to be used in high temperature TES show that the use of calcium aluminate cement (CAC) brings higher thermal conductivity (up to 5 W m^{-1} K^{-1}) (Lucio-Martin et al., 2021), and the use of metal fibres shows an increase up to 2 W m^{-1} K^{-1} (Miliozzi et al., 2021). Finally, the literature shows that thermal cycling can lead to a decrease in thermal conductivity, usually attributed to an increase in open porosity (Boquera et al., 2021; Roig-Flores et al., 2021).

Therefore, it is possible to increase the thermal conductivity of concrete with improved formulations.

(iv) Thermal oil or molten salts with limited operating temperature range

Vignarooban et al. (2015) presented the thermophysical properties of commonly used heat transfer fluids (HTFs) in CSP plants. According to the data presented, the maximum temperature that the thermal oils (mineral or synthetic) can withstand is 450 ºC, therefore they cannot be used in CSP plants working at higher temperatures. Moreover, the other commercial HTF, molten salts, can theoretically withstand 600 ºC (Arias et al., 2022). Therefore, future CSP plants are considering the use of air as HTF (Bilal Awan et al., 2020).

(v) Migration of the HTF into the concrete

The use of thermal oils or molten salts as HTF when there is direct contact between the HTF and concrete would lead to migration of the HTF into the concrete, but also the contrary, contamination of the HTF by concrete components. The use of air as HTF avoids such migration and contamination, however, the low conductivity of the air presents new challenges to overcome.

In the design by Laing et al. (2008), the idea of using a tubeless design was investigated. The advantages of low cost and direct heat transfer were identified as the main drivers to go in this direction. Nevertheless, according to the authors, the concrete did not allow for a high enough level of impermeability, even when restressed, causing leaks of the oil. Moreover, in this design, the pipe-storage unit junction became a technical challenge.

The challenges identified related to the use of concrete as high temperature storage medium can be summarized according to Figure 1.

