ENERGY PERFORMANCE AND COST ANALYSIS OF PHASE CHANGE MATERIALS WITH DIFFERENT MELTING TEMPERATURE IN HEATING SYSTEMS

Mehdi Rezaei

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MEHDI REZAEI

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Abstract

Usage of thermal energy storage (TES) for storing energy is a favorable technology which is used in current years. It improved extremely during previous years by application of phase change materials (PCMs). One of the major applications of the storage is heating and cooling in the buildings. The normal TES for application in buildings is water which is used in the heating system but recently PCM technology improvement helpd to use different types of PCMs for increasing energy and exergy efficiency of TES system. In some researches the energetic and exergetic analyses of systems which work with PCMs in fixed Melting temperature has been investigated. In present work the effect of different PCMs with different melting temperatures on the energy and exergy efficiencies is investigated by considering the price of energy, exergy and each PCM type. Change of melting temperature causes different energy and exergy efficiency and according to different properties of PCMs the mass of storage material will change and leads to different total life cycle cost. The cost of lost energy and destroyed exergy is calculated for each PCM type in their life cycle and their share in total life cycle cost sketched as a circle diagram to show their importance. It is concluded that the role of exergy in each melting temperature is more important than energy and price of PCM. The amount of average lost exergy cost share is about 70.49%, average lost energy cost share is about 29.45% and average PCM price share is about 0.06% which means for having more optimum PCM choosing, the exergy concept have more significant role in choosing melting temperature of PCM than energy and price of PCM.

Keywords: Energy; Exergy; Phase change material; PCM; Economic Analyze; Solar heater;

Abstrak

Penggunaan alat penyimpan tenaga haba telah digunakan dengan meluas sejak beberapa tahun kebelakangan ini. Malah, penggunaan bahan ubah fasa bersama dengan alat penyimpan tenaga haba telah meningkatkan lagi kecekapan peranti tersebut. Salah satu aplikasi yang boleh digunakan dengan menggunakan alat tersebut adalah dalam pemanasan dan penyejukan di dalam suatu bangunan. Air merupakan bahan biasa yang digunakan untuk alat penyimpan tenaga haba, tetapi dengan adanya teknologi bahan ubah fasa, pelbagai bahan yang boleh dilabelkan sebagai bahan ubah fasa telah digunakan untuk menggantikan air. Ini secara langsung telah memperbaiki kecekapan sistem alat penyimpan tenaga haba dari segi tenaga dan eksergi. Beberapa kajian telah dilaksanakan dengan sistem-sistem yang menggunakan beberapa bahan ubah fasa dengan takat lebur yang telah ditetapkan. Di dalam laporan penyelidikan ini, kesan penggunaan beberapa bahan ubah fasa yang mempunyai takat lebur yang berlainan telah dikaji dari segi harga tenaga, eksergi dan bahan ubah fasa itu sendiri. Kos tenaga yang hilang dan eksergi yang terhapus telah dikira bagi setiap bahan ubah fasa dalam suatu kitar hayat dan dilakar dalam suatu gambarajah bagi menggambarkan kepentingan masing-masing. Kesimpulan daripada kajian ini mendapati peranan eksergi dalam setiap takat lebur bahan adalah lebih penting daripada peranan tenaga dan harga bagi setiap bahan ubah fasa yang telah dikaji. Jumlah purata eksergi yang terhapus adalah 70.49%, tenaga yang hilang 29.45% dan harga bahan 0.06%. Ini bermaksud, peranan eksergi di dalam pemilihan suatu bahan ubah fasa adalah lebih penting berbanding jumlah tenaga dan harga bagi bahan tersebut.

Keywords: Tenaga; Exergy; Fasa perubahan material; PCM, Ekonomi Analisa, pemanas Suria;

