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Research Paper

Heat Transfer Aspects of Using Phase Change Material in Thermal Energy Storage Applications

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I. INTRODUCTION

Indoor thermal comfort represents one of the most important living quality standards in modern lifestyle. The overall energy spent in indoor climate control, such as heating and cooling, may reach as high as 37% of the total energy use in building in the USA (US Department of Energy, 2009). In Sweden, 45% of the total residential and service sector energy use goes to indoor comfort cooling and heating (Swedish Energy Agency, 2009). Contrary to what is commonly believed, countries in the cold climatic regions, for instance the Scandinavian States, require remarkably high cooling demand. The distributed district cooling showed an average 12% annual increase from 1999 to 2009 (Swedish District Heating Association, 2009). The cooling is essentially required for temperature control and indoor dehumidification need. In 2009, district cooling and heating supply in Sweden reached 811GWh for cooling and 55TWh for heating, among which 90% was used in residential/service sector and 10% in industrial sector. In the residential/service sector, electricity use for heating makes an additional energy use of 21.2TWh (Swedish Energy Agency, 2009). Thermal Energy Storage (TES) allows storage of heat and cold for use at shifted time, for instance, solar heating may be stored during the day for later use at night; and night time cold may be stored for use during day cooling. As a result, the size of heating and cooling equipment can be cut down and overall electricity and thermal energy requirement during peak periods is reduced. Many Cold Thermal Energy Storage (CTES) systems have gained attention in recent years. Applications such as storage of cold energy during off peak hours for later use and charge of free cooling when sustainable cold energy source is available would alleviate high cooling load demand and cut down the peak thermal energy production cost. Marginal energy consumption is reduced, fossil fuels are conserved and greenhouse gas (GHG) emissions are cut down (Dincer,2002).

II. REVIEW OF THERMAL ENERGY STORAGE MATERIALS

Latent heat thermal storage is one of the most promising technologies in terms of energy conservation, grid load alleviation, and energy security maintaining in a built environment. However, due to the low thermal conductive property of PCMs, thermal energy storage/extraction rates are low and need to be ameliorated through advanced system design with optimized storage layout. It is of primary importance to pursue material development so as to obtain novel PCMs with desired material properties that can provide sufficient thermal storage/extraction power, high ice packing factor (IPF, ratio of PCM volume to total tank volume), and stable charge capacity. This section gives an overview on the currently available TESs and special emphasis will be placed on the extensive literature review presented in Paper I.

2.1 CATEGORIZATION

TES systems are divided into two main categories: active and passive systems. Active TES systems are comprised of control mechanisms for charging and discharging of the storage. Passive TES systems, on the other hand, do not have any mechanical components. Examples of active storage system are ice scraping storage and TES implemented air-conditioned systems; while passive storage systems can be PCM impregnated plasterboards in building envelops and TES used for insulation purpose. Energy storage process can further be sub-categorized into physical storage, via sensible heat and latent heat, and chemical storage through ex-Othermic and endothermic reactions. An overview of the three types of storage process with their applications is shown in Figure 2-1. Sensible heat storage is attractive in a large number of applications such as underground energy storage: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and cavern thermal energy storage (CTES), where space uptake is not limited and where the resource is already made available. Sensible heat storage normally has the advantage of requiring smaller heat exchange surface area between the storage and the heat transfer fluid due to better heat exchanger surface contact. In some applications, the energy storage medium is also the heat trans-fer fluid, such as hot water storage in households.

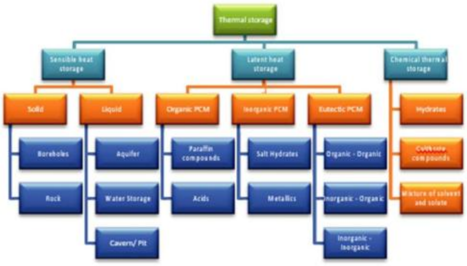
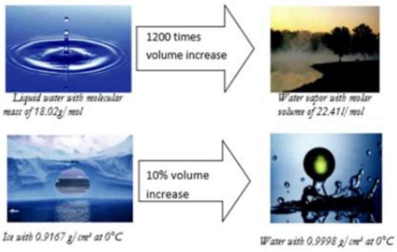


Figure 2-1 Categorization of Thermal Energy Storage (adapted from CompEdu Chiu, et al., 2011)