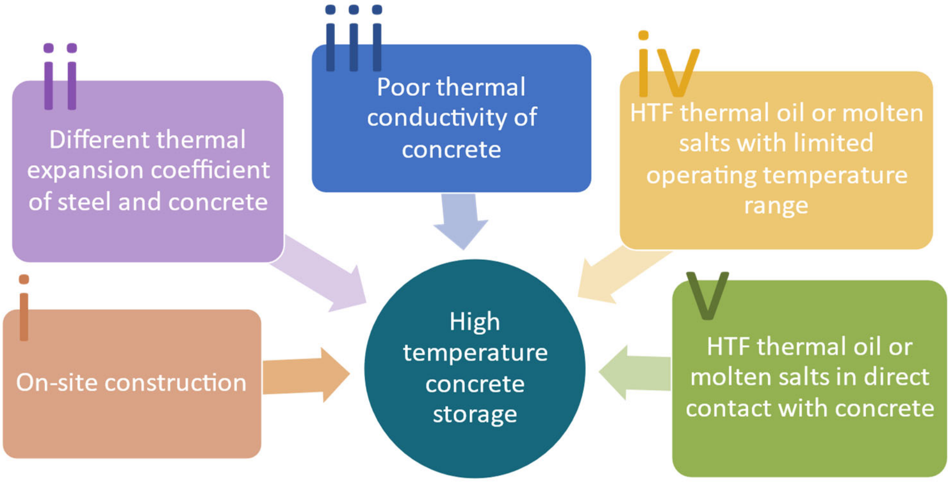


Figure 1. Challenges of high temperature concrete

3. New concept proposal

To address the challenges presented in section 2, a new concrete TES design developed in Autodesk Fusion 360 (Autodek, 2022) is presented in this paper. The new concept is designed to work with air as HTF, and is based on hexagonal geometry concrete blocks of 460 mm diameter and 2000 mm height (Figure 2) with a modular design with simple direct-fit male-female connections (Figure 3). The blocks were designed to be stacked (Figure 4a) and nested (Figure 4b) to suit the thermal needs of the installation and the space available. To meet challenge (i), the design is based on a modular concept with blocks of relatively small dimensions that allow them to be manufactured in a controlled industrial environment and then transported to the installation site. In addition, to meet challenge (ii), the blocks are made exclusively of concrete, eliminating the need for metallic piping and thus the problems of thermal expansion differences between materials. Related to challenge (iii), a concrete mixture with improved thermal properties (Boquera et al., 2022) was implemented in the model, nevertheless, this challenge remains the subject of future work by optimizing the thermophysical properties of the simulated concrete with new materials that are being experimentally validated. Finally, the temperature limitation of molten salts and thermal oils, and their migration into the concrete due to the non-use of metallic pipes (challenges (iv) and (v)) are solved by using air as HTF.

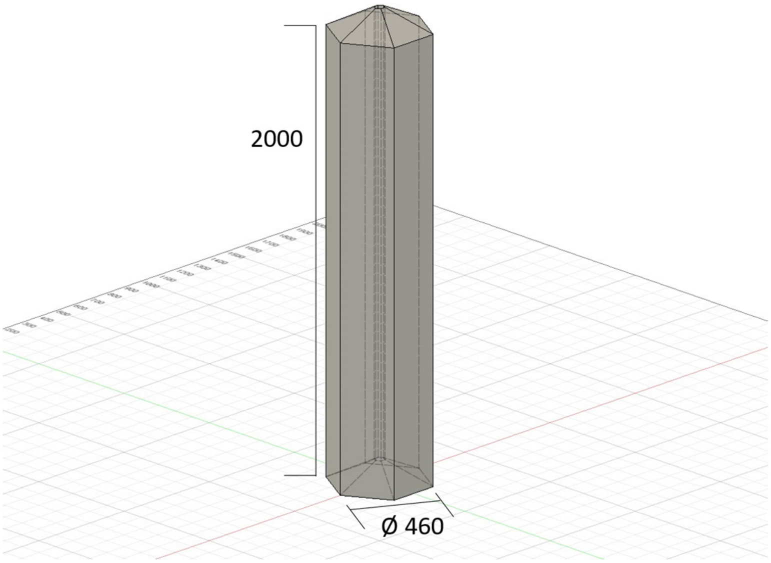
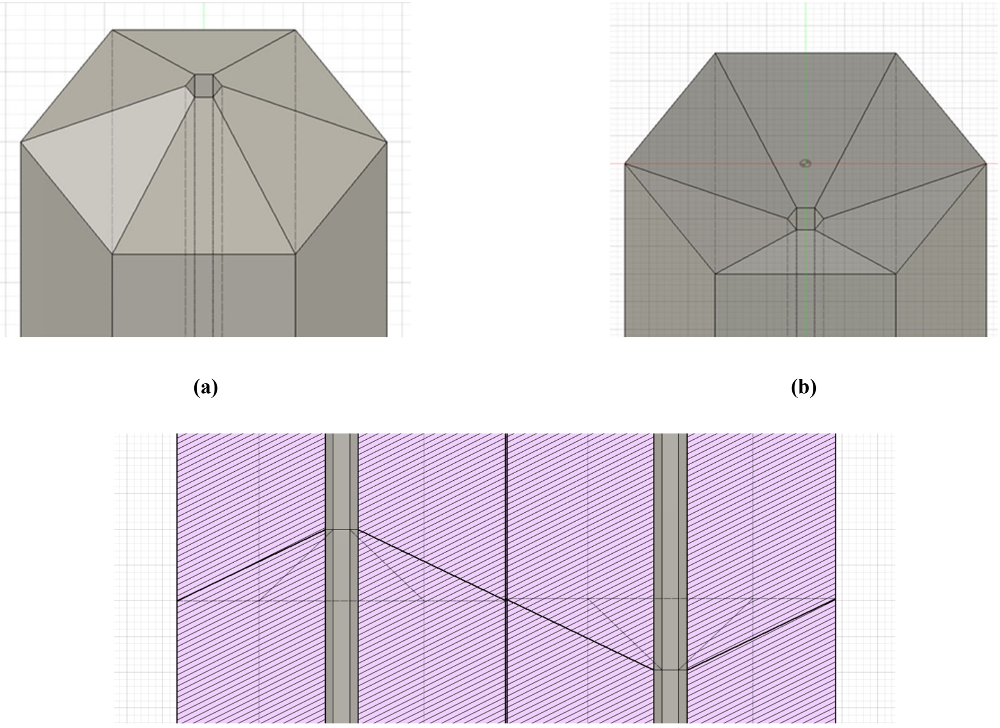


