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Latent heat based high temperature solar thermal energy storage for power generation

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Abstract

The design of a phase change material based high temperature solar thermal energy storage device is presented. Said unit will be used as an energy reserve for a 1 kWe domestic CCHP system using a Stirling engine to produce electric power. The thermal energy storage is conducted by means of the exploitation of the latent heat of fusion of the material contained inside the tank. This method was chosen because a great energy density is obtained and, at the same time, it is possible to extract the stored energy with very small variations on the temperature, which is a favorable feature for its intended purpose. The selection of the phase change material is discussed and the design of the different components of the proposed storage model is described. It is analyzed, as well, the insulating solution applied that minimizes heat losses. Finally, a comparison between experimental results of the tests performed on the first built to scale prototype and the data obtained from computer simulations is shown.

"Keywords: Solar thermal energy storage; Phase change material; Latent heat; Stirling engine; PCM; CCHP; TES"

1. Introduction

Numerous organizations estimate that global net electricity generation will increase in an 87 % over the next years, reaching 35000 TWh in 2035 as a result of demographic growth and population's economic development. [1].

Specifically in Mexico, the net domestic power consumption will experience an average annual growth rate of 3.9% [2,3]. This, together with the known fact that the kWh cost in Mexico has increased more than 250% in the last 10 years and the trend is still on the rise [4], will represent a serious outflow in the family economy of consumers.

Rise in the global power consumption is not exclusively an economy-related problem for population, but represents a serious environmental threat. It is important to know that in Mexico, USA and many other countries, more than 75% of electricity is produced by burning fossil fuels in thermoelectric plants, which consume either natural gas, fuel oil or coal [5], thus an increase in power consumption translates directly in an increase in the emission of CO2 and other greenhouse effect gases harmful for the atmosphere and

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the environment. It is estimated that in 2035, 42 billion tons of CO2 will have been emitted to the atmosphere as a residue of global power generation [6].

High cost of electricity and environmental impacts have prompted the search for power supply alternatives that lead to a reduction of the huge environmental impact that current power generation has. Different technologies that allow harvesting of existing renewable resources have been developed in the wake of this. Solar energy has had extensive acceptance because is the most reliable renewable energy source available. There are 2 main approaches in solar energy use for power generation; one is the thermal approach, in which solar radiation is concentrated to heat a work fluid, which is then used to drive a steam turbine or a Stirling engine to produce electricity. The other is the photovoltaic approach, in which sunlight is transformed directly into electricity by means of solar cells; this means that solar panels are only effective during the hours of the day in which solar resource is available because the cost of storing electricity in batteries is considerably high. Thermal energy storage is much less costly, which makes the solar thermal approach very attractive for big scale power generation [7].

In the present article the design of phase change material based high temperature solar thermal energy storage is presented. This unit is currently under development as a key component for a 1 kWe domestic CCHP system using a Stirling engine to produce electric power. The premise of the design of this distributed system is that it is cheaper to store energy as heat and convert it to electricity when needed than to store it directly as electric energy, furthermore; on site production eliminates the cost and losses of the transmission.

Nomenclature

CCHP	Combined cooling, heating and power
h_0	Air convection coefficient (W/m^2 K)
K_n	Thermal conductivity of the n layer of insulation (W/m K)
L	Height of the PCM container (m)
LHS	Latent heat storage
PCM	Phase change material
r_n	Thickness of the n layer of insulation (m)
T_0	Average ambient temperature (°C)
T_1	Melting temperature of the PCM (°C)
T_3	Temperature at the surface of the first insulation layer (°C)
T_4	Desired outermost surface temperature (° C)
TES	Thermal energy storage
W	Lambert-W function, also known as product logarithm

2. Thermal Energy Storage Methods

There are three methods for storing thermal energy storage, being the first 2 the most widely used in TES systems: sensible heat storage, latent heat storage and thermochemical storage

Latent heat storage consists in heating a material until reaching a change of phase, generally from solid to liquid, when the material reaches its fusion temperature it absorbs a very large amount of heat to carry on the phase change, this way energy is stored [9]. Liquid-gas transitions contain enormous amounts of phase change heat, however the huge density changes render the system very complex and unpractical, due to this, the solid to liquid phase change is mostly used [10].