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ΔE_{sys}	System energy changes
E_{in}	Input energy
E_{out}	Output energy
η	Energy efficiency
E_{des}	Desired energy
E_{req}	Required energy
η_{char}	Energy efficiency of charging period
η_{dis}	Energy efficiency of discharging period
$\eta_{char}(t)$	Energy efficiency of charging period at time (t)
$E_{PCM}(t)$	Energy of PCM at time (t)
$E_{PCM,i}$	Initial energy of PCM
$E_{HTF}(t)$	Energy of Heat Transfer Fluid at time (t)
$\dot{\mathrm{m}}(t)$	Mass flow rate at time (t)
C_{HTF}	Specific heat capacity of Heat Transfer Fluid
$T_{in}(t)$	Input temperature at time (t)
$T_{out}(t)$	Output temperature at time (t)
η_{net}	Energy efficiency of the net
ψ_{char}	Exergy efficiency of charging cycle
ψ_{dis}	Exergy efficiency of discharging cycle
$\psi_{overall}$	Overall exergy efficiency
$\dot{E}x_{input}$	Input exergy rate

$\dot{m}_{HTF,in}$	Mass flow rate of inlet Heat Transfer Fluid
$T_{HTF,in}$	Inlet temperature of Heat Transfer Fluid
$T_{HTF,out}$	Outlet temperature of Heat Transfer Fluid
T_o	Ambient temperature
$\dot{E}x_{stored}$	Stored exergy rate
$\dot{E}x_{output}$	output exergy rate
m	Mass of PCM
Q	Heat energy
C_{liquid}	Specific heat capacity of liquid phase of PCM
C_{solid}	Specific heat capacity of solid phase of PCM
ΔT_1	Temperature difference during liquid phase of PCM
ΔT_2	Temperature difference during solid phase of PCM
L	Latent heat of PCM
D	Discount factor
PC	Present cost
C_t	Cost at time t
I	Interest rate

1 Chapter One: Introduction

1.1 General consideration of latent thermal energy storage

Thermal energy storage (TES) generally and phase change materials (PCM) in a particular manner has been a head subject of conversation in last 30 years. Nowadays, there are many researchers interested in the field of efficient and logical consumption of natural resources, most efficient use of renewable energy and methods which are dealing with energy saving. For catching these goals TES can provide opportunity to save energy in a period of time and create time delay between production and consumption of energy. This ability provides this opportunity for TES to be used in the field of temporary sources of energy like solar energy. In this case application of TES in renewable energy is frequent. Also it can be used for cogenerating equipment to reduce electrical prices by saving energy during off-peak production time and consume it during peak hours. Another capability of TES is its usage in making energy providing more secure. In the traditional method water is used as sensible heat storage and it needs extra equipment which extremely increases the price of storage tanks and its relevant equipment. Implementing PCM could help to decrease price and escape from additional equipment. Two concepts of thermal protection and thermal inertia are major characteristic which rise PCM’s ability to achieve TES market in higher level.

Two factors of poor stability and correlation between PCM and container is causing insufficient long term stability for PCM, storage equipment and storage tank and limits extensive application of latent heat stores. This problem is solved by encapsulation of PCMs in the size of nano and in common size.

Concept of energy and exergy has been analyzed since many years ago by many researches. A whole review of TES in chapter 9 of (Dincer & Rosen, 2010) shows that the concept of exergy has a great role in having a better view of what is happening in the system. Analysis of irreversibility and implementation of second law of thermodynamic are discussed and investigated from long times ago and are used for increasing efficiency. Exergy value is clearly showing the availability of heat temperature in thermal storage operation and hence it properly expresses economic and thermodynamic value of TES operation.

In some designs a determined melting point is needed at which there is no pure material to cover that melting point, in this situation a mixture of pure material with other materials can be used to reach new melting point. At this time analysis of boundary problem is occur and making this point clear is a problem in PCM industry. When used material as PCM is pure the melting and solidification happen in a single temperature but in the opposite side which uses mixtures, impure materials and alloys the melting and solidification happen in a range of temperatures. How to handle PCM in these cases is discussed in (Zalba et al., 2003).

Most of the researches investigate the energy and exergy analyzes of different inlet and storage temperatures of the heating systems which are using solar collector as the source of energy and they have used water as the fluid and some types of PCMs as thermal storage (Aghbalou et al., 2006; Koca et al., 2008; Li et al., 2012). However, the investigation of thermal storage unit by choosing different commercial PCMs with different melting temperatures and analyzing the exergy has not been done yet. In energy analyzes section considering energy as equivalent money is obvious but in exergy analyzes equivalent money is another issue which needs more attention and investigation (Dincer, 2002).