Figure 2. Concept of concrete block and block dimensions [mm]



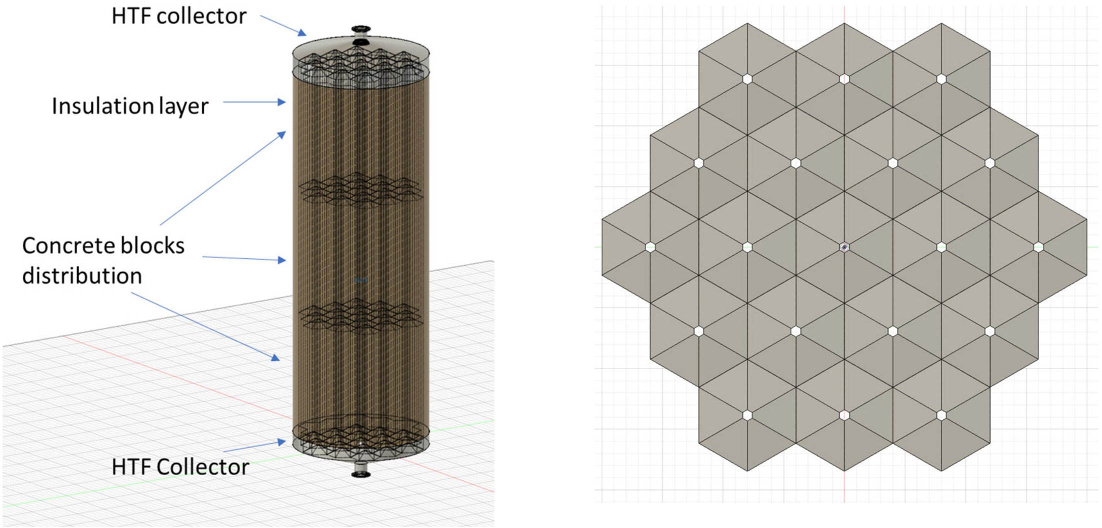
(a)

(b)

(c)

Figure 3. Concrete concept: (a) fitting connections, (b) stacked distribution example, and (c) connection points

In order to analyze the performance of the modular block design, a storage tank of 10 MWh (temperature of operation 265 ºC – 1000 ºC) was developed (Figure 4a) and simulated for static thermal analysis to determine the fully charged steady-state temperature distribution and resultant heat flow. The tank consists of 57 concrete blocks distributed in three columns (Figure 4a) of 19 blocks in a honeycomb distribution (Figure 4b), two metallic collectors, and initially with a layer of 140 mm of calcium silicate board as insulation.



(a) **(b)**

Figure 4. Concrete concept storage: (a) complete storage and (b) blocks distribution

The thermophysical properties of the concrete were extracted from Boquera et al. (2022) and shown in Table 1. Moreover, Table 2 shows the insulation material properties used from the Autodesk database. In both cases, an isentropic model of the material with linear behavior was considered. Finally, the mesh dimensions were set to automatic with the parameters of Table 3.

Table 1. Thermophysical and optical properties of concrete implemented in the model

Property	**Size**
Thermal conductivity [W m^{-1} K^{-1}]	1.01
Density [kg m^{-3}]	2.7
Specific heat [kJ kg^{-1} K^{-1}]	1.2
Thermal expansion coefficient [μm m^{-1} K^{-1}]	1
Emissivity [-]	0.95
Transmissivity [-]	0