The distinctive characteristic and main advantage of this kind of storage over sensible heat storage is that it operates in a nearly isothermal way on the melting point of the material, meaning that it is capable of delivering the stored energy at an almost constant temperature. Another advantage is its compactness, since latent heat of fusion is much bigger than sensible heat in the majority of materials.

Given their properties, phase change materials are employed primarily on applications where space and weight are restrictive and thus a high energy density is required, or when a thermal load which requires an energy supply at constant temperature is in use.

3. Application in distributed power generation

As aforementioned, ITESM, a renowned Mexican university, is currently developing a domestic power generation solution based on solar thermal energy, capable of generating cool, heat and power for a whole house on a 24/7 basis; thanks to its state-of the art solar concentration and high temperature thermal energy storage technologies.

This system is focused on two main goals, the first one is to offer the public an affordable alternative for their household electric supply and a real opportunity to completely eliminate the monthly electric company's receipts, and secondly, but not least, contribute to the environmental protection by being an emission-free energetic solution based on renewable resources, that radically minimizes the negative effects associated with the indiscriminate usage of fossil fuels.

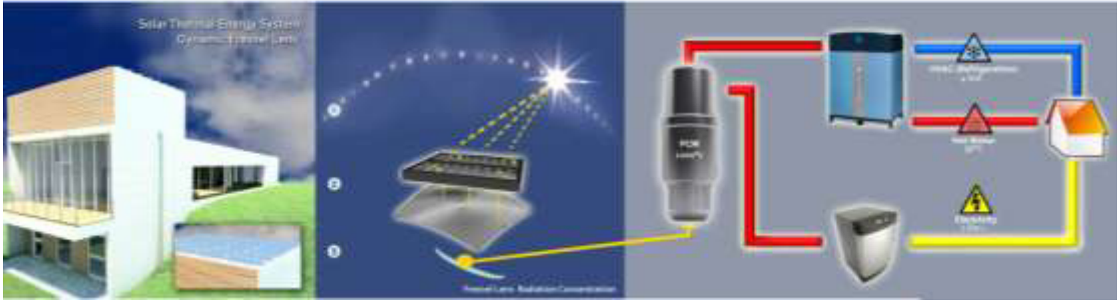

Figure 1. Diagram of the Solar CCHP system in development by ITESM

A diagram of the system is shown in figure 1, it captures the energy coming from the sun, in the form of thermal radiation, by means of a Fresnel lens with an innovative minimum movement reflective blinds system mounted on top that redirects solar rays so that they strike completely perpendicular on the lens surface allowing it to concentrate radiation on a spot, to be later introduced into the thermal energy storage unit (TES).

The interior of the thermal energy storage unit is filled with a phase change material (PCM), as the energy flows into the interior of the unit, the temperature of the PCM rises until it reaches its fusion point at approximately 1200°C, this transition from solid to liquid is what allows the energy to be stored by the material at a constant temperature during a long period of time.

The TES is connected to a 1 kW_e Stirling engine through a heat exchanger, the movement of the engine's output shaft drives an electric generator that will deliver electrical current 24 hours a day; it's important to mention that the system will not supply the house power demand directly, instead, it will be connected to the electric grid, sending the generated power through the grid in order to achieve a neutral (or positive) balance between consumed and given power at the end of each billing period.

The heat exchangers are also capable of producing hot water (<50°C) to satisfy all the common household needs and to drive a third party absorption based refrigeration machine (<100°C) or any other thermal powered refrigeration system; covering in this way a house's basic needs, power, heating and cooling. It is also important to note that the functionality and efficiency of the system resides on the thermal storage, the fact of having an energy reserve means that the system is able to operate even during night time when no solar radiation is available.

The system development has been planned in three stages, the first of which contemplates the design and development of the concentration and storage prototype units, the second stage regards the integration of the technologies including the Stirling engine, focusing solely on power generation; the third and final stage is the integration of the power generation system with the water heating components to have the full operating domestic CCHP system.

4. Design of the solar thermal energy storage unit

The design of a suitable thermal storage unit for the CCHP system begins with the selection of the storage method, as mentioned earlier the CCHP will produce power through a Stirling engine, which demands a continuous heat flux on its power input for a smooth operation, furthermore, its operation is quite sensible to temperature changes on the hot side. Latent heat based storage was chosen because both aspects can be covered as it provides an almost isothermal energy delivery at the melting temperature of the material, allowing to reach an optimum engine performance.

