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INSULATION AND APPLICATIONS OF THERMAL ENERGY STORAGES

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Bachelor's thesis 23.02.2017
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ABSTRACT

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2017

Bachelor's thesis.
33 p.

Examiner: Jero Ahola

The use of wind and solar energy sources is increasing rapidly and because of their varying power production values, balancing supply and demand of the electricity consumption has become an area of research. For this several different energy storages have been invented. Their use is not limited to electricity generation and they have varying advantages and disadvantages. The purpose of this study is to research thermal energy storages and compare them to different energy storages by cost, efficiency and power generation. The heat transfer fluids and filler materials used in thermal storages are discussed. Insulations are examined, while focusing on materials suitable for high temperatures. Heat losses and insulation properties of small scale thermal energy storage that uses solar salt as a phase change storage material was studied. The different insulation methods used for the experiment, where vacuum and expanded perlite in a vacuum. Due to the radiative heat losses T^4 correlation with the temperature, the focus during the experiments was the radiative losses. One experiment was conducted with the annular gaps pressure lowered to 0.02 mbar and in the second experiment the annular gap was filled with expanded perlite and the pressure lowered to 0.02 mbar. During both experiments the solar salt was heated to around 320 °C and then cooled down to room temperature at a natural rate. The insulation capabilities were observed. The heat flux at 306.3 °C at the first experiment was 306.42 W/m^2, which was the main source of heat loss. At 80 °C the heat flux in the first experiment was 14.76 W/m^2. The second experiment with expanded perlite in the annular gap at 318 °C had the radiative thermal conductivity of 0.01010 W/(mK). At 80 °C the radiative thermal conductivity in the second experiment was 0.00344 W/(mK). It was observed that at lower temperatures, when the radiative heat loss is not dominant, the heat loss was reduced. In a thermal energy storage the choice of heat transfer fluid and the filler material is important for efficiency and cost. To prevent heat losses at high temperatures the insulation material that also reduces radiative heat loss is effective.

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2017

Kandidaatintyö.
33 s.

Tuuli- ja aurinkovoiman käyttö yleistyy maailmassa nopeasti. Nämä energialähteet ovat vaihtelevia tuotantoarvoiltaan ja niistä johtuvan sähköntuoton tasapainottamisesta ja säädöstä on muodostunut tutkimusalue. Tätä ratkaisemaan on kehitetty erilaisia energiavarastoja. Niiden sovelluskohteet eivät ole pelkästään sähköntuotannossa sekä niiden ominaisuudet, edut ja haitat vaihtelevat. Tässä tutkimuksessa selvitettiin lämpöenergiavarastojen toimintamalleja sekä vertailtiin niitä kustannusten, hyötysuhteen ja tuotantokyvyn perusteella muihin olemassaoleviin energiavarastoihin. Lämpöenergiavarastoihin keskitytttiin ja niissä käytettäviä lämmönsiirtoaineita ja varastointiaineita tarkastellaan tarkemmin. Eristysratkaisuja selvitetään ja keskitytään materiaaleihin jotka soveltuvat korkeisiin lämpötiloihin. Erilaisten eristysratkaisujen kustannuksia, lämmönjohtavuuksia ja asentamisen rajoituksia vertaillaan. Pienimuotoinen lämpövarasto rakennettiin jolla pystytään tutkimaan eristysratkaisuja. Koska lämpösäteily kasvaa lämpötilan muuttuessa T^4- verrannollisesti, tutkimuksessa keskityttiin lämpösäteilystä aiheutuviin lämpöhäviöihin. Tutkimuksessa käytettävässä lämpövarastossa on solar salt suolaa lämmönvarastoiniaineena. Ensimmäisessä tutkimuksessa säiliö täytetiin suolalla ja välitila jätetiin tyhjäksi, sekä välitilan paine alennettiin 0.02 mbar. Tämän jälkeen suola lämmitettiin noin 320 °C ja annettiin jäähtyä huoneenlämmössä. Toisessa tutkimuksessa säiliön välitila täytetiin perliitillä ja alennettiin 0.02 mbar paineeseen. Eristyksen ominaisuuksia tarkailtaessa huomattiin, että korkeilla lämpötiloilla suurin lämpöhäviö johtuu säteilystä. Ensimmäisen kokeen lämpövuo 306.3 °C lämpötilassa oli 306.42 W/m^2 ja 80 °C lämpövuo oli 14.76 W/m^2. Toisessa kokeessa säiliön säteilystä aiheutuva lämmönjohtavuus 318 °C lämpötilassa oli 0.01010 W/(mK) ja 80 °C lämpötilassa säteilystä aiheutuva lämmönjohtavuus oli 0.00344 W/(mK). Havaittiin, että lämpötilan laskiessa lämpöhäviöt pienenivät, koska lämpösäteilyn merkitys pieneni. Lämpövarastoissa lämmönsiirtoaineen ja energian varastointiaineen valinta vaikuttaa kustannuksiin ja hyötysuhteeseen. Korkeissa lämpötiloissa olevien lämpövarastojen hyötysuhdetta voidaan parantaa estämällä säteilystä aiheutuva lämpöhäviö.

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

CSP	Concentrated solar power
EPS	Expanded polystyrene
ESS	Electrical energy storage
GSHP	Ground source heat pump
HTF	Heat transfer fluid
NIM	Nano insulation material
PCM	Phase change material
PUR	Polyurethane
PV	Photovoltaic
TES	Thermal energy storage
TPV	Thermophotovoltaic
VIM	Vacuum insulation material
VIP	Vacuum insulation panel
VSI	Vacuum super insulation
XPS	Extruded polystyrene
C_{p}	specific heat capacity
d	gas molecule diameter
E	energy
e^*	total mass-specific extinction coefficient
ΔH	heat of fusion
K_{n}	Knudsen number
l_{mean}	average distance between air molecules
l_{ph}	mean free path of thermal photons
n	refractive index
P_{g}	gas pressure
P	power
q	heat flux
r	radius
T	temperature
t	time
β	energy transfer efficiency
ε	emissivity
δ	pore size
λ	thermal conductivity
ρ	density
σ	Stefan-Boltzmann constant

Subscripts

conv	convection
coupling	coupling effect of thermal conductivity
g	gas
r	radiation
s	solid
tot	total

1. INTRODUCTION

The use of wind and solar energy sources is increasing rapidly, with the year 2015 having the largest addition to the global energy capacity to date. Both solar and wind power capacity was increased with over 50 GW from 2014 to 2015, partially because of their continued declining prices. In 2015 in the developing countries such as Brazil and India the investments in rewenable energy sources increased 19 % from 2014 (Sawin et al. 2016).

This however brings a growing demand for alternative ways for maintaining the balance of supply and demand for electrical power grids. Other concerns include global warming and prolusion of the environment. These factors have led to the increase of renewable energy sources, which mainly have a varying power generation efficiency and the dependence on environmental factors. To answer the need for power regulation and to help maintain the balance of supply and demand, different kinds of energy storages have been and are currently being developed. Their purpose is to help to maintain the power balance in electrical power grid and to lower the generation cost during peak demand periods. Power balancing the energy storages improves the efficiency of power plants. Energy storages can also help provide electricity as a backup during a blackout (Zanoni and Marchi 2014).

In Table 1.1 are gathered some alternative ways to store energy. Each system has its advantages and weaknesses for various applications. Mechanical energy storages such as pumped water rely on potential energy or kinetic energy. In pumped water storage, large amounts of water is contained in an elevated position and when electricity is needed it is released through a turbine. When electricity is cheaper of there is a surplus it is pumped back up for later use. Compressed air is contained in high pressure storage and when released through a turbine it generates electricity. Energy is stored by compressing air with the use of surplus electricity. Flywheels preserve energy via kinetic energy. Battery storages are familiar to most and can also be used as large scale energy storages. Usually they consists of small batteries connected in series. Power-to-Gas converts electricity into an energy-rich gaseous storage medium, usually hydrogen or methane (Lehner et al. 2014). Super capacitors are large scale capacitors that have very high discharge currents and capacity when compared to a regular capacitor. Superconducting magnet energy storage stores energy in the magnetic field that is generated around a coil that has a direct current going through it. The thermal loses that would normally come from resistance are removed by cooling the coils to the point in which it becomes superconductive. Thermal energy storage (TES) can use either sensible heat, latent heat or phase change to store energy. Sensible heat uses temperature change to store energy, while latent heat stores energy in the phase change. Phase change is a combination of the two. The stored heat can later be converted into electricity. A deeper analysis on thermal energy storages will be conducted later in Chapter 3 (Biczel 2008).

Table 1.1 Different kinds of energy storages (Biczel 2008; Lehner et al. 2014).