PCMs utilize the latent heat resulted from phase change to store and re-lease thermal energy. Advantages of using latent heat are narrow temperature fluctuation during charge and discharge of cold/heat, high storage density as compared to sensible heat storage and temperature flexibility for application. The latent heat is obtained through change of state from solid to solid, solid to liquid, liquid to vapor, or solid to vapor. The most commonly utilized PCMs are solid to liquid phase change due to their smaller volume change as compared to that of liquid/solid to vapor, c.f. Figure 2-2 for ice/water/steam density change, and the energy storage density is typically greater than that of solid-to-solid trans-formation. In active LHTES system, where thermal energy has to be extracted and stored at certain required thermal extraction/storage rage to meet the end user demand, it has become a major concern to design TES system with adequate energy storage material so as to meet the thermal energy extraction/storage requirement. PCMs are classified into two main categories: organic materials and inorganic materials. Eutectics are sometimes considered as a third category; they are mixtures of organic and/or inorganic materials that have a fixed phase change temperature. Common organic materials are paraffins and acids, while inorganic materials are salt hydrates and metallics. A non-exhaustive list of the most studied salt hydrates are sodium sulfate decahydrate, calcium chloride hexahydrate, sodium thiosulfate pentahydrate, sodium carbonate decahydrate, disodium phosphate dodecahydrate, and their derivatives.



Liquid water with molecular mass of 18.02g/mol

Water vapor with molar volume of 22.41l/mol

Ice with 0.9167 g/cm³ at 0°C

Water with 0.9998 g/cm³ at 0°C

Figure 2-2 Water volume increase at phase change (pictures taken from various sources)

2.2 PCM ADVANTAGES AND LIMITATIONS

While PCMs show many advantages, a number of issues are yet to be overcome. Table 2-1 summarizes pros and cons of the common PCMs. First, non-eutectic latent heat storage materials often do not have a fixed phase change temperature, their melting and freezing temperatures lie over certain temperature range. Second, the melting and the freezing temperature often differ from each other; this is known as the hysteresis of the material and cause a temperature swing in charging and discharging of thermal energy. Third, subcooling is largely present in inorganic salt hydrates and it lowers the nucleation temperature to a level much lower than the solidification temperature. Fourth, flammability of organic material and corrosive nature of inorganic salts often put extra constraints and limitations on the containment of the storage. The fifth concern is the low thermal conductivity rate of PCMs; in active systems, this presents especially a bottleneck in storing and in extracting thermal energy at the required rate. The above listed drawbacks mark the challenge in using PCMs in indoor thermal comfort control systems where the acceptable temperature swing is small. Comparing organic and inorganic materials in terms of applicability, in-organic materials are non-flammable and have higher volumetric energy storage density; on the other hand, organic materials undergo low level of phase separation and some are not affected by subcooling. Organic materials have low thermal conductivity in the order of 0.2W/m-K, whereas inorganic materials have double to triple the thermal conductivity reaching to that of water in the range of 0.4 to 0.6W/m-K. Nonetheless, the thermal transfer of non-gelled organic PCMs may be assisted by convection in the melt state. In summary, the choice of PCMs for use in energy storage depends on the specific application requirements as well as the constraints in the energy system.

Table 2-1 Advantages and Disadvantages of Organics, Inorganics and Eutectics.

	Organic	Inorganic	Eutectic
Pros	Low Cost (120Euro/kWh) (Ribberink, 2009) Self-nucleating Chemically inert and stable. No phase segregation Recyclable Available in large temperature range	Moderate cost (130 Euro/kWh) (Julin,2008) (Ure, 2008) High volumetric storage density (180-300 MJ/m³) Higher thermal conductivity (0.6W/m-K) Non flammable Low volume change	Sharp melting point High volumetric storage density
Cons	Flammable Low thermal conductivity (0.2W/m-K) Low volumetric storage density (90-200 MJ/m³)	Subcooling Phase segregation Corrosion of containment material	Limited availability

Achieving energy efficient energy systems has prompted researchers and engineers to look into the possibility of utilizing PCMs in TES. IEA implemented Annex 17: “Advanced thermal energy storage through phase change materials and chemical reactions” (Hauer, et al., 2005) investigated in commercialized products and novel chemicals that may be utilized in latent heat-based TES. PCMs from five PCM suppliers in the temperature range of -40°C to 100°C are shown in Figure 2-3 and lab grade products are provided in Figure 2-4. As a general remark, water has the highest level of latent heat storage density as compared to commercial and lab grade PCMs, however water is characterized with a phase change temperature located around 0°C which can be unsuitable for certain applications. Despite the large diversity of PCMs, the number of chemical materials suitable for TES in indoor climate control and thermal comfort use is still limited. The commercialized products presented here can be grouped into three distinct temperature categories: below 0°C, 0°C to 40°C, and above 40°C. It can be seen from the categorizations in Figure 2-3 that the commercialized products are based on the same chemicals blended with additives to reach new phase change temperatures; this in consequence lowers the storage capacity. For high thermal power and capacity demanding storage applications, there is thus an imminent urgency to develop and search for novel materials that exhibit suitable storage properties.