Once the energy storage mechanism has been defined, the selection of the material to be used as storage medium needs to be addressed. The Stirling engine requires to maintain a temperature on its hot side above 550 °C, this is the first selection criteria, the phase change material needs to have a fusion temperature meeting this condition, a wide variety of high temperature PCMs which for their melting point and storage capabilities have the potential for being used as storage media in solar power plants or industrial waste heat recovery systems have been studied, this high temperature group includes inorganic salts, salt eutectic compounds, metal alloys and metallic eutectics. An appropriate fusion temperature and a high latent heat are very important aspects to consider but not the only ones, the material need to possess the right combination of the following parameters: a high thermal conductivity, chemical stability, chemical compatibility with the container and low corrosivity, low toxicity and flammability, small volumetric variations due to phase change, commercial availability and a reasonable cost. [12]

Figure 2 shows a comparative graph of diverse materials in terms of melting temperature and latent heat [13][14]. It can be easily distinguished a group of materials that possess a latent heat of fusion above 700 kJ/kg integrated by inorganic salts such as lithium fluoride (LF), magnesium fluoride (MgF_2), and sodium fluoride (NaF). It is possible to identify a second group of salts placed in the 400 to 600 kJ/kg range comprised by sodium chloride (NaCl) and potassium fluoride (KF), among others compounds; this group results very interesting because it offers a very good level of energy storage in a temperature range lower than the first thus easier to handle.

Soda-lime glass (window glass) was selected as the first option to be used as phase change material, in view of its high latent heat storage capacity, about 2740 kJ/kg, elevated but still manageable melting temperature, around 1000° C, handling safety unlike some of the salts, and ease of acquisition. The use of glass as a PCM will introduce some technical complexity to the system as glass compounds instead of having a defined melting point present a melting temperature range, what causes a lack of a defined latent heat of fusion as well. Table 1 summarizes some of the PCM properties.

The Stirling engine has an estimated average efficiency of 25%, meaning that it has to be supplied 4 kW_{th} in order for it to produce $1kW_e$. The thermal storage unit has to be able to store at least 64 kWh to be able to maintain the engine operating for the 16 hour period without usable solar radiation. The storage unit prototype will contain a total 60 L of solid material (approximately 150 kg) which is sufficient to secure a 24 hour system operation plus an extra 20% to compensate for heat losses and to prevent cloudy periods.

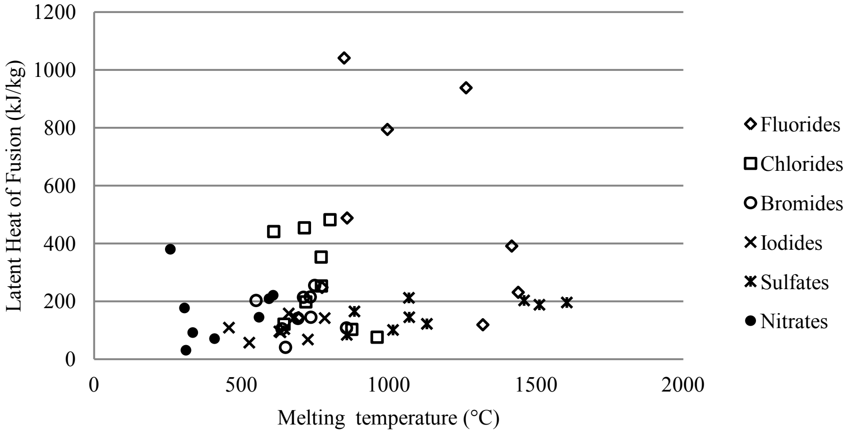

Figure 2. Comparison of the latent heat of fusion and melting temperatures of various inorganic salts

Table 1. Thermal properties of selected storage media [15] [16]

Soda-Lime Glass (74% SiO_2) Properties	
Density	2710 kg/m^3
Melting point	1000 °C
Thermal Conductivity	0.79 W/m K
Specific Heat	0.837 J/g K
Thermal Diffusivity	0.348 x 10^{-6} m^2/s
Specific Energy	0.76 kWh/kg
Energy Density	1.9 kWh/L

The main structure of the unit, where the phase change material is contained is made of a high density extra high alumina (96%) castable refractory concrete, capable of withstanding severe cyclic thermal loading and corrosion caused by contact with the molten storage media. Although the container doesn't perform any relevant energy storage of heat transfer function, safety-wise is a very important component; therefore design and manufacturing processes of the ceramic container are of great importance. Thermal stresses in the application are by no means negligible and can easily fracture poorly designed refractory components, potentially causing leaks of molten PCM at elevated temperatures. Molten glass has a very high viscosity so even if fractures appear on the container; the risk of leakage is quite low because the molten material will solidify before escaping sealing the cracks.