1.2 Phase change materials and their applications

The usage of PCM with classic storage tank in buildings is one of the initial studied applications. Telkes (1975) investigated solar application for heating and cooling system and Lane (1983) investigated storage tanks for cooling application in three decades ago. Barkman and Wessling (1975) investigated the application of building structure component to be used as thermal storage for heating and cooling purpose in 1975. Later this issue investigated by other authors (Hawes et al., 1993; Inaba & Tu, 1997; Morikama et al., 1985).

Safety is a very important issue for using PCM in building materials and for the first time the reaction on fire reported by Salyer and Sirkar (1990) and mentioned a list of fire-retardant additives to decrease response to fire in some materials. This paper mentioned advantageous and disadvantageous and attributes of materials which used as PCM which have this ability to be used in building for heating and cooling storage purpose. It mentioned paraffin type as the best choice with least disadvantageous in the range of 60-80 degree centigrade.

One application of PCM is its usage in light buildings which have low thermal mass due to PCM’s ability for saving energy and having smooth thermal variation. Light buildings have light thermal fluctuation and need high cooling and heating request (Mehling et al., 2002; Shapiro et al., 1987).

An important concept in this field is free-cooling system which employs PCM for saving coldness from ambient during the night and absorbs the heat from the building air during the hot day. It’s a natural usage for PCM and brings high thermal inertia for the building (Bruno & Saman, 2002; Vakilaltojjar & Saman, 2001).

Thermoelectric refrigeration in the cooling system is another application of PCM in the building to improve the effectiveness of the heat sink by using PCM in the thermal diode (Omer et al., 2001; Riffat et al., 2001).

Possibility of using PCM curtain in a window investigated in in order to decrease the solar gain during the day in hot weather and coldness in the winter in buildings. The window which is double sheeted and has a gap between two sheets could be filled by PCM and during very cold weather from outside by freezing can prevent thermal fluctuation in the room air (Ismail & Henríquez, 2001; Ismail & Henríquez, 2002).

Cassedy (2000) claims that in the economic view usage of PCM is not logical compare to the low cost of water for thermal storage at low temperatures of 50 to 100 degree centigrade because paraffin price is about doubled of water. However, he mentioned pleasant advantageous like long chemical stability and low corrosion for paraffin.

In a precious research which has done by Mehling et al. possibility of PCM usage at the top of a storage stratified water tank is investigated and concluded that this application of PCM can cause the system to have higher performance and save more energy (Mehling et al., 2002; Mehling et al., 2003).

In a research has been done by Safarik et al. (2002) paraffin as latent heat storage with ammonia water is used in a solar climatisation system. The goal of this study was to extend the operation time and solving the problem of time coincidence between air conditioning and solar radiation during the day.

Many companies like Calmac International (2011) have commercialized ice as thermal storage for decreasing total consumed electricity price. They use some additives to the water to cause different melting temperatures and are producing wide range of products. Many cold storage tanks are investigated in some researches like (Velraj et al., 2002).

A review on developments in the field of PCM usage in building is done by Pasupathy et al. (2008) which mentioned integration of PCMs with architecture of the building for cooling and heating in the building. This research mentioned the type of PCM, the percentage conventional material mixed with PCM, melting temperature of PCM, orientation of construction of the building and the climate as effective factors in thermal improvement in the building.

Vegetable cooling is another application for PCM which is investigated in (Kowata et al., 2002). Moreover the PCM usage for greenhouse temperature controlling and its management is investigated in (Bakenhus, 2000). Investigations show that amounts of phase change material per square meter and the type of heat exchanger are different in each study.

By inspection the history of PCM usage in solar collectors became obvious that Sokolov and Keizman (1991) were the first guys who used this application in 1991. Solar cookers are another application of PCM to lengthen their usage time (Buddhi & Sahoo, 1997). Application of PCM in increasing thermal comfort in vehicles is another issue which is came into consideration.

To cut the story short in this part should be mentioned that one of the best renewable sources of energy is solar energy and according to the periodic characteristic of this source of energy, storage issue is a vital concept to keep it alive. Other advantageous of thermal energy storage is increasing the efficiency of the system and decreasing the size of power plants for producing electricity (Erek & Dincer, 2008).

Currently one the most effective way to store energy and use the high-energy storage density is the application of phase change materials ability to save latent heat (Zalba et al., 2003). Unfortunately, the huge size and large-scale of this technology is the main disadvantage of storage systems and should be resolved by applying innovating methods and finding new materials in this field (Sharma et al., 2009).