Energy storage				
Mechanical	Chemical	Electrochemical	Electrical	Thermal
Compressed air Flywheels Pumped water	Hydrogen Power-to-Gas	Secondary batteries Flow batteries	Super capacitors Superconducting magnet energy systems	Phase change materials Latent heat Sensible heat Chemical heat

This study focuses on the applications of TES and the insulation options available now and possibly in the future. The aim is to research different energy storages and their applications and use, while focusing on thermal energy storages. The concept of various energy storage systems is explained and a comparison of properties, capacities and prices are presented. The advantages and disadvantages of energy storages are discussed. How thermal energy storages operate and what affects their efficiency is investigated. Heat transfer fluids and filler materials are presented with the focus on solar salt. Thermal conductivity, price and properties of traditional insulation and state-of-the-art insulation is compared. The requirements for high temperature insulation are examined. The effects of high temperatures on the thermal concuctivity of insulation materials is discussed. A small scale TES with solar salt as heat transfer fluid is used to study heat loss and insulation properties. The heat energy is stored by using the solar salt as a phase change material. The focus of the heat loss is on radiative heat loss. Insulation methods used are vacuum and evacuated perlite.

1.1 OUTLINE OF THE THESIS

In this study a comparison of properties, application and prices between different energy storages is briefly discussed in Chapter 2. The concept and workings of thermal energy storage, such as the methods in which the thermal energy can be stored, is explored and presented in Chapter 3. The most common insulation materials and promising possibilities are reviewed and compared in Chapter 4. Potential applications for high temperature thermal energy storages are discussed in Chapter 5. Finally an experiment was conducted to determine the insulation properties of a small scale thermal energy storage and the experimental set-up and results are presented in Chapters 6 and 7, respectively.

2. ENERGY STORAGE SYSTEMS

The installed capacity of renewable energy sources is increasing rapidly (Sawin et al. 2016). However, since they are dependent on environmental factors they require other electricity production methods to help them maintain network stability and load balance. Electrical energy storages (ESS) could provide a solution for this problem. ESS can be used for steady power generation, thus improving renewable energy sources reliability and management. Their use could help meet the load demand during peak electrical consumption, reducing the need to import electricity during peak demands. Varying types of storages would be required, such as daily, weekly, monthly and seasonal storages. Appropriate ESS can be chosen for the applications and purpose. The increase of ESS could lead to the development and use of smart grids, because they enable the management of distributed power generation (Luo et al. 2015). The comparison for advantages and properties for different ESS can be found in Table 2.1. Gathered were such properties as capacity, startup time, storing time and costs, because they help determine the appropriate ESS for the selected application. From battery storages, two promising options were listed, Lithium-ion (Li-ion) battery and sodium-sulfur (NaS) battery. Maintenance costs is also factor that needs to be taken into consideration when selecting ESS. Expenses of maintenance vary for different storage methods, for example pumped water storage maintenance costs are approximately 3 – 5 $/kW per year, while for nickel – cadmium batteries it is 5 – 25 $/kW per year and for hydrogen fuel cells 50 – 120 $/kW per year (Malyshenko and Schastlivtsev 2015).

Table 2.1 Comparison of different properties of energy storage systems (Biczel 2009; Ciez and Whitacre 2016; DOE 2014; Lehner et al. 2014; Luo et al. 2015; Malyshenko and Schastlivtsev 2015).

Storage method	Capacity	Power	Startup time	Storing time	Lifetime (years)	Power cost ($ / kW)	Energy cost ($ / kWh)
Pumped-storage hydroelectricity	10 000 MWh	10 – 10 000 MW	2-5 min	Months	>30	2500 – 4300	5 – 100
Compressed air	100 MWh	100 MW	12 min	Months	15 – 20	800 – 1000	2
Flywheels	0.1 – 20 MWh	100 kW	Seconds – minutes	Hours	15 – 20	250 – 350	1000 – 14,000
Batteries	0.1 – 50 MWh	0.1 – 100 MW	Milliseconds	Days – weeks	5 – 10	1200 – 1400 (Li-ion),	200 – 300 (Li-ion),
Superconducting magnet energy storage	1 MWh	0.5 MW	Seconds	Minutes	20 – 30	200 – 400	1000 – 10,000
Supercapacitor	0.0005 MWh	0 – 0.3 MW	Milliseconds	Minutes	~10	100 – 450	300 – 2000
Hydrogen storage	0.1–50 MWh	0.01 – 2 MW	Seconds	Hours – months	10 – 25	1500 – 3000	2 – 15
Thermal storage	0.1 – 300 MWh	0.1 – 300 MW	Long	Days – weeks	>20	100 – 400	30 – 60

The advantages of pumped-water storages are low cost and the potential to store energy for long periods of time. Drawbacks are the requirement for two large volume reservoirs and since the height difference is major contributor to the stored amount of energy, it has a significant impact. Underground pumped-water storages are being developed. The compressed air storage can also store large amounts of energy for several months. Due to the high cost it is not feasible for small scale storages. Flywheels are used for short term storing of mechanical energy such as in electrical vehicles. They are simple in design and have low maintenance costs. Stored energy is however low and thus limits the applications of flywheels. Batteries are possible to build near the loads and can provide frequency and voltage control which are important in maintaining the power grids balance. Their disadvantages are high cost, low lifetime and limited discharge depth (Malyshenko and Schastlivtsev 2015). Superconducting magnet energy storages require very low temperature in order to properly work and therefore the cooling costs are high. Storing time is also low, but can produce high power, has fast response time and unlike batteries, can fully discharge their stored energy. Supercapacitors have long lifetime, high efficiency and can be discharged fast and with can generate high currents. Their drawbacks are high self-discharge rate along with high costs and low energy density. Power-to-Gas technologies that use hydrogen could potentially be used as seasonal storages that can store energy for months. These storages could be integrated into existing gas and electrical grids, however a number of problems would have to be considered first, such as impacts to the infrastructure and transport capacities (Lehner et al. 2014). A major problem is storing and transporting large amounts of hydrogen due to its low specific volume. Thermal energy storages have good specific energy and low self-discharge loss and can be scaled for large applications. It also has relatively small costs, but has low cycle efficiency (Biczel 2009; Luo et al. 2015).

3. THERMAL STORAGE

Thermal energy can be stored as sensible heat, latent heat or thermochemical heat. In a phase change material (PCM) energy can be stored as both sensible and latent heat. In a thermal energy storage, heat transfer fluid (HTF) is circulated through a heat receiver and then flowed in to storage where it can be used as a storage medium. To lower the costs the storage is usually filled with cheaper filler material which stores the heat.

There are different methods to store thermal energy. Electricity can be stored by heating the storage with a resistor, or if the PCM is magnetic or electrically conductive an inductive heater could be applied. Solar power can be stored as heat via concentrated solar power and then be converted into electricity when needed. Heat can be converted into electricity by different methods such as flowing a heat transfer fluid through a heat exchanger to superheat steam and making it power a turbine, thus generating electricity. Heat can also be released as electricity by using a thermophotovoltaic converter (TPV). TPV uses infrared sensitive photovoltaic cells to generate electricity similar to that of regular photovoltaic (PV) cells. TPV can be used with high temperatures and has a high power density. Because it lacks moving parts and working fluids it has low maintenance costs. It can also be utilized in collecting industrial waste heat which, along with its moderately high efficiency, makes it an interesting technology when it comes to thermal energy storages. However currently the main development is in the area of fossil fuel applications (Bauer 2011; Datas et al. 2016).

Important requirements for an efficient thermal storage are:

- High energy density
- Chemical and mechanical stability
- Low thermal losses
- Long lifetime
- Efficient charge and discharge cycle
- Good heat transfer between HTF and storage medium

(Gil et al. 2010).

3.1. HEAT TRANSFER FLUIDS

Different liquid media can be used as a heat transfer fluid, such as molten salts, water and synthetic oils, from which molten salts have been found to be effective. Molten salts are suitable for thermal energy storages because of their low cost and the fact that they are liquid in atmospheric pressures. The operating temperatures of molten salts are also compatible with high temperature steam turbines (Gil et al. 2010). Other crucial properties that a HTF should have are:

- Good heat exchange
- High heat capacity for storage volume reduction
- Low viscosity to reduce pumping losses
- High boiling point
- Low melting point
- Inflammable
- Nontoxic
- Chemical stability

(Boerema et al. 2012; Kenisarin 2009).

From these molten salts two most widely used are Solar Salt and HITEC. Solar salt is a mixture of sodium nitrate $NaNO_3$ and potassium nitrate KNO_3 (60-40 wt. %). The mixture of $NaNO_3$, KNO_3 and sodium nitrite $NaNO_2$ (7-53-40 wt. %) is called HITEC (Peng et al. 2010). The thermodynamic properties of these molten salts are shown in Table 3.1. The operating temperature for these salts is roughly the same, except Solar salt has a significantly higher melting point of 238°C although it also has lower cost than that of HITEC. Because of their high melting point measures need to be taken so that damage to pipes and equipment from solidifying and possible clogging can be avoided (Yang and Garimella, 2010). Both the solar salt and HITEC also become unstable at temperatures higher than 600 °C (Boerema et al. 2012).