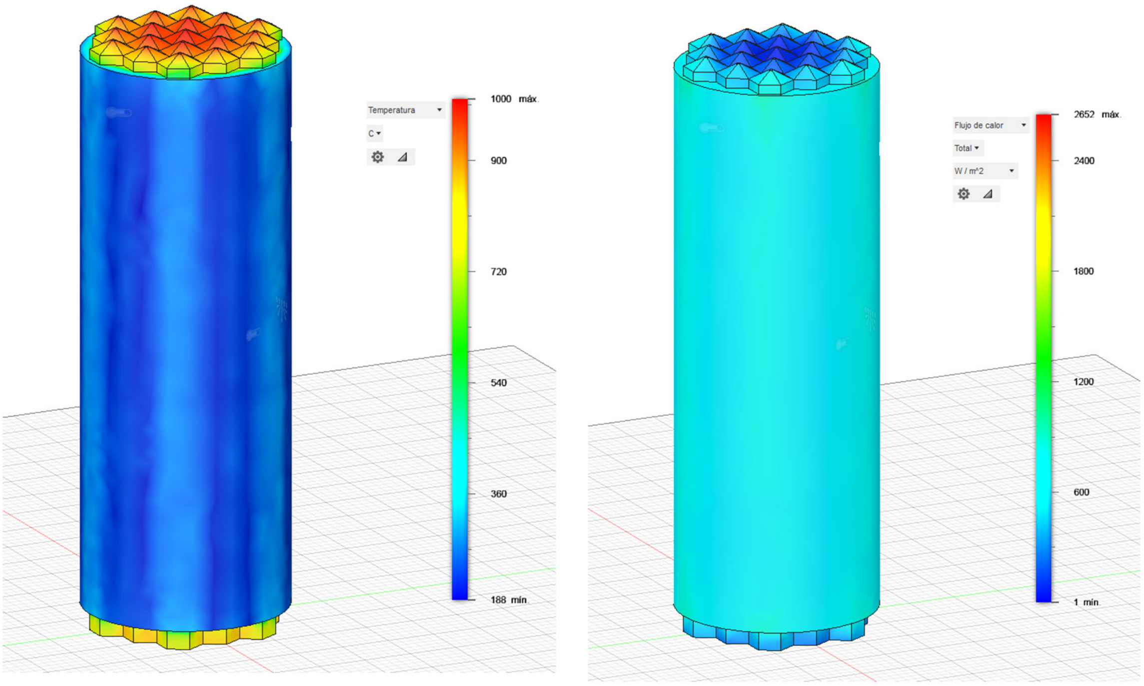
Table 2. Thermophysical and optical properties of the insulation material implemented in the model

Property	**Size**
Thermal conductivity [W m^{-1} K^{-1}]	0.002
Density [kg m^{-3}]	0.23
Specific heat [kJ kg^{-1} K^{-1}]	3.1
Thermal expansion coefficient [μm m^{-1} K^{-1}]	1
Emissivity [-]	0.2
Transmissivity [-]	0

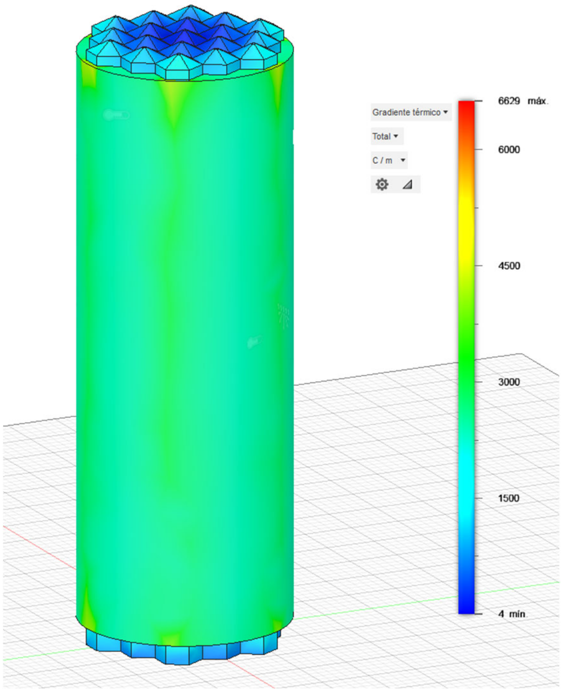
Table 3. Simulation mesh parameter

Property	**Size**
Resolution factor	1
Edge growth rate	1.1
Minimum points on edge	2
Points on the longest edge	10
Surface limiting aspect ratio	20