Using solid-liquid transition PCMs has a number of technical complications; one of the biggest problems that researchers face and has contributed to the widespread use of LHS remains unsatisfactory so far is the very low thermal conductivity of the PCMs, glass is no exception, besides that, there are other challenges such as phase segregation and subcooling, which can be very severe and completely impede the extraction of the stored energy [17] [18]. Low thermal conductivity means that the material is resistant to heat flux, so energy can't flow easily inside the material and it takes longer to reach the particles further away from where energy is supplied. In order to improve overall thermal conductivity of latent heat storage systems researchers have been studying the use of fins and extended surfaces and the dispersion of highly conductive particles within the PCM, integration of metallic structures and PCM embedded porous matrices.

On the interior of the storage unit, immersed on the molten PCM, a thermal conductor made of graphite (a highly conductive material) is located. Said conductor was designed specifically to address the problem of the low thermal conductivity of the storage media, the objective is to provide a low resistance path for the received heat to flow easily inside the container and to minimize the distance traveled between it and the most distant particles of phase change material.

The thermal conductor is the core of the storage unit, it is in charge of receiving the concentrated radiation coming from the lens and conducting it to the PCM, ensuring a uniform temperature distribution inside the container, one important design challenge of the thermal conductor is to minimize as much as possible the distance to the farthest particles of PCM without incrementing too much the total volume of the unit.

A CAD model of the design of the solar thermal energy storage unit is shown on figure 3, the conical shaped component on top is where concentrated solar radiation strikes; it is connected to the internal thermal conductor (black). The mass pictured in orange is the molten PCM surrounding the internal thermal conductor walls, the clear cylinder and green piece are the refractory container and closing lid, respectively. Blue rings connected with rods are made of stainless steel; they serve as a safety mechanism to maintain the container closed. White cylinders around the container are solid refractory pieces used to keep the container centered inside the metallic outer shell (not shown).

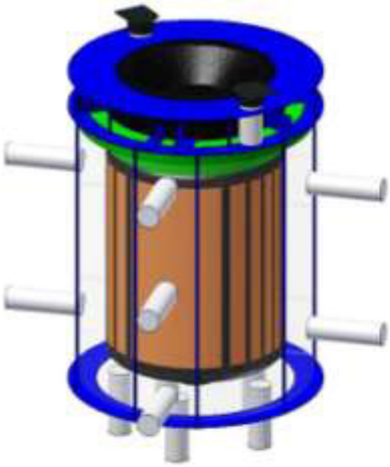

Figure 3. Isometric view of the inner core of the latent heat based-solar thermal energy storage unit prototype

When operating within the CCHP system there is never a charge only period, instead charging and discharging are simultaneous. During daylight hours, approximately 8 hours or 1/3 day, while the Stirling engine is running, the storage unit receives from the Fresnel lens an average of 150kWh, equivalent to the energy for the entire day operation; it is responsibility of the internal thermal conductor to distribute 2/3 of the received energy to the PCM for it to absorb and store for sustaining the operation during night-time (the remaining 2/3 of the day) and to let 1/3 of the heat to flow freely for the Stirling engine to keep generating electricity. In other words, during daytime the unit is charged while being discharged at a slower rate, meanwhile during night-time the unit is purely discharged.

The heat transport from the PCM to the Stirling engine will be performed by means of heat transfer fluid flowing through the bottom graphite plate, the high thermal conductivity of the graphite walls will help to extract heat from the upper portions of PCM, and the heat will be delivered by convection to the Stirling head.

Another very important aspect of the TES unit design is the thermal insulation; the unit must have an insulation solution that minimizes energy losses to the surroundings to improve the efficiency, it should also allow to have a surface temperature that doesn't represent a risk for the user, the challenge is to achieve the previous keeping to a minimum the overall diameter of the apparatus.