Table 3.1 Thermodynamic properties for two of the most common molten salts. Solar salt properties are for a 60-40 wt. % mix (Boerema et al. 2012; Kenisarin 2009; Serrano-López et al. 2013; Zavoico AB 2001).

	Solar salt	HITEC
Melting point	238 °C	142 °C
Operating temperature	< 585 °C	< 535 °C
Density ρ (kg/m^3)	$2263.628 - 0.636 \times \mathrm{T}$ (K)	$2279.799 - 0.7324 \times \mathrm{T}$ (K)
Specific heat capacity C_p	$1396 + 0.172 \times \mathrm{T}$ $(\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot K^{-1})$	1560 $(J \cdot \mathrm{kg}^{-1} \cdot K^{-1})$
Heat of fusion ΔH J/g	117	80
Thermal conductivity λ	0.45 $\mathrm{W/(m \cdot K)}$	0.48 $\mathrm{W/(m \cdot K)}$
Price ($/kg)	0.49	1.92

Low cost filler material is used to lower the cost of TES a storage, such as quartz or silica sand (Brosseau et al. 2005). This is usually applied to thermocline storages which will be discussed later in Chapter 3.3. Recyclable materials such as asbestos waste have been studied for potential of serving as a filler material (Calvet et al. 2012). Some recyclable materials have and their properties are presented in Table 3.2.

Table 3.2 Thermodynamic properties of possible recyclable filler materials for thermal energy storages. High temperature concrete shown for comparison (Motte et al. 2015; Py et al. 2009).

	High temperature concrete	Cofalit	Coal fly ash	Blast furnace slags
Density ρ (kg/m^3)	2750	3120	2600	2800
C_p ($J \cdot kg^{-1} \cdot K^{-1}$)	916	860	735 – 1.300	N/A
λ $W/(m \cdot K)$	1.0	2.7	1.3 – 2.1	1 - 1.5
Price (€ / ton)	80	8	N/A	N/A

Cofalit, which is made from industrial asbestos containing waste, is found to be an attractive option for filler material due to its low price and sustainability aspect. High temperature concrete which is shown for comparison is relatively low cost and easy to use, while its disadvantages include short life time of estimated 10 years (Py et al. 2009).

3.2. CORROSION

The corrosion effects of molten salts on alloys needs to be taken into account in TES designs. Molten salts have relatively small effects of corrosion on stainless and carbon steel (Gil et al. 2010). A study was conducted where thirteen alloys were tested for long time corrosion effects from contact with solar salt at 600 °C. While the metal losses were low, the corrosion morphology showed significant variation between the samples tested. Due to insufficient time step data in the study, the time dependent nature of the corrosion was not determined conclusively (Kruizenga et al. 2013). The effects of different salts on asbestos containing waste, Cofalit, have been studied and found that nitrate salts have no or little corrosion effect on Cofalit, which means that it can be used as a filler material (Guillot et al. 2011). Among other studied industrial waste products, coal fly ash and blast furnace slags were among those that could resist the corrosion of the molten salts. They were considered potential filler materials for TES applications (Motte et al. 2015).

3.3. DESCRIPTION OF DIFFERENT STORAGE SYSTEMS

When the hot molten salt and the cold molten salt is stored in separate tanks it is called a two tanks system. When charging the system, cold salt is pumped through a receiver to be heated and then salt is stored in the hot tank. The used temperatures for cold and hot salt depend on the heat transfer fluid, in the case of solar salt the temperatures are usually around 300 °C for cold salt and 550 °C for hot salt (Angeliini et al. 2014). During discharge the hot molten salt is pumped through a heat exchanger to produce superheated steam to power a turbine. Storage system can be either indirect or direct. In the direct storage systems the HTF is stored in the hot tank while indirect system uses a storage material. A block diagram of two tank system is illustrated in Figure 3.1 demonstrating its operation cycle. Because the hot and cold fluids are stored separately there is no risk of mixing, but require a lot of HTF and materials which makes it very expensive (Yang X. et al. 2012).

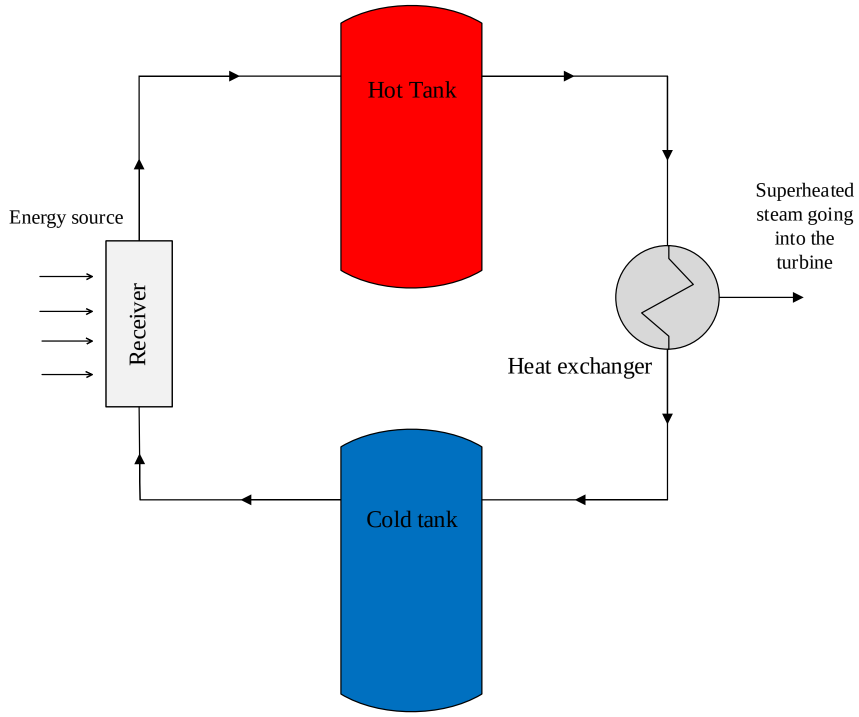

Figure 3.1 A block diagram of a two tank storage system (Ju et al. 2016).

Thermocline storage is displayed in Figure 3.2 as a block diagram. In the thermocline system the hot and cold molten salt is stored in a single tank storage at the same time. Denser cold salt stays at the bottom of the tank and the hot salt is at the top. Between them a thermal gradient forms and the layers are maintained by buoyancy effects. The formed thermal gradient is called thermocline and the system is named after it. The system is charged by pumping cold salt from the bottom of the tank and passing it through a receiver. Discharging is performed by pumping hot salt from the top and passing it through a heat exchanger. During the cycles the thermocline moves up and down. Thermocline storage can be filled with cheaper filler material such as quartz to lower costs and work as a storage material, while also helping to control the thermal gradient (Yang et al. 2016).

During the charging the thermocline moves towards the bottom of the tank and when it reaches the bottom, the tank is fully charged. The temperature of the cold fluid drawn from the bottom of the tank begins to rise and can lead to decrease in heat collection efficiency. When discharging the thermocline moves towards the top of the tank. The outlet temperature during discharging process needs to be a certain level so that generating superheated steam is possible. Therefore not all stored thermal energy can be retrieved from a thermocline storage (Yang and Garimella, 2010).

Thermocline can save up to 35 % in costs when compared to the two tank system. But its storage capability is dependent on maintaining the thermocline. It was found that thermoclines available amount of useful outlet temperature, meaning the discharge efficiency, increases with the storage tanks height and decreases when the Reynolds number of the HTF increases (Yang and Garimella 2010). The thermocline storages performance can be increased with the appropriate choice of filler material. Filler material with low diameter, low thermal conductivity and high thermal capacity is best suited for thermocline storage and will improve storage capacity and charging and discharging efficiency (Yang X et al. 2012).

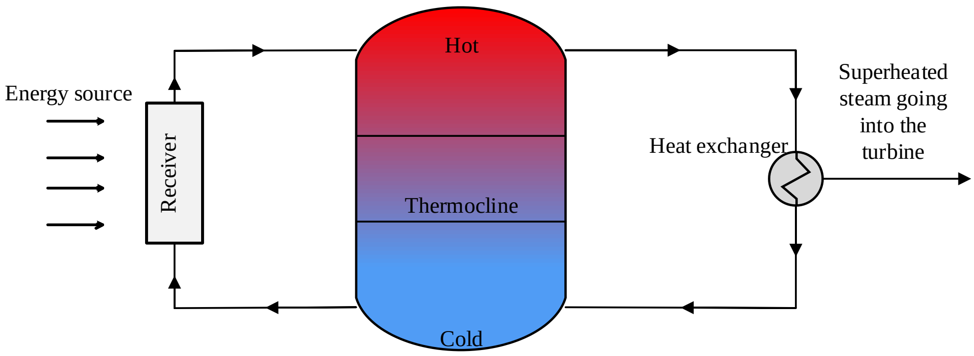

Figure 3.2 A block diagram of a thermocline storage system (Ju et al. 2016).