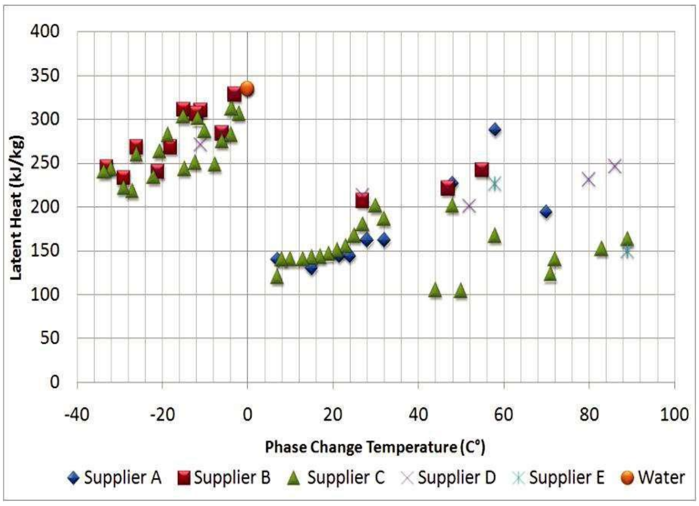


Figure 2-3 Commercialized PC

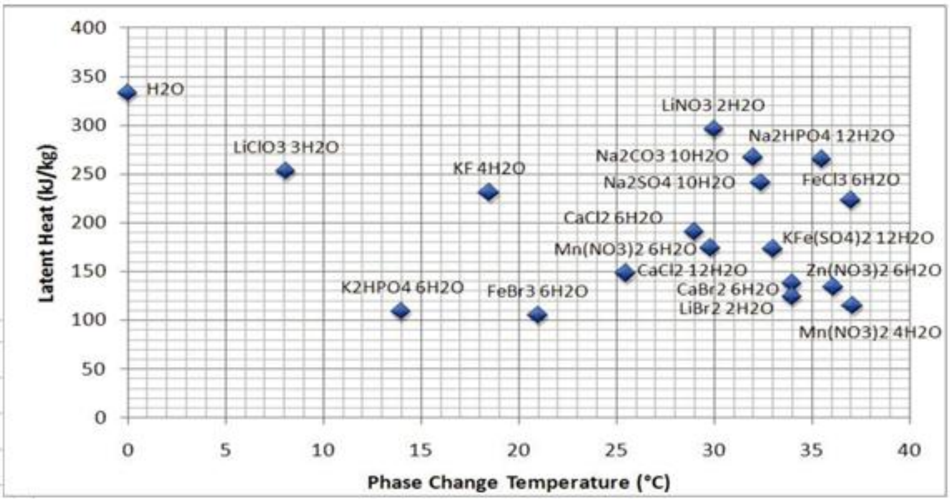


Figure 2-4 Lab grade PCMs

2.3 RESEARCH DIRECTION

While inorganic materials, especially salt hydrates, are highly rated for their high energy density and the non-flammable properties for integration to the built environment, the phase separation and the subcooling constitute major obstacles to their implementation. To overcome these issues, addition of gelling agents to the salt hydrate mixture has been practiced to immobilize PCM so as to reduce the phase segregation. However, gelling also inhibits the flow of melted salt hydrate; this limit thus the convective heat transfer mechanism and brings down the heat exchange rate. Research has been widely carried out to obtain novel additives and original gelling agents to ensure high material stability over repeating charge/discharge cycles while maintaining high heat capacity and high heat transfer rate. Salt hydrates suffer especially phase separation in repeating charge/discharge cycles. A few of the common gelling agents utilized are bentonite, cellulose, and other substances as listed in Table 2-2 (left). Subcooling is a result of phase change temperature shift where solidification occurs below its melting temperature. The subcooling can be limited through introduction of nucleating agents that facilitate crystal formations. Nucleating agents are particles scattered in the PCM for the purpose of forming artificial nucleating sites. A large number of nucleating agents have been reported to have shown positive effect on subcooling reduction, notably borax (sodium borate, sodium tetraborate, or dis-odium tetraborate), powder (aluminium, carbon, copper), and other inert substances, see Table 2-2 (right). Despite the high potential of LHTES in achieving improved overall system efficiency, only a relatively small number of results have been re-ported on successful system studies with high capacity and high power rated storage units. The research axes in terms of PCM development in the near future will be on a large extent on the lookout for more suitable material properties, namely higher thermal conductivity, improved storage density, and lower material cost. In the scope of this thesis, all feasibility studies will be based on the currently available PCMs. The goals in this thesis are quantification of the interdependency among storage capacity, thermal transfer rate, storage component design, proactive control strategies, case studies with implementation of LHTES, and potential of TES as climate change mitigation solution.