The analysis was carried out by performing a full charge test of the tank at an initial temperature of 265 ºC simulating a real storage cycle and maintaining an applied temperature in the HTF of 1000 ºC until reaching a steady state. The results are shown in relation to the temperature distribution (Figure 5a), heat flux (Figure 5b), and thermal gradient (Figure 5c). The analysis demonstrates that the honeycomb design manages to maintain a homogeneous distribution in the blocks without generating hot spots. However, due to the temperature difference between the concrete and the ambient temperature, the insulation becomes a critical factor in the design of the TES. For this purpose, the simulation was performed one more time, keeping the same conditions but increasing the thickness of the insulation layer of the tank from 140 mm to 280 mm (Figure 6). Figure 6 shows that the increase of the insulation reduces the temperature on the outer surface of the insulation by 30 ºC, therefore decreasing the thermal losses of the TES, and achieving a higher energy storage density.

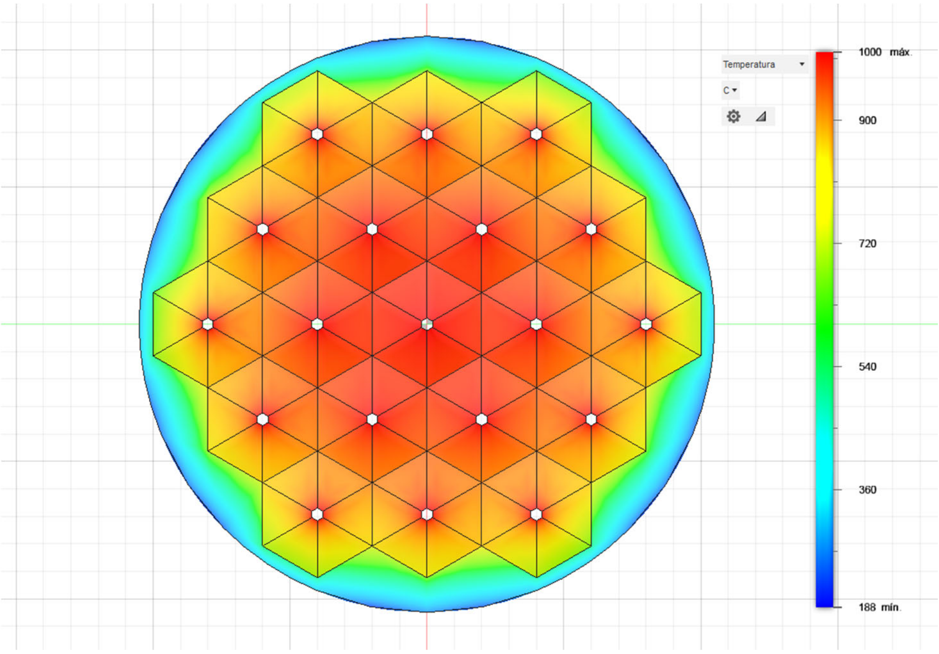


(a) **(b)**

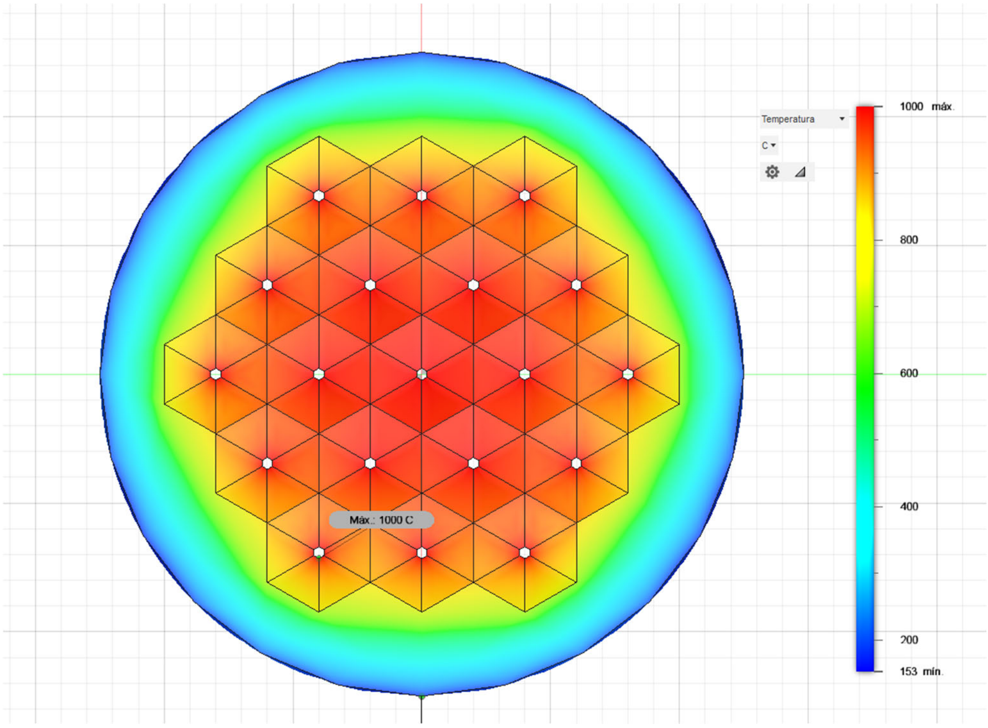


(c)

Figure 5. Concrete concept storage steady-state thermal analysis: (a) temperature distribution (in ºC), (b) heat flux (in W m^{-2}), and (c) thermal gradient (in K m^{-1})



(a)



(b)

Figure 6. Concrete concept storage steady-state thermal analysis: (a) analysis with 140 mm thick insulation and (b) analysis with 280 mm thick insulation

4. Conclusions

High temperature thermal energy storage has shown great potential to increase the penetration of renewable energies in the energy mix. The use of concrete represents a viable option due to its versatility, relatively low cost, and the possibility of reaching a high operating temperature above 565 °C. However, to become technologically and economically feasible, concrete storage systems must overcome a number of challenges.

This paper, through a comprehensive literature review, identified and analyzed the five key issues that current systems present. These are: (i) in-situ construction, (ii) different thermal expansion coefficient of steel and concrete, (iii) poor thermal conductivity of concrete, (iv) HTF thermal oil or molten salts with limited operating temperature range, and (v) migration of oil/salt into concrete in direct contact.