Because of the thermoclines shifts in the storage the temperature of the cold fluid can increase too high, resulting in heat collection efficiency loss due to risk of damaging equipment or rising the temperature of the HTF too high. During discharge the outlet temperature starts to drop when the thermocline reaches the top of the tank and the generation of superheated steam is no longer possible. This results in a decreased discharge efficiency when compared to two tank system, which can discharge more heat at a suitable temperature level for generating superheated steam. These factors are controlled by the tanks height and size. Small tanks have a high discharge efficiency but fill up too fast, while big tanks have larger capacity but suffer from larger thermoclines. It was found that thermocline is able to provide only 64% of the stored heat compared to two tanks systems 100 % that is above the required temperature level to produce superheated steam (Angeliini et al. 2014).

The two tank systems main disadvantage is the cost of material and large amounts of HTF needed. Thermoclines challenge is maintaining the thermocline. Heat lost through the tank walls or possible disturbances can cause the thermocline region to expand causing a decrease in efficiency. Also frequent charge and discharge cycles can increase the thermocline region and stratification loss through local disturbances. Therefore thermocline storages integrated with concentrated solar power (CSP) plants would not be effective in coping with constant solar fluctuations. To resolve these issues a hybrid of the two systems was presented. By utilizing both a thermocline storage and a small scale two tank system it is possible to minimize costs and avoid constant charging and discharging of the thermocline storage, thus preserving the thermocline region and discharge efficiency (Ju et al. 2016).

3.4. COMPARISON OF THERMAL STORAGES INTEGRATED WITH SOLAR POWER PLANTS

Integrating a thermal storage for a solar plant can increase the efficiency of the solar plant. By storing the excess energy that is produced during peak solar activity it will be possible to generate electricity with more flexibility. A CSP power plant with a thermal energy storage can also provide electricity continuously for longer periods of time and better cope with solar fluctuations. The two most mature technologies for CSP plants are a parabolic trough and central receiver. In a parabolic trough, a large field is filled with parabolic collectors which concentrate the sunlight onto a tuber receiver in which flows a HTF. Central receiver utilizes a tower that is surrounded by thousands of sun-tracking heliostats. These heliostats focus the sunlight onto the tower and the HTF is pumped into the tower where it will be heated and then stored. Table 3.3 shows capital cost comparison for different TES methods (EPRI 2010).

Table 3.3 Comparison of capital cost for different types of CSP plants equipped with a thermal energy storage. Includes both direct and indirect costs (EPRI 2010)

	Capital cost ($ / kWh)					
Storage method	100 MWh	500 MWh	1000 MWh	1500 MWh	3000 MWh	3500 MWh
Direct thermocline with a central receiver	132	61	46	44	37	34
Direct two tank with a central receiver	181	78	57	55	50	50
Indirect thermocline with a parabolic trough	246	106	84	70	72	73
Indirect two tank with a parabolic trough	275	143	116	111	95	89

According to Table 3.3, the thermocline storage is more economical than the two tank storage and the central receiver has lower capital costs than the parabolic trough. The larger storage sizes lead to lowered capital costs per kilowatt-hour (kWh).

4. INSULATION FOR THERMAL ENERGY STORAGES

Efficient insulation is crucial in TES to prevent heat loss and for maximizing energy efficiency. Heat loss occurs through several ways. Heat can transfer via solid state, gas, radiation, convection or coupling. For porous materials heat can transfer by conduction via solid material or the pore medium. Convection can occur through pore medium. Heat transport by radiation happens by solid to pore fluid and solid to solid within the material (Koebel et al. 2012). Because thermal conductivity is pressure dependent, applying a high vacuum ($p < 0.01$ mbar) removes the effects of gas conduction (Beikircher et al. 2015). Eq. (4.1) gives the total thermal conductivity of a material (Jelle 2011).

$$\lambda_{\mathrm{tot}} = \lambda_{\mathrm{s}} + \lambda_{\mathrm{g}} + \lambda_{\mathrm{r}} + \lambda_{\mathrm{conv}} + \lambda_{\mathrm{coupling}} \tag{4.1}$$

Where λ_{tot} is the total thermal conductivity, λ_{s} is solid state thermal conductivity, λ_{g} is gaseous thermal conductivity and λ_{conv} represents thermal conductance through convection. $\lambda_{\mathrm{coupling}}$ accounts for effects that the thermal resistances on have between them. Coupling term is sometimes neglected due its complex nature and small impact on the overall thermal conductivity (Jelle 2011; Wiener et al. 2009). However it is relevant in case of porous material (Beikircher and Demharter 2013; Kalnaes and Jelle 2014). This porous material is used in insulation, because in a porous material the gas thermal conductivity is affected by pressure and the size of the pores of the material. By lowering the pressure and having a material that has small pore size the insulation properties of a material can be improved. In porous materials the solid thermal conductivity scales with the bulk density of the material (Beikircher and Demharter 2013). Eq. (4.2) – (4.4) give the gas thermal conductivity in a porous material that is expressed with the Knudsen effect (Baetens et al. 2011; Fricke et al. 2006; Shufer 2015):

$$\lambda_{\mathrm{g}} = \frac{\lambda_{\mathrm{g,0}}}{1 + 2\beta K_{\mathrm{n}}} = \frac{\lambda_{\mathrm{g,0}}}{1 + \frac{p_{\frac{1}{2}}}{P_{\mathrm{g}}}}, \tag{4.2}$$

where:

$$K_{\mathrm{n}} = \frac{l_{\mathrm{mean}}}{\delta} \tag{4.3}$$

and

$$l_{\mathrm{mean}} = \frac{k_{\mathrm{B}}T}{\sqrt{2}\pi d_{\mathrm{g}}^{2} P_{\mathrm{g}}}, \tag{4.4}$$

where K_{n} is the Knudsen number. It is the ratio between the mean free path where l_{mean} is the average mean free path of molecules and δ is the pore size. P_{g} is the gas pressure, σ is the Stefan-Boltzmann constant, T stands for the temperature, d_{g} is for the gas molecule diameter. k_{B} is the Boltzmann constant. Energy transfer efficiency β is a constant between 1.5 and 2.0 and $\lambda_{\mathrm{g,0}}$ is the gases open space thermal conductivity (Baetens et al. 2011; Shufer 2015). $p_{1/2}$ is the pressure where gaseous thermal conductivity is half of the original value $\lambda_{\mathrm{g,0}}$ and for air is 230 mbar. For air, the energy transfer efficiency $\beta \approx 1.6$ and $\lambda_{\mathrm{g,0}} = 0.026$ W/(mK) at 300 K (Fricke et al. 2006).

The thermal conductivity of a porous material is effectively lowered by small pores and low density because they limit the heat transport methods. Pores limit the convection of through air in the material and low density reduces the conduction through solid pathways. The gas conduction can be further suppresses with the use of a vacuum, where even rough vacuums limit the gas conduction due to porosity (Koebel et al. 2012). Heat transfer by radiation is not a major factor with low temperatures, but dominates the thermal losses at high temperatures. In most TES applications high temperatures are used, which results in high radiative losses. To prevent this, porous material can be used to reduce heat loss via radiation (Beikircher et al. 2015). Radiative thermal conductivity λ_r is given in Eq. (4.5) and radiative temperature T_r in Eq. (4.6) (Beikircher and Demharter 2013).

$$\lambda_{\mathrm{r}} = \frac{16\sigma n^2 T_{\mathrm{r}}^3}{3\rho e^*(T_{\mathrm{r}})}, \tag{4.5}$$

where ρ is the density of the insulation material, σ is Stefan-Boltzmann constant. n is the refractive index and it can be approximated with $n = 1$. e^* is the total mass-specific extinction coefficient, which is the function of the radiative temperature T_r. The mass extinction coefficient e^* describes how radiative heat transport extinciton is wavelenght dependent in absorbtion and scattering (Beikircher et al. 2015). In Eq. (4.6) the temperatures T_1 and T_2 are temperatures at the boundaries of the insulation material and T_r is the mean value of these temperatures (Beikircher and Demharter 2013).

$$T_{\mathrm{r}} = \sqrt[3]{\frac{1}{4}(T_1^2 + T_2^2)(T_1 + T_2)} \tag{4.6}$$

Thermal losses affect the storage life of TES significantly. To maintain high temperatures and high energy efficiency, an appropriate insulation material that takes all the contributors of thermal conductivity into account should be used. Because of the T^3-nature of the radiative conductivity, an insulation material that prevents radiative loss is important.

4.1. PROPERTIES OF DIFFERENT INSULATION MATERIALS

Materials used for thermal industrial and building insulation are sometimes divided to traditional insulation and super insulation or state-of-the-art insulation. This study focuses on high temperature insulation materials. Traditional insulation materials have relatively low thermal conductivity and are low cost. Super insulation have better thermal conductivity, thus reducing the needed insulation thickness required for the same thermal insulation.