Table 2-2 Gelling, and Nucleating Agents, adapted from (Shin, et al., 1989) (Wang, et al., 2008)

Gelling Agents	Nucleating Agents
Alginate	Aluminum
Bentonite	Borax
Cellulose	Carbon
Diatomaceous earth	TiO2
Polymer	Copper
Polymeric poly-carboxylic acid	Na2SO4
Silica gel	SrSO4

Starch	K2SO4
Thixotropic (attapulgite clay)	Na2P 2O7
	SrCl2
	BaI2
	BaCl2
	Ba(OH)2
	BaCO3
	CaC2O4
	Sr(OH)2
	SrCO3
	CaO
	MgSO4
	Acrylamide/acrylic acid copolymer (AACP)
	Sodium hexametaphosphate (SHMP, (NaPO3)6)

III. POWER & CAPACITY

The majority of the commercial PCMs have relatively low thermal conductivity; typical value ranges in between 0.2W/mK and 0.7W/mK (Hauer, et al., 2005). This characteristic marks the low thermal performance of TES and creates possible nonmatching between thermal power supply and demand. Heat transfer enhancement techniques that provide sufficient thermal power are thus vital to ensure proper operation of LHTES in the system. The enhancement techniques are of many kinds, typical solutions are surface extension of heat exchanger and PCM thermal property amelioration. Examples of heat transfer surface increase are addition of Lessing rings, fixation of fins on tube type heat exchanger, impregnation of PCM in high conductive graphite matrices. As to material property enhancement, examples are blending with highly conductive powders, notably graphite and aluminium powder. Finned type heat exchangers with latent heat thermal storage have gained particular interest among the storage engineering community as the fabrication cost is relatively low and the level of engineering techniques is mature. However, there is a lack of standardization in TES performance assessment. Power, capacity and available energy source are the three main storage aspects and are interconnected in the design of a storage system. As a matter of fact, the TES performance is judged upon the capability of fulfilling the energy demand. In the prospect of this study, a numerical model was built to study the interdependencies of the above-mentioned storage design parameters. Furthermore, an experimental test rig was later constructed for model validation. This validated model allowed representative parametric study of the LHTES and made this specific numerical model a design tool for PCM based LHTES. The results presented in this chapter are based on papers IV and V.

3.1 MODEL DESCRIPTION

A heat transfer model for studying TES unit was created under Mat lab. The model is a two-dimensional fixed grid finite difference enthalpy-based heat transfer simulation. Salt hydrate was chosen as the storage material for it exhibits high energy density per storage volume and has non-flammable property. For the considered gelled salt hydrate based PCM, conduction was the main heat transfer mechanism and was implemented to the numerical model. The solving of numerical model is based on the enthalpy method. The use of enthalpy temperature (hT) in phase change modelling was first developed by Date (Date, 1992), where material thermal property varies as a function of material temperature. In Date's model, the latent enthalpy arises at a fixed temperature. A more generalized linear hT over the phase change range was later implemented in LHTES simulations and showed better concordance for PCMs having phase change temperature range

(Velraj, et al., 1997). In this work, Heaviside function and its derivative were adopted in formulating heat capacity to temperature relation (Comsol Multiphysics, 2008); this allows the specific heat to be weighted over the considered phase change temperature with the maximal specific heat peaking at phase change temperature. The specific heat is formulated in 31. with D (T) approximate derivative of the Heaviside function,

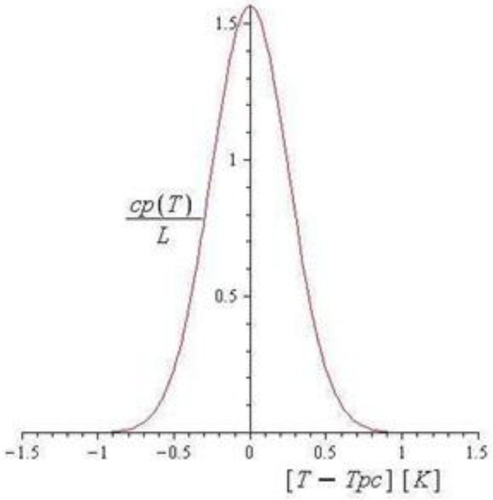


Figure 31 Representation of cp(T)/L

One representation of the Dirac approximation, equation 32 is shown in Figure 31. In this example, the area below the curve, cp T. counts for 95% of the total latent heat over a temperature range of Tpc±0.5°C. This mathematical formulation allows definition of the phase change temperature range, choice on the peak phase change temperature and in consequence determination of the enthalpy over a temperature range. The finite difference method was utilized in modelling the thermal performance of a finned tube submerged heat exchanger TES unit. The general formulations of energy equations are shown below in 2D Cartesian coordinates and in radial symmetric 2D cylindrical coordinates, with α the thermal diffusivity, two scenarios have been proposed to identify the energy storage performance. The first scenario is set for a charging duration of 10 hours, while the second is granted for unlimited charging time. The model simulates charging of cold to a PCM based TES from 2°C above melting point to 2°C below. The driving temperature between the heat transfer medium and the PCM is taken as 9°C at the start of the charging. Other conditions considered in this simulation are listed as follows: Fin thickness of 2mm Constant tube and fin temperature Equal fin and tube spacing Isotropic material properties Salt hydrate PCM with phase change at 13°C (PCM Products, 2007) A graphical representation of the heat exchanger is shown in Figure 32. The objective of the study is to demonstrate the interdependency between the thermal extraction/storage power and the storable capacity as a function of available thermal source input. As the low thermal conductivity of PCM has long shown to be the limiting factor in a LHTES, means have been adapted to increase the heat transfer rate of TES systems. The improvement in thermal storage/extraction rate may, however, under certain circumstances cause drop in system performance, such as decrease in overall thermal energy storage capacity due to decrease in IPF of the storage material. On the other hand, a non-justified pursuit for high storage density will compromise the thermal power of the system. Furthermore, in a system where thermal source is limited to time and availability, full utilization of the storage capacity may not be achieved. There is hence a preponderant interconnection among thermal power, capacity and available resource.