A custom 2 layers insulation solution with an optimum thickness was developed. Thermal information of high-end insulation products commercially available was collected previously to any calculation effort. The goal was to obtain the minimum possible insulation thickness, while attaining an outermost surface temperature below 50°C. The calculation was performed in an iterative way, using the mathematical model described in equations (1) to (3), where r_4 is the thickness of the outer insulation layer and W is the Lambert-W function, also known as omega function or product logarithm. The model parts from a simple equation regarding convective heat transfer between the outermost surface and the ambient and from the premise that heat flow is constant through each layer of the system.

$$r_4 = \frac{AK_3}{W\left(\frac{AK_3 e^{K_3 B}}{r_3}\right)} \tag{1}$$

$$A = \frac{T_1 - T_4}{h(T_4 - T_0)}\ , B = \left[\frac{ln\left[\frac{r_2}{r_1}\right]}{K_1} + \frac{ln\left[\frac{r_3}{r_2}\right]}{K_2}\right] \tag{2}$$

To perform the calculation of the minimum required insulation thickness it is necessary to know the values of certain parameters, including: the temperature inside the container (T_1), average ambient temperature (T_0) and the desired outermost surface temperature (T_4), thermal conductivity of the materials (K_1, K_2, K_3), dimensions of the container (r_1, r_2, L) and the air convection coefficient (h_0). Iterations are performed assuming different thicknesses for the first insulation layer (r_3) and monitoring that the temperature on its surface (T_3) does not exceed the maximum operation temperature of the material that will constitute the second layer. The process is repeated for every combination of materials until the optimum value is found. A total thickness of 20.5 cm was achieved; the total diameter of the storage unit is 104 cm.

Computerized simulation is a tool that has been very helpful in the prototype design process since through specialized software as Autodesk's Multiphysics simulation it is possible to observe the flow of thermal energy inside the storage unit, the temperature distribution in both, the internal thermal conductor and the PCM itself, energy flow through different layers of insulation and heat losses by both, convection and radiation to the surroundings, amidst other things. Figure 5 shows the temperature distribution in the refractory container outer wall as well as in the phase change material and internal thermal conductor.

5. Prototype experimental testing

The Fresnel lens prototype is not ready at the moment, so TES experimentation will have to be using combustion heat. The plans is to place a furnace on top of the prototype and heat its interior through a gas burner with an air blower, until reaching temperatures above 1300 °C on the inner refractory brick walls and irradiate heat to the energy entrance of the storage unit as shown in figure 5. The furnace approach was chosen because it emulates best radiant heat that will be received from the lens, unlike electrical resistances or direct flame.

Numerous attempts were made until having a functional test setup; which is partially automatized using a Honeywell burner control, UV flame sensor, several control valves, etc. Experimentation done so far consisted of heating the unit to reach maximum operating temperature; the prototype was heated for 6 days and 20 hours, reaching a temperature of 970 °C on the glass, the graphite components at the entrance of the unit exceeded 1200 °C. The process consumed 313.5 m^3 of propane gas. Further analysis of obtained data is still required to determine to how much energy was stored in the PCM, how much was spent heating the furnace and how much was lost in the ambient. During heating, measurements were taken at more than 10 different points on the prototype every 5 seconds to study its behavior in function of the energy supplied. Figure 6 shows a plot of the measurements obtained in the experiment; it includes the curves of seven thermocouples considered the most important.

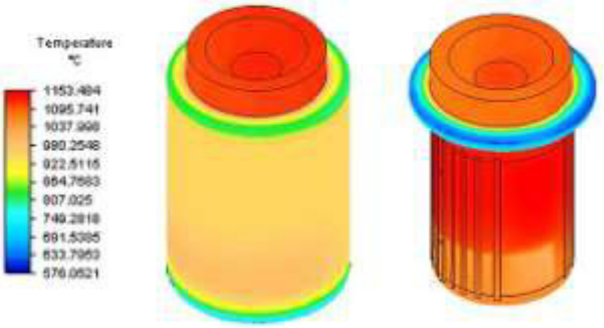

Figure 4. Computer simulation of temperature distribution inside thermal energy storage unit

Figure 5. Solar thermal energy storage prototype and experimental setup

Thermocouples 1, 2, 6, and 7 are type R thermocouples, immersed in the PCM at different depths and heights, the remaining 3 are type K thermocouples, 8 is in the graphite plate at the bottom of the container while 0 and 5 are on the top graphite plate just above the molten glass.