Traditional insulation includes such materials as mineral wool, Expanded polystyrene (EPS), Extruded polystyrene (XPS), polyurethane (PUR). For high temperatures mineral wool called stone wool is used. These materials are inexpensive and have relatively low thermal conductivity between 20 – 40 mW/(m·K) at ambient temperatures. They also may be cut and adjusted at the building site without loss of efficiency. A disadvantage of most traditional insulation material is that the moisture content can increase the thermal conductivity (Jelle 2011). The ability to adjust at the building site is important because, for high temperature applications, usually two or more layers are applied. These layers have metal linings to reduce radiation heat loss. For pipelines and storage tanks the insulation design and thickness may vary. Common insulation thickness for traditional insulation materials in high temperature applications is around 80 – 200 mm (Paroc 2014).

The state-of-the-art insulation materials have the lowest thermal conductivities available today. These materials can reduce the thickness of the insulation layer and thus save space, transport and construction costs. Their major drawback is the relatively high cost (Jelle 2011). In the following there is presented the super insulation materials and their properties. Later, potential future insulation materials are addressed.

Aerogel

Aerogel is a low density nanostructured solid that has a high porosity and a small mesopore diameter. Their porosity is over 90 % and mesopores diameters range from 4 to 20 nm. Because of its high porosity, the bulk density of aerogel can be 3 kg/m^3 (Baetens et al. 2011). Aerogels have low density and small pores which leads to a low conductive and convective gas transport, resulting in a low thermal conductivity of 12 – 20 mW/(m·K). Silica based aerogels are the most common and commercially available. Aerogel is produced by first creating a precursor in single or two step reaction. In a single step the gel structure is formed when colloidal particles and silica blocks aggregate simultaneously. In two step the colloidal particle solution is created through hydrolysis or acidification. The obtained solution is then supercritically dried. The formed aerogel is monolithic, but tends to break into granular or powdered form. Hybrid or composite aerogels are created and researched to improve cost-efficiency and mechanical or thermal properties. For insulation application a blanket type can be created, however due to mechanical restrictions, composite aerogel are used for these forms (Koebel et al. 2012).

Vacuum insulation panels (VIP)

Vacuum insulated panels (VIP) is made up from a porous core material that is enveloped by a vapour and air tight barrier. The barrier is then heat sealed. By making the cores structure open pore, air can evacuate and vacuum can be created. In pristine condition a VIPs thermal conductivity is around 4 mW/(m·K). However, due to aging and moisture and air diffusion this number increases over time. In VIPs the core material provides the main insulation and mechanical properties, while the envelope maintains the vacuum and keeps the air and moisture outside. The envelope is usually made of a metal or metalized multilayer polymer laminate. To obtain the best thermal conductivity several core materials have been tested, while fumed silica and aerogel can be found as a core material in commercialized products (Kalnaes and Jelle 2014).

Some studies have focused on core materials made from either low cost composites or green option hybrid materials. Diatomaceous earth and glass bubbles were tested for a low cost alternative core material to fumed silica, and Diatomaceous earth was found to be a potential option with only 26 % higher thermal conductivity when compared to fumed silica (Chang et al. 2016). One study tested different mixes of fumed silica, rice husk ash, black carbon, titanium oxide and chopped polyester strand in order to find a low cost hybrid core material. The resulted core material had thermal conductivity of around 5.5 mW/(m·K) and 32 % lower cost than fumed silica (Li et al. 2016).

Vacuum super insulation (VSI)

In a vacuum super insulation (VSI) heat storage, a tank comprising of two concentric steel cylinders is used. The annular gap is filled with perlite and evacuated to 0.01 mbar or lower. The lowered pressure suppresses gas conduction and the perlite reduces radiation heat transport resulting in a thermal conductivity of 9.2 mW/(m·K) (Beikircher et al. 2011).

Perlite is a porous powder that is made from volcanic material, obsidian. It is mainly composed of SiO_2 (65 – 75 %) and Al_2O_3 (10 – 15 %). The bulk density of expanded perlite varies from 30 kg/m^3 to 240 kg/m^3 and has a porosity value from the range of 0.75 to 0.97. The small pore diameter (10 – 200 µm) results in gas conduction suppression even at the vacuum level of 0.01 mbar. Perlite is also effective at reducing the effects of thermal radiation, while having a low price of 50 €/m^3 and being stable at temperatures up to 800°C. Because of these properties, perlite is suitable for VSI. In VSI applications perlite has the advantage of being low cost, but other materials such as silica aerogels and fumed silica can be considered for future research (Beikircher and Demharter 2013). Beikircher et al. (2015) calculated that the VSI could be used in high temperature applications, and has potential for a seasonal storage, because it can keep heat stored for long periods of time.

Glass ceramic foams are a porous insulation material while being soundproof. It can be applied as an insulation material. They have relatively low thermal conductivity, have low density and are incombustible, making them an interesting alternative as an insulation material. One study prepared from coal fly ash, waste glass along with fluxing and foaming agents, a glass ceramic foam that had thermal conductivity of 360 mW/(m·K) at 800 °C. It had a bulk density of 460 kg/m^3 and a compressive strength of more than 5 MPa, while being able to withstand temperatures of 800°C and possibly provides a green option for insulation materials, however use in high temperature applications is unlikely because materials with better thermal conductivity are available (Zhu et al. 2016). Ryzhenkov et al. (2016) researched the thermal efficiency of a honeycomb structure filled with vacuumized microspheres. Honeycomb structure is regular and is more durable than foamed plastics. Hexagonal cells are most durable and relatively easy to manufacture. Structure was calculated to be efficient and promising for future research.

Thermal insulation materials of the future focus on nanotechnology. Idea being to control the nano – sized pores of the material. Vacuum insulation materials (VIM) are homogenous materials in which, a closed pore structure maintains a vacuum. VIMs thermal conductivity is at its best condition lower than 4 mW/(m·K). These materials could be cut at the building site. The biggest challenge for VIMs is maintaining the vacuum and preventing the water and air diffusion through the material from affecting the thermal conductivity. Also, the material has to have a long lifetime and be able to maintain the vacuum throughout its life cycle. In a nano insulation material (NIM) the pore size is below 40 nm and the structure is either closed or open nano structure. This result in a thermal conductivity of less than 4 mW/(m·K). Unlike VIMs, the NIMs structure do no need to prevent moisture or air diffusion through itself in order to maintain its low thermal conductivity. However the development and production of these materials is currently a challenge. Also properties such as mechanical strength and load bearing need to be addressed (Jelle 2011). Overview of traditional insulation, super insulation, along with other interesting insulation options have been gathered into Table 4.1.

Table 4.1 Properties of some thermal insulation materials of today and futures potential options (Beikircher et al. 2015; Beikircher et al. 2013; Jelle 2011; Zhu et al 2016).

	Mineral wool (stone wool)	Expanded polystyrene	Aerogel	VIP	Glass ceramic foam	VSI	VIM	NIM
thermal conductivity $mW/(m \cdot K)$	30 – 40	30 – 40	13 – 14	3 – 4	360	8 – 20	< 4	< 4
Building site adaption / cutting	Yes	Yes	Yes	No	Yes / maybe	No	Yes	Yes
Load bearing capabilities	No	No	No	No	Yes / maybe	Yes / maybe	No / maybe	No / maybe

The traditional insulation materials have a higher thermal conductivity, but are less expensive and can be adapted at the construction site, which is significant advantage over VIPs. Super insulation materials have a low thermal conductivity, but are expensive to make. Possible future insulation materials could have lower thermal conductivity, be adaptable at construction sites and have relatively low price (Jelle 2011). Because the thermal conductivity changes depending on the temperature, not all insulation materials are suitable for high temperature applications. Some examples of the change of thermal conductivity at differend temperatures can be seen in Table 4.3.

4.2. COMPATIBILITY FOR HIGH TEMPERATURES AND FUTURE CONSIDERATIONS

Aerogels can be used at high temperatures, however because of their brittle structure, hybrid aerogels are seen as an alternative. To strengthen aerogels mechanical properties implementing components such as biopolymer, carbon and alumina have been tested. A study on carbon aerogels found that at 1500 °C the thermal conductivity of carbon aerogel in vacuum was 9 mW/(m·K) (Wiener et al. 2009). Using alumina a study was able to create aluminosilicate aerogel that was able to maintain its mesoporous morphology at 700 °C for extended period of time (Frances et al. 2014). Aerogels other weakness is its dust production (Baetens et al. 2011). To solve this and its mechanical properties issue, a study produced a biopolymer-silica hybrid aerogel. The hybrid had minimal dust production while the thermal conductivity was not significantly increased. The aerogel prepared also had high stiffness and compressive strength (Zhao et al. 2015). Aerogels main disadvantage currently is its high cost. High temperature silica aerogel, commercially called pyrogel, costs ~40 $/m^2 in blanket form and can be used for up to 650 °C (Aerogel Technologies, 2016).