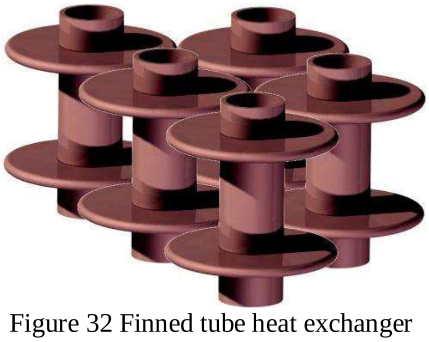
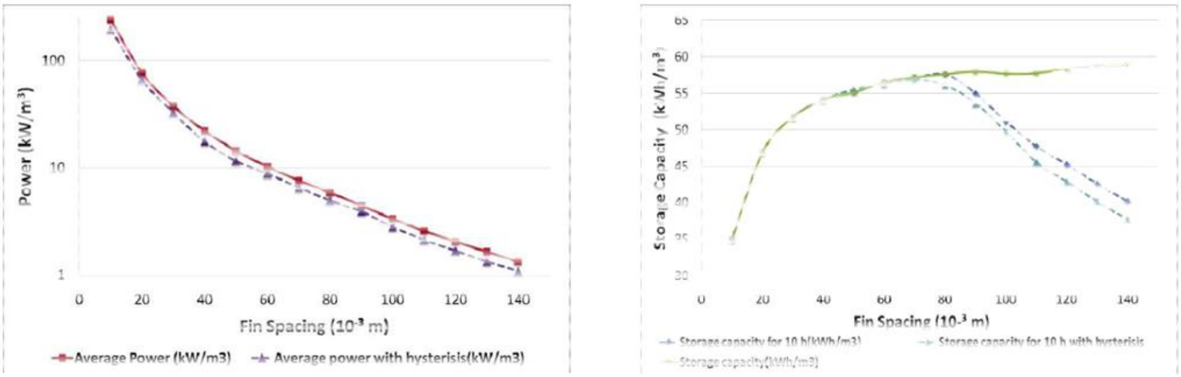


Figure 32 Finned tube heat exchanger

3.2 RESULTS ON POWER AND CAPACITY

Here, thermal power and energy storage capacity are studied for a variety of fin and tube spacing. Effect of the subcooling and influence of enhancement through insertion of Lessing rings and graphite powder are also investigated. Figure 33 shows the charging power and storage capacity per unit volume of TES for fins spaced from 10 mm to 140 mm apart. The effect of hysteresis on thermal power storing rate has also been studied. The results show that under the studied conditions, hysteresis of 1K brings down the thermal extraction rate by 16%, Figure 33 a. The reasons for the drastic drop-in thermal power rate are the smaller driving temperature difference from heat transfer fluid to heat store due to hysteresis effect on freezing temperature; on top of that, under real circumstances, subcooling further accentuates the drop in driving temperature difference. It is concluded that the non-uniformity in phase change temperature, e.g., hysteresis or subcooling, is one of the most undesirable properties with regards to salt hydrate LHTES. In the perspective of short-term storage for daily storage/extraction, charge and discharge time are limited by the availability of heat source and heat sink. A specific study of available charge time limited to 10 hours is hence imposed. Figure 33 b shows the theoretical available storage capacity in solid lines, and the dashed lines represent energy that is charged under 10 hours period for both with and without hysteresis. It is observed that the storage capacity may not be fully charged for a given 10hour charge period for fins and tubes spaced farther than 80mm apart in this specific application. While with 1°C hysteresis, the total charged capacity is further decreased by 5%. This demonstrates the interdependency between resource availability, power and capacity, as well as the adverse effects of hysteresis on overall TES performance.



(a) (b)

Figure 33 a.) Charging Power and b.) Storage Capacity for Various Fin Spacing with 1°C Hysteresis (dotted-line)/ without Hysteresis (solid line). The power and capacity study for enhanced PCMs, e.g., blending with graphite and insertion of Lessing rings, are compared with non-enhanced storage in Figure 34.