Further work is required to smooth the graphs and create from them an equation describing the heating and cooling of the unit with respect to the temperature at the entrance.

Figure 6 reveals some interesting information; it is possible to observe that all internal components follow a similar heating pattern, which means that the arrangement of graphite conductive walls performs satisfactorily its energy distribution function, managing to achieve a relatively small temperature variation within the interior of the storage unit.

The following steps on the experimentation will be to repeat heating to maximum operating temperature and after reaching it, the prototype will be allowed to cool during nighttime and heated up again next day repetitively to simulate operation on the actual system; this was attempted with no success due to failures on the furnace, the attempts explain the peaks on the cooling part of the graph. Results will be compared to simulation data currently being on preparation. After the lens and Stirling's connection are ready the integrated system will be tested on a similar way.

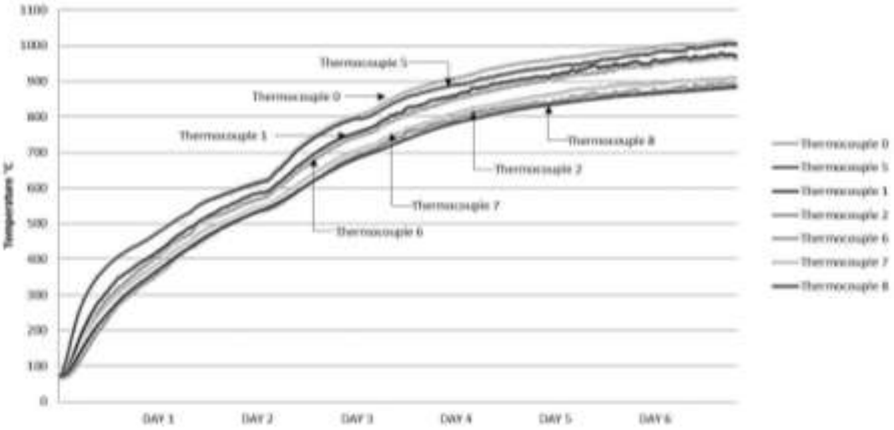

Figure 6. Experimental TES prototype heating and cooling processes

6. Conclusions

Thermal energy storage is a promising technology to solve the serious problems of energy demand in the future, because, as solar thermal plants have demonstrated, it is easier and cheaper to store heat in a thermal storage for its later conversion into electric power than to produce electricity and store it in conventional electric batteries, hence, TES greatly increases the efficiency of solar thermal systems allowing a continuous operation.

A first prototype of the solar thermal energy storage unit with a 114 kWh energy storage capacity has been developed to be utilized with a Stirling engine in a domestic CCHP system for 24/7 power generation. The unit employs molten soda-lime glass as its storage media and an array of graphite components for improved heat transfer and performance.

Experimentation performed is still inconclusive but helped to prove some of the design concepts used on the prototype, the internal thermal conductor is actually capable of maintaining a very low temperature difference between the PCM on top of the container and the PCM in the bottom. Measurements also reveal that the heating of different components followed a similar pattern which means an equitable distribution of heat flow.

The design of a thermal energy storage unit can be divided in 2 sections: first there is the materials research part related to storage media selection, while the second part is the design of the heat transfer components and structure containing the PCM.

For choosing an appropriate storage media it is necessary to evaluate several properties of the material: melting temperature which must be in the range of required temperature of the application, high latent heat of fusion, good thermal conductivity, thermal diffusivity and overall heat capacity, besides other factors such as chemical stability, non-flammability, cost and commercial availability.

It is important to include some thermal performance enhancer such as metallic fins or extended surfaces, high conductivity particles dispersed on the PCM or conductive structures to assure a good heat transfer inside the unit and facilitate energy extraction. Container structure requires also special attention in terms of the refractory and ceramic materials and mold design, since thermal stresses to which it will be submitted due to cyclic charge and discharge aren't negligible and a fracture can lead to PCM leakage at very high temperatures. Unit must have an insulation solution that minimizes energy losses to the surroundings and achieve a surface temperature that doesn't represent a risk for the user.

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