While the VIPs can withstand high temperature, they have some disadvantages. If the VIPs vacuum is punctured or loss of vacuum happens otherwise the thermal conductivity can increase significantly. Because of this, the VIPs are not construction site adaptable. Also the moisture and air diffusion increases the thermal conductivity of the VIPs over time. The cost of a 6 centimeter thick VIP panel is 200 €/m^2 (Jelle 2011). The drawbacks of VIPs increase when dealing with a large TES. The thermal bridge effect occurring at the joints of the panels can cause higher thermal conductivities, making VIPs less cost effective (Fantucci et al. 2015). The vacuum degradation was researched in a study and found that the outgassing rate increased with the increase of temperature (Yang C.G. et al. 2012). Future research on VIPs needs to focus on reducing the price of VIPs while improving lifetime and ensuring the integrity of the vacuum. The possibility to adapt VIPs at construction site can help make it a widespread technology (Kalnaes and Jelle 2014).

The VSI allows the storage of high temperatures for long periods of time, making it a valid option when compared to other insulation methods or other ESS. Fuchs et al. (2012) showed that an important factor in long term storing was the surface to volume ratio of the tank. Smaller tanks need to be better insulated for long term storages due to their bigger surface to volume ratio. With big storages the insulation chosen can increase the surface area of the tank due to thick insulation layer. Table 4.2 presents the thickness required for insulation materials to have the same insulation effect.

Table 4.2 Theoretical calculation of required insulation thickness for different insulation materials at ambient temperatures (Beikircher et al. 2015; Beikircher et al. 2013; Jelle 2011; Zhu et al 2016).

	Mineral wool	Expanded polystyrene	Aerogel	VIP (Pristine)	VIP (Aged)	VSI	VIM	NIM
Thermal conductivity W/(m·K)	0.035	0.035	0.0135	0.0035	0.008	0.014	0.004	0.004
Thickness for U = 0.25 W/(m^2K)	14 cm	14 cm	5.4 cm	1.4 cm	3.2 cm	5.6 cm	1.6 cm	1.6 cm

Traditional insulation materials are relatively inexpensive, with mineral wool being 50 €/m^3 while fumed silica, one of the most common core materials for VIPs, costs 1000 – 1500 €/m^3. Mineral wool insulations disadvantage compared to high temperature VSI is that leakage can cause fire safety hazards when the hot HTF, such as molten salt, comes in contact with the mineral wool (Beikircher et al. 2015).

And while VIPs have almost 10 times higher performance in pristine condition, because of the costs and weaknesses listed before, VIPs are not always cost effective enough to be a viable option. VIMs and NIMs could potentially solve these challenges in the future.

The thermal conductivity of an insulation material depends on the temperature as well as pressure. In Table 4.3 are some thermal conductivities of insulation materials at varying temperatures. The effects of temperature can increase the required thickness of the insulation significantly due to thermal conductivitys dependance on the temperature. As a result the costs of materials and the needed surface area increase.

Table 4.3 Thermal conductivities of some insulation materials at different temperatures (Beikircher et al. 2015; He and Xie 2015; Vepsäläinen et al. 2012).

Temperature (K)	Mineral wool, blanket, metal reinforced mW/(m·K)	Extruded polystyrene mW/(m·K)	Silica aerogel mW/(m·K)	perlite mW/(m·K)	Evacuated perlite (0.05 mbar) mW/(m·K)
270	-	25	-	49	-
310	35	29	21	56	10
420	58	-	30	-	18
530	88	-	42	-	26
600	-	-	60	-	35

From these materials extruded polystyrene is usable only up to 350 K. Mineral wool blanket can be used for up to 815 K (Vepsäläinen et al. 2012). Mineral wools thermal conductivity increases significantly with the increase of temperature, requiring a thick insulation layer or layers when used in high temperature applications. Evacuated perlite has a thermal conductivity of 15 mW/(m·K) at 100 °C. It can be used at high temperatures and has a low cost, making it a promising area for future research.

5. APPLICATIONS

Thermal energy storages can be utilized in various ways depending on used temperatures and material. Temperature for TES applications vary from ultra-high (over 1410 °C) (Datas et al. 2016) to almost room temperatures of 25 °C (Li and Zheng 2016). A large scale TES applications is a CSP plant. For TES that use PCM materials, possible applications also include space systems, building cooling and heating systems, heat exchanger designs and domestic solar applications (Fleischer 2015).

5.1. PRESENT

Currently there are numerous operational solar power plants which utilize molten salt thermal storages, most of which are located in Spain, while some are situated in the United States and South Africa (DOE 2014). Mainly these thermal storages use sensible heat to store the energy, such as a two tank system. There are projects that aim to improve the design and properties of TES so that it can be better applied to renewable energy sources or as an electricity storage. Important points of interest are properties such as scalability of the storage and the use of different temperatures for different applications (Bergan and Greiner 2014).

5.2. FUTURE ASPECTS

Thermal energy storages could be integrated in many forms in the future to improve sustainability. TES could be used to store excess heat from different industrial processes and be used for district or water heating later. Integrating PCM TES into building material could help save in heating and cooling costs. Using TES for solar cooker systems could provide ways to decrease energy consumption in the domestic sector and for developing countries with a hot climate it can reduce the need for fuel-wood. Increasing the use of TES in power production cycles and cogeneration systems improves the efficiency of electricity production and can help make renewable energy sources a more viable option (Li and Zheng 2016). Applying TES for domestic solar applications, or as packed bed energy storages, can have significant benefits such as decreasing energy consumption and thus improving sustainability (Fleischer 2015). Another interesting use for TES that has been studied recently is integrating TES with a ground source heat pump (GSHP). GSHP integrated with TES and using various technologies such as solar collectors or PCM, can help reduce electricity costs and increase the usage of renewable energy. Challenges concerning this technology are different performances of the TES that use different energy storing method such as sensible heat or PCM. The thermal storage needs to be designed based on the location, system capacities and type of the intended application (Zhu et al. 2014).

Ultra-high temperature TES that uses silicon and a TPV converter has been proposed. This kind of TES could potentially have electrical energy density output in the range of 200 – 450 kWh/m^3. Silicon is low cost and abundant, so the TES would also be relatively cheap. And while using TPV converters the discharge efficiency is around 20 – 45 % (Datas et al. 2016). Another potential application for TES with silicon as the molten salt, could be microsatellites. These microsatellites would have high temperature latent heat TES that would be used in their solar thermal propulsion systems (Gilpin et al. 2014).

6. EXPERIMENTAL SET-UP

To study insulation properties of a vacuum insualtion and evacuated perlite insualtion a small scale TES has been constructed. The purpose was to examine the heat losses happening in the TES. A double vessel container has been obtained, in which a vacuum or a low pressure insulation layer could be created in the annular gap. Three type K thermocouples were installed into the container. One in the middle of the container, one in the inside lining of the container near the bottom and one on the outside lining of the container. Lastly a thermocouple was installed to measure the test room temperature. Pressure meters were placed on the container and its lid, so that the state of the vacuum could be monitored. For measuring the temperature a Fluke Hydra series II was used. Power consumption was measured with a NZR standby energy-monitor SEM 16+ - USB. Edwards E1M18 rotary vacuum pump was used to lower the pressure of the annular gap to 0.02 mbar for the experiments. The container was filled with 24.51 kg of solar salt that was mixed to a 50-50 wt % and heated 3 times using a 1.5 kW heating element, past its melting point and let cool down with a natural rate. The heating element was placed close to the middle of the container. The heating element was then replaced with a 2.0 kW heating element and more salt was added to compensate the decrease of the salts volume caused by the change from powder to solid during melting and cooling. Then the salt was melted and mixed for an even composition of salt. The total mass of the salt was 33.90 kg. The setup of the container and thermocouples can be seen in figure 6.1. The inner lining within the annular gap of the container was also enclosed with an aluminum sheet to reduce radiation heat loss.

Figure 6.1 Preparation of the container and thermocouples for the experiment.

The first experiment was conducted without filler material at the annular gap. The pressure was lowered to 0.02 mbar and heated with 10.50 kWh of energy. The Temperature was not allowed to exceed 330 °C and the heating was performed without the lid in place. This was done so that the heating element and its electrical components were not harmed by the high temperature. During the heating process the liquid salt was stirred several times. After the salt was completely liquid and at 330 °C, the lid was put in place and the salt was cooled down to room temperature at a natural rate.

The perlite used in the second experiment was coarse-grained and had an average bulk density of 88.75 kg/m^3 and the average particle size was 5 mm. Figure 6.2 shows a sample of the perlite used. Perlite was inserted into the annular gap after the first experiment and the pressure lowered to 0.02 mbar.