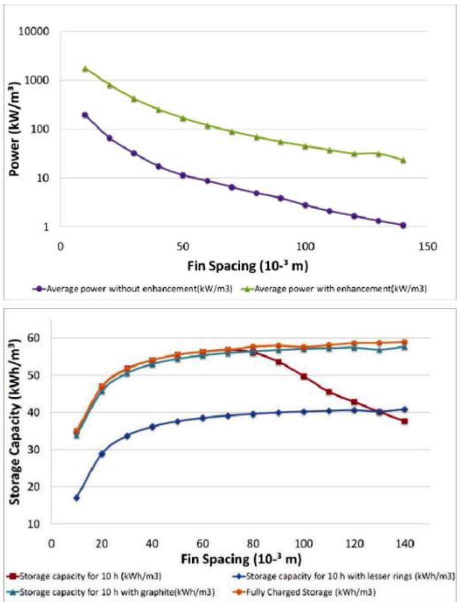


Figure 34 Finned Tube Thermal with/without enhancement a.) Power Rate and b.) Storage Capacity

In the case of enhanced PCM, blends with 3% volume graphite powder and 30% volume Lessing rings are considered. The equivalent power increase is shown to be 20 folds, Figure 34 a, similar results were obtained by Medrano (Medrano, 2009). The results show a drop in overall storage capacity, as seen in Figure 34 b. The drop in storage capacity is due to volume uptake of the thermal enhancing material. Nevertheless, as enhancement ensures higher thermal transfer rate, the total storage capacity at fins and tubes placed further than 80mm apart may be still fully utilized in spite of the limited 10hour available resource time. Here, a clear trade-off is seen between power extraction rate and the achievable storage capacity.

3.3 CONCLUDING REMARKS ON INTERDEPENDENCY OF POWER AND CAPACITY

The theoretical study shows the close interdependency of the thermal energy extraction/storage rate and the utilized storage capacity for a given resource availability. For a fixed available energy charge/discharge duration, e.g., free night time cooling and daytime solar heating, the thermal power rate determines the amount of storage capacity that can be replenished. During charge/discharge period, the required thermal power extraction rate constitutes the limiting factor for the TES system. An insufficient heat transfer system will lead to incomplete utilization of the total available storage capacity. However, an excessively high thermal power rated system requires higher volume uptake of the heat exchanger and/or more generally of the thermal enhancing agents. This reduces the IPF of the TES and cuts down the storage volumetric energy density. From this, it is concluded that the optimal balance between design of power and capacity is case specific and application dependent. A holistic understanding of the energy system requirement as well as meticulous design of the TES performance is essential in obtaining a functional and adapted solution in energy alleviation through load shifting and peak shaving. Numerical models comprise assumptions that are very often case specific. Verification of input data as well as output results through experimentation is crucial in terms of reaching for in-depth understanding of the actual phase change phenomena in charging and discharging processes. The following chapter is devoted to the characterization of PCM thermal properties, which was shown with parametric study as one of the most crucial factors in design of a LHTES.

IV. TES AS CLIMATE CHANGE MITIGATION SOLUTION

TES is shown to have positive contributions in terms of peak load alleviation and on peak load shift so as to increase the overall system efficiency. In this section, we will identify the potential in using TES for greenhouse gas (GHG) emission reduction in the Swedish energy system through reduction of fossil fuel based marginal electricity and thermal energy production. This study is composed of an overview of Swedish energy use, a presentation on the methods considered for GHG reduction, and results on the potential GHG emission reduction. This section is based on paper VI.

4.1 OVERVIEW OF SWEDISH ENERGY USE

Sweden is among the world leading countries with the highest share of renewable energy use reaching 45% of total energy use (Swedish Energy Agency, 2009). In indoor thermal comfort, however, heating and cooling amount to more than 45% of the total energy use in Swedish residential and service sector (Swedish Energy Agency, 2009). This section exploits the possibility of further reduce the non-renewable share in the energy system through use of TES for indoor climate control. Figure 81 shows the monthly conventional thermal power production and wind generated electricity over the last decade. Due to increase in electricity demand in winter time, we observe a double to triple of the conventional thermal power production rate, i.e., 700GWh of electricity was produced in July 2009 against 2500GWh in Feb 2010. Wind energy, as a renewable energy source, on the other hand, does not contribute to any marginal electricity production as the availability is limited. The marginal electricity production often rhymes with lower energy efficiency and lower level of flue gas treatment. Out of the 146TWh annual electricity production, 4.3TWh comes from fossil fuel-based electricity generation. It is thus of primary importance to find means to reduce the fossil fuel dependency which will lead to decrease in CO2 emission.