Considering the challenges identified, a first approach to a novel design of a high temperature thermal energy storage system with concrete was proposed and analyzed using thermal steady-state analysis techniques. The new design is composed of modular concrete blocks with direct-fit male-female connections and hexagonal design. These were designed to be stacked and interlocked in a honeycomb shape, thus enabling quick and easy customized sizing according to energy needs. The novel design proposed was able to overcome 4 of the 5 challenges identified. Only the low conductivity of the concrete remains to be further studied in future works. In addition, the plug and play design facilitates the construction of the modules, which can be manufactured under controlled conditions, guaranteeing the properties of the concrete.

Moreover, the streamlined design of the modules, the large abundance of material used, the potential low manufacturing cost once implemented on an industrial scale, as well as the results of the simulations present the proposed design as a highly competitive thermal energy storage solution. However, this new design also presents new challenges to be overcome such as the low specific heat capacity and convective heat transfer coefficient of the air used as heat transfer fluid, the tight junction between modules, and the debris of the concrete interacting with the HTF. Furthermore, the design of high temperature storage presents new challenges for adequate insulation. Therefore, material selection and optimal sizing of the insulation should be the subject of future studies.

Moreover, future work will address the following topics: analysis of the proposed design with other concrete formulations or the addition of aggregates to increase the thermal conductivity of the storage material while maintaining the specific heat values; optimization of the design to improve the coefficient of internal convection to overcome the low conductivity of the air when it is used as HTF; the analysis of the connection between the modules and the heat supply/demand.

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