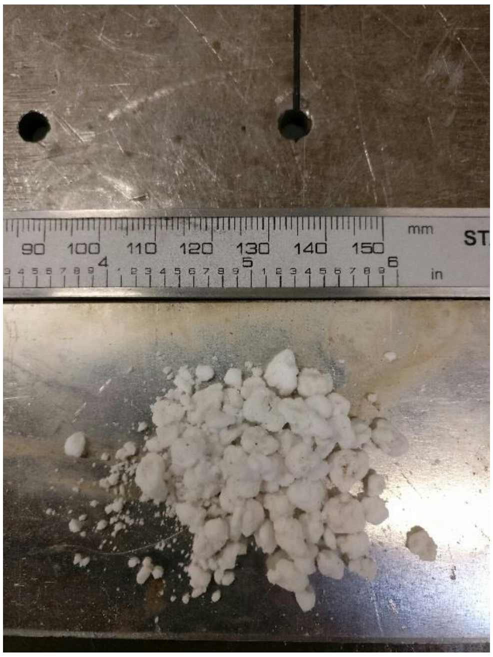

Figure 6.2 Sample of the expanded perlite used in the experiment.

The perlite experiment was heated with 10.50 kWh of energy and stirred several times during heating. The heating was done without the lid in place. When the salt was completely liquid and at 330 °C the lid was put in place and the salt was cooled down to room temperature at a natural rate.

7. RESULTS AND DISCUSSIONS

The temperatures during heating can be seen in figures 7.1 and 7.3. It can be seen that the salts temperature at the inside lining rose slower and that stirring caused it to peak. This was caused by the salt that was still solid at the bottom. The temperatures during the cooling phase can be seen in figures 7.2 and 7.4. At high temperatures the heat flux and heat loss is mainly radiative. Also the conductive and convective heat transfers are suppressed by the vacuum in the annular gap. The aluminum sheet that was placed inside the annular gap did not reduce the radiative heat loss effectively, because it was in direct contact with the inside lining of the annular cap.

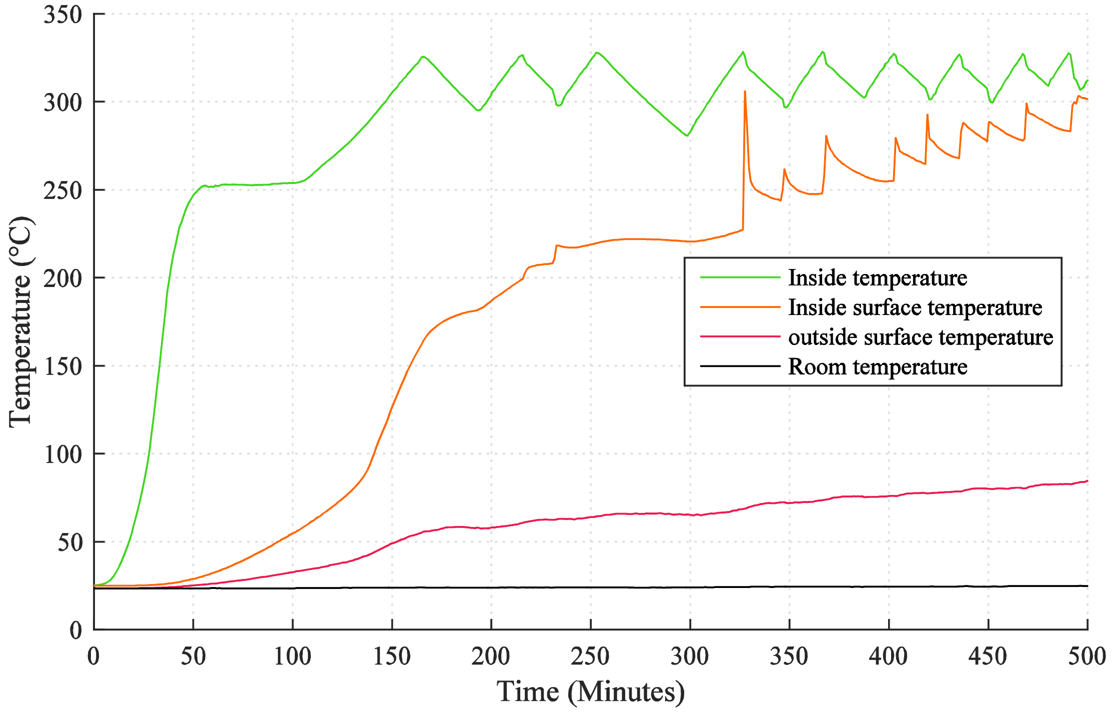

Figure 7.1 Heating curve with no filler material at the annular gap, air pressure at 0.02 mbar.

The radiative heat flux q was calculated for experiment 1 at 306.3 °C with the Eq. (7.1) (Vepsäläinen et al. 2012).

$$q_{12} = \frac{\sigma A_1 (T_1^4 + T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)}, \tag{7.1}$$

where A is the surface area, r is the radius of the cylinder and ε is the emissivity. The used emissivity for polished stainless steel is 0.15 (Vepsäläinen et al. 2012). The outer surface area of the inner lining A_1 is 0.4998 m^2. The radiuses r_1 and r_2 of the cylinders are 0.1365 m and 01465 m respectively. The surface temperature of the inner and outer linings were 306.3 °C and 85.7 °C. The radiative heat flux q_{12} was then calculated with Eq. (7.1) to be 306.42 W/m^2.

At high temperatures the radiative heat flux was high and resulted in fast temperature drop. At lower temperatures where T_1 = 80 °C and T_2 = 37.6 °C the radiative heat flux q_{12} was then calculated with Eq. (7.1) to be 14.76 W/m^2.

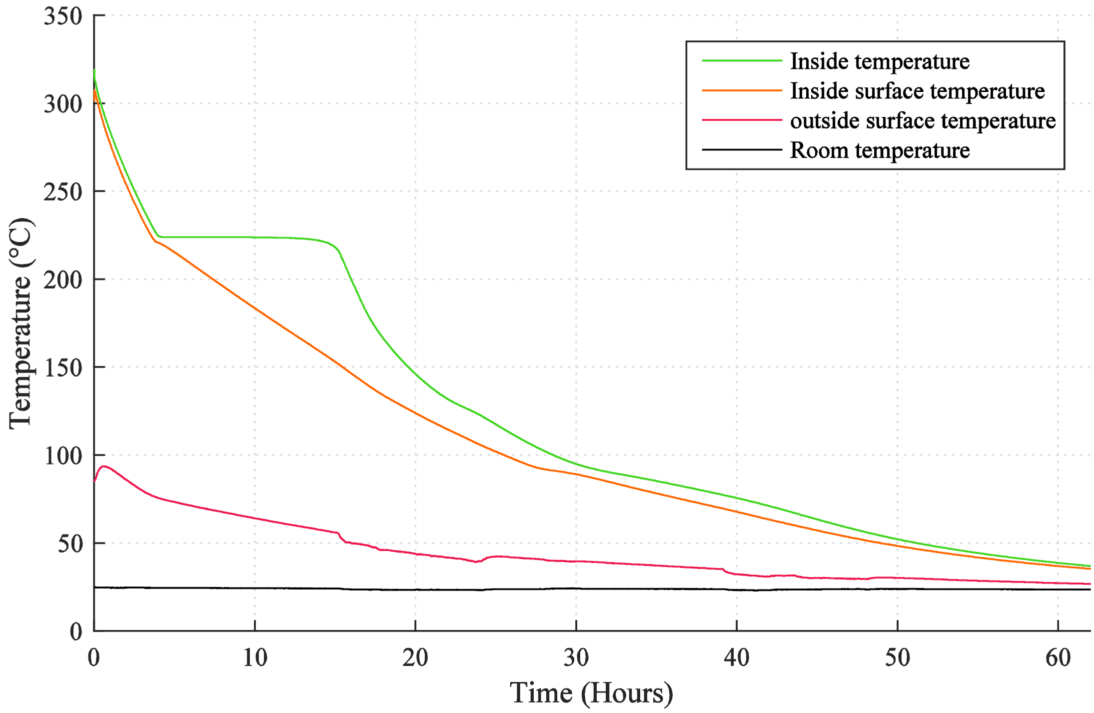

Figure 7.2 Cooling curve with no filler material at the annular gap, air pressure at 0.02 mbar.

In the figure 7.2 the temperature dependance of the radiative heat flux can be observed. At higher temperature the radiative heat flux is greater so the temperature decreses faster than at lower temperatures where the radiative heat flux is smaller.