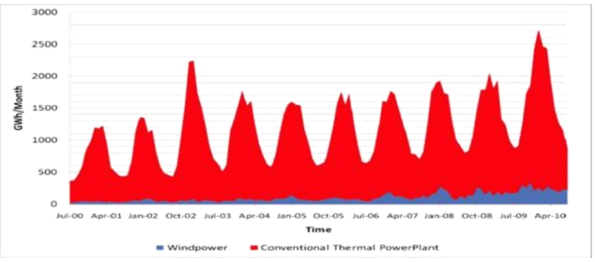


Figure 81 Monthly Electricity Production (from wind and thermal power plant) in Sweden in the Last Decade, adapted from ENTSOE (European Network of Transmission System Operators for Electricity, 2011)

The indoor thermal comfort control in Sweden is divided into district based and individual heating. Figure 82 shows the share of different sources-based contribution to the district heating in Sweden. Fossil fuel heating amounts to 17.5% and electricity based thermal production reaches 12%. A substantial amount of fossil fuel may be avoided if it is possible to shift fossil fuel based marginal load to off peak period with use of renewable energy sources.

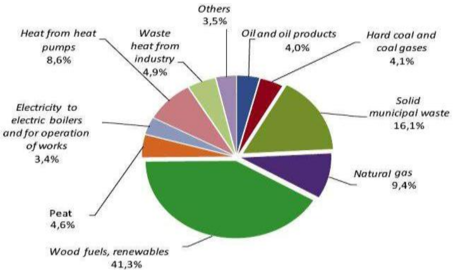


Figure 82 Supplied Energy to District Heating in 2009(Swedish Energy Agency, 2010)

4.2 METHOD FOR GHG REDUCTION

GHG emission reduction can be achieved through several means. One of the most direct methods is to shift fossil fuel produced marginal peak energy to off-peak period with TES. The avoided marginal energy production will be replaced by off-peak non-polluting means of electricity and thermal energy production and leads thus to substantial amount of GHG emission reduction. Figure 83 shows the schematic of the energy system in the study. The heating means considered in the study are oil burner, heat pump and electric heater-based systems. The marginal energy sources are fossil fuel. The TES units placed between energy suppliers and end users provide marginal peak thermal load to users. Fossil fuel use is decreased and the GHG emission is reduced. The economy of the TES is considered on the overall system level, this means that the initial capital cost for the installation and the return on investment is shared among energy suppliers and the end users. The payback on TES is done through cost saving on fossil fuel, on CO2 tax and on plant operation. In the current energy structure, only utility companies receive direct cost benefits with TES system installations and not the end users; adequate policies are yet to be set up to promote this.

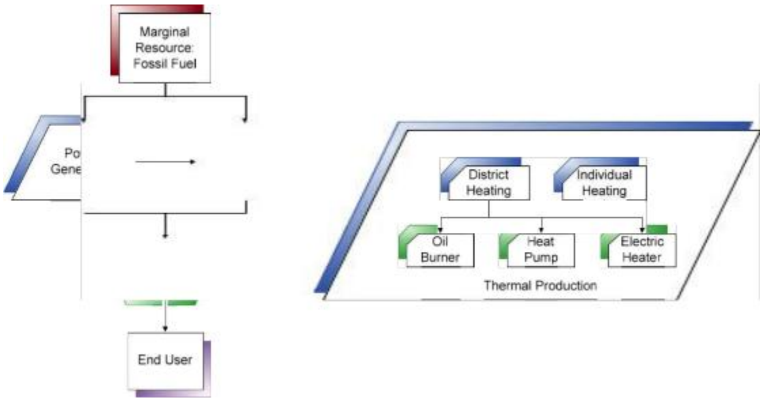


Figure 83 Considered Energy System (left) and Thermal Production Means (right)

4.3 LINEAR OPTIMIZATION MODEL

The model constructed is based on a linear optimization scheme. The cost of TES implementation follows a learning curve which takes the following form,

81 —

with LP the learning parameter, C the new unit cost, C0 initial unit cost, X accumulated capacity, and X0 initial cumulative capacity

The learning parameter is defined with the learning rate (LR),

1 2 82

The learning rate is high for a technology at its infancy and decreases as the technology reaches maturity. The learning rate adopted in this study for TES technology is taken from the learning rate for indoor air conditioning studied and categorized by Ferioli et al. from compilation of 108 applications (Ferioli, et al., 2009). The objective function is established to minimize the cost difference between TES installation, saved fossil fuel cost and avoided power/thermal plant cost so as to reach a cost breakeven point for a maximal fossil fuel replacement while maintaining cost effectiveness of the system. The objective function is expressed as the Peak Shave Cost (PSC),

$$PSC= TESCPCRAFFC \tag{83}$$

where TESC is thermal energy storage cost, PCR is the production cost reduction, and AFFC is the avoided fossil fuel cost (including CO2 tax). The production cost reduction represents the cost saving on fixed operation and maintenance (FOM) and on variable operation and maintenance (VOM). The FOM is a cost coming mainly from the rating of the production or the peak shaved power (PSP), while the VOM is a cost from the capacity of the production or the peak shaved load capacity (PSL). The PCR is expressed as follows,

$$PCR=PSP*\{FOM*[1(1+R)N]/R\}+ PSL*\{VOM*[1(1+R)N]/R\} \tag{84}$$

With the number of payments, N, taken as 20 years and the discount rate, R, taken as 6%. The AFFC is the total peak shaved fuel cost, with FRS the fuel reduction share and C the fuel cost.

$$AFFC=FRSCoal*CCoal+FRSGas*CGas+FRSOil*Coil \tag{85}$$

4.4 RESULTS AND DISCUSSIONS ON CO2 MITIGATION POTENTIAL

On top of the currently available measures taken for GHG emission alleviation in the Swedish society, TES gives possibility to further reduce GHG emission. The cost breakeven point for TES implementation against marginal fossil fuel saving is met with an installation of 14GWh storage system. This storage allows a replacement of 2TWh/year fossil fuel based thermal power production and 0.5TWh/year of fossil fuel-based electricity production. The emission reduction achieved corresponds to 620kTon CO2/year, which represents 13% of the fossil fuel based GHG emission in residential and service sectors, or 1.1% of the Swedish annual emission. In this study, displacement of heating load in residential and service sectors with TES is shown to lead to environmental benefit. It is believed that free cooling, absorption cooling, solar heating, and waste industrial heat may lead to further GHG emission reduction. In the future work, we will consider the potential of utilizing cold storage for load displacement through use of free cooling and off-peak cold production as well as heat storage combined with solar heating.

V. DISCUSSION AND CONCLUSIONS

The overall objective of this thesis has been to shed light and to provide novel knowledge in the field of thermal energy storage in terms of: 1) overall storage performance and characteristic mapping, e.g. application studies on interdependency between power and capacity, and model establishment with meticulous material characterization; 2) advanced knowhow in design of technically and economically robust storage systems for integration to the built environment, e.g. incorporation of LHTES to a district cooling network for office cooling; and 3) potential analysis on sustainable development contribution, e.g. GHG emission reduction through peak shaving and load shifting. A major contribution of this work has been the clear identification of the dynamic interdependency between the thermal power rate and the storage capacity as a function of resource availability for adequate TES design. For example, this dependency has been shown to be particularly significant as seen through the application studies where thermal resource availability was limited in time. A TES with too low heat transfer rate to allow full replenishment of the storage during charging/discharging cycle will lead to unutilized storage capacity which not only cuts down the overall thermal performance of the storage system but also leads to higher storage cost. To overcome this, heat transfer enhancement is considered. Heat transfer enhancement may be achieved through various means. One of the most common heat transfers enhancing methods consists of pursuing for larger heat transfer area, e.g., finned type. However, a large number of fins reduce the IPF of PCM, this leads thus to a decrease in energy storage capacity. Furthermore, the fins lead to higher fabrication cost and overly narrow fin spacing makes the filling of PCM difficult. Improving PCM thermal properties is an alternative for increasing the thermal power rating; a methodology has been proposed to perform thermal properties characterization and modelling. The proper design of the storage must thus take into account proper material characteristics, available resource availability, desired storage rate, and required energy storage capacity; the system may be only by then designed for its optimal use. TES has been shown to provide sound solutions in displacing peak energy demand and eventually in reducing both marginal fuel cost and network expansion investment in a built environment. The economic viability is however ensured only to a certain load shift percentage, higher than which, the PCM TES solution becomes non cost effective. This is due to three major reasons. The first is smaller number of full capacity TES cycle utilization, which can be translated to unused storage capacity. The second is the improperly designed tariff system which causes penalty with low district cooling return temperature during charging of the LHTES. Finally, charging and discharging processes add two extra heat transfer efficiency losses to the system. In order to overcome these issues, adequate energy policy schemes, novel PCMs development aiming for lower cost, and adapted heat exchange design are needed. The twenty first century is marked with the aim of reaching out for a more sustainable future. It has been shown with the commercial prototype study that TES provides sustainable solutions for indoor climate control, namely through greater use of free/waste energy. TESs also contribute to better management of load profiles and lead to higher system operating efficiency. For example, the cooling requirement in the studied office building can be peak shaved cost effectively with implementation of TES to reduce expansion cost. This reduces marginal energy requirement, and therefore cuts down GHG emissions through lower fossil fuel based marginal energy production. In this Licentiate thesis, new knowledge is brought forward on the material level, on the component level, and on the system level of TES system integration to the built environment. In the future work, we will investigate in performing TES design through cross level approach and carry out holistic system evaluation in terms of performance and techno economic feasibility assessment for market specific applications. A full size LHTES demonstration unit is currently in the conceptual phase for integration to a combined heat and power poly-generation project at the Royal Institute of Technology, Sweden. The proper control strategy as well as energy and environmental management will be the main key in rolling out to a technologically and economically sound storage solution.

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