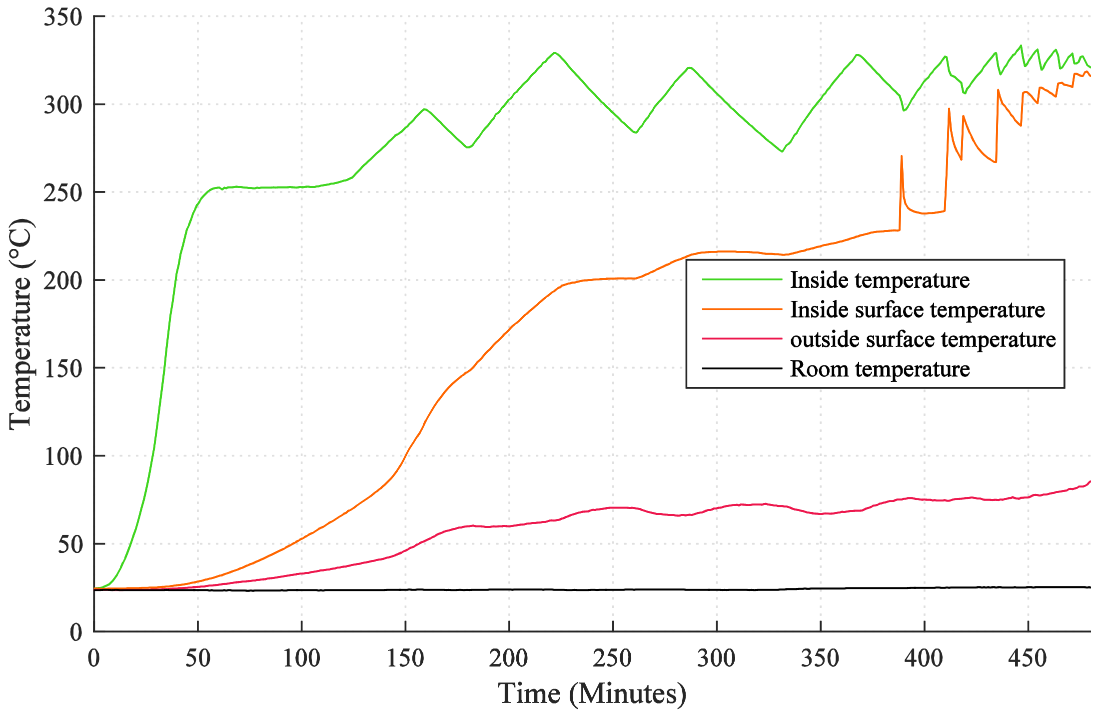

Figure 7.3 Heating curve with perlite as the filler material at the annular gap, pressure at 0.02 mbar.

For the second experiment where the annular gap was filled with perlite, the radiative thermal conductivity at 318 °C was calculated using Eq. (4.5) and Eq. (4.6). The used mass-specific extinction coefficient e^* was 38 m^2/kg (Beikircher and Demharter 2013). The inner and outer lining temperatures T_1 and T_2 were 318 °C and 82.9 °C respectively. Eq (4.6) gives the mean temperature value 482.99 K. The average density of the perlite used was 88.75 kg/m^3. The radiative thermal conductivity was calculated with Eq. (4.5) to be 10.10 mW/(mK) at the start of the cooling phase. This leads to high radiative heat loss. When the inner and outer lining temperatures T_1 and T_2 were at 80 °C and 35.3 °C the calculated mean temperature was 331.15 K. With the Eq. (4.5) this gave the radiative thermal conductivity of 3.64 mW/(mK). This change can be seen in figure 7.4 where the heat losses are reduced as the temperature lowers, which is because the radiative losses do not dominate the heat loss at low temperatures. This slows the cooling process.

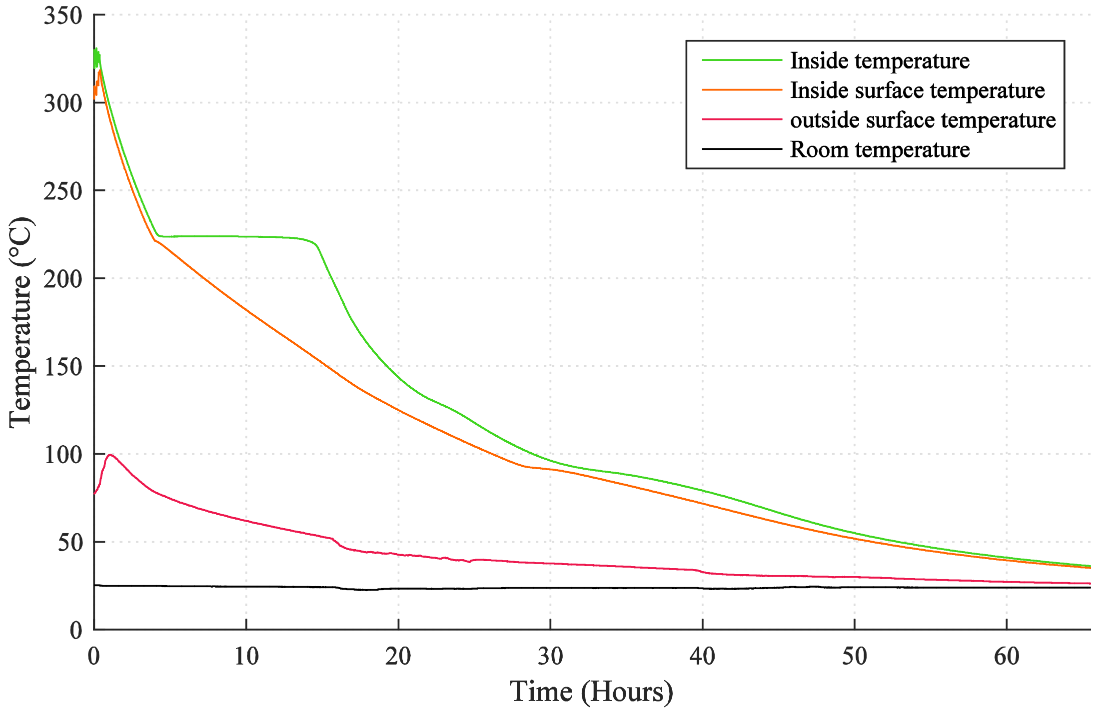

Figure 7.4 Cooling curve with perlite as the filler material at the annular gap, pressure at 0.02 mbar.

With the perlite as filler material in the annular gap, the cooling process was slower. The perlite reduces the radiation loss slightly while rising the surface temperature of the container. The measurements aling with the theory and the hypothesis that the heat losses would be high at high temperatures and be reduced as the radiative heat losses become less dominant at lower temperatures. The vacuum measurement had mainly radiative heat loss. This insulation solution could possibly be improved by using a material in the annular gap that reflects the radiation back into the storage, such as an aluminum sheets. The perlite reduced the radiative heat loss, but had more convective and conductive heat loss than the vacuum experiment. The perlites insulation properties could be improved by maintaining the vacuum level and removing any possible moisture from the perlite. The bulk density of the perlite affects the solid and radiative thermal conductivity and optimizing the density, a better insulation for the thermal storage can be achieved (Beikircher and Demharter 2013). The thickness of the annular gap and its effects on the thermal conductivity of evacuated perlite insulation is a potential research subject.

8. CONCLUSIONS

The aim of this study was to inspect different energy storage systems. Thermal energy storages was focused on and its operating models and properties was reseached. The required insulation for its high temperatures was studied. Based on this information a small scale thermal energy storage with solar salt as the phase change storage material was constructed so that its insulation properties could be observed. One experiment was conducted with the annular gaps pressure lowered to 0.02 mbar and in the second experiment the annular gap was filled with expanded perlite and the pressure lowered to 0.02 mbar. During the experiments the solar salt was heated to around 320 °C and then cooled down to room temperature at a natural rate.

The heat flux at 306.3 °C at the first experiment was 306.42 W/m^2. At 80 °C the heat flux in the first experiment was 14.76 W/m^2. The second experiment with expanded perlite in the annular gap at 318 °C had the radiative thermal conductivity of 0.01010 W/(mK). At 80 °C the radiative thermal conductivity in the second experiment was 0.00344 W/(mK). The results from the experiments show that the heat transfer at high temperatures is mainly radiative which can be explained due to its T^4 correlation. But in the experiment with the evacuated perlite, heat loss through conduction also occurred.

Pressure levels might have been inaccurate and leakage occur, because of the inaccuracy of the pressure meters. Perlite quality could have been a finer grade with smaller pore size and lower bulk density to minimize the solid thermal conductivity. It could also reduce the high surface temperature of the container, which needs to be lowered if practical use is considered. In the vacuum experiment the surface temperature rose up to 93 °C and in the evacuated perlite experiment the surface temperature rose to 99 °C which are too high for most applications and could be a hazard. This temperature could possibly be lowered by increasing the thickness of the annular gap, while effecting the thermal conductivity and would be a possible subject for further research. For future experiments the heating elements position could be repositioned to the bottom of the container for better distribution of the heat and to prevent the heating element from breaking. Overall, the experiment shows promise and possibility of practical applications. However further research is required.

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