1.3 Energy and exergy analyzes

In the past decade energy analyses is conducted in many cases. The energy analyses is fundamentally based on first law and the exergy is based on the second law of thermodynamic and in most cases is calculating for each part separately and at the final step will be multiples to each other (Jegadheeswaran et al., 2010; Li et al., 2012). In the storage systems which exergy and energy are analyzed, the total amount of energy and exergy efficiency are calculated in charging, storage and discharging periods by multiplying there 3 steps. Better insulation and more efficient exchangers in all steps can prevent loss of energy.

Exergy is a quality of energy and its thermodynamic aspect is defined as the maximum possible work compared to a reference environment and could be determined for produced work by a system or energy flow through a system (Edgerton, 1982; Kotas, 1995; Moran & Sciubba, 1994; Moran, 1982). When a system is not completely in equilibrium with the environment has the ability to do work and when this distance from the environment is higher, more work can be done by the system, this concept is exhibited by the value which is defined as exergy. It is important to know that the conservation law is useful for understanding the concept of energy but exergy is not subject to this rule. In a real process exergy can destroy or consume due to irreversibilities.

Fundamentally, people are involved in the energy which is capable of do more work for them and this concept has a value which named exergy and price of energy reflects its exergy rather than its energy content. Thus low-exergy source of energy should have a lower price and vice versa. However, for calculating energy price the total investment for supply energy to the end user is important.

1.4 Economic analyzes

In macroeconomics, exergy can be used as a concept to prevent more environmental and natural resource depletion by putting tax on resource consumptions and in microeconomic, this concept can be used as a very powerful tool for catching a more efficient system design. By minimizing losses of exergy the environmental effect will decrease, by minimizing the life cycle cost the best the best economic design will be possible, but for having a cost effective system which can cover the environmental issue the concept of exergy should be evaluated by money. Nowadays, one of important challenges which engineers are facing is to design a cost effective system which can handle environmental issue. In the other word, because of large energy demand which increases dramatically, it is important to find the mechanism which the energy degrading is working with to prevent waste of natural resources and save them for future generations. Economics combined with exergetics are powerful tools for catching this significant goal of whole system optimization.

“Exergoeconomic” which used by Bejan in 1996 and “exergonomic” which used by Yantovskii 1994 are names which chosen for the concept of exergetic and microeconomic shape of “thermoeconomic” which used by Evans and Tribus in 1962 and shows the traditional aspect of relation between thermodynamic, exergy and economy. Nowadays, taxing is a great example to show how exergy could be introduced to the microeconomic (Dincer, 2002).

Analyzes which worked on the energy and exegy part of the systems are clear because make energy equivalent to the money is sensible. But energy, exergy and cost analyze is another issue which should be done currently. For catching this purpose the relation between destroyed exergy and money should be clear.

In the next step cost analyzes is one of the important ways to make new methods more commercial. After improving one devices efficiency and finalizing the increased prices for a device, in the part of economic analysis some precious works has been done to make detailed calculation by considering all the economic factors during increasing efficiency easier. For the PCM choosing part, some companies exist which encapsulate many types of PCMs and categorize them with their melting temperature range. In this analyze by changing the melting temperature, different designs of the system have chosen and the energy and exergy efficiency of these designs are compared due to their prices.

1.5 Correlation between exergy and economy

Lozano and Valero (1993) mentioned that the usage of exergy as a criterion for cost allocation for the first time was exhibited by Keenan in 1932, who recommended that exergy instead of energy, should be a cost gauge in a cogeneration plant products cost analysis. Since then the exergy content of energy carriers and the exergy loss of process are developed and most of researchers summarized this term as “thermoeconomics”. In another word, “thermoeconomics” term is made for the concept of combination between economics and second law of thermodynamic.

Deng et al. noted that different theories and nomenclatures in various methodologies and cause prevention and made some confusion in the progression of thermoeconomics but in all of investigations second law analysis method with cost accounting are the basic principles to calculate a price for exergy (Deng et al., 2008).

A general mathematic formulation which is using linear model developed by Valero et al. (1993) by using all the thermoeconomic methodologies as structural theory of thermoeconomic and is considered as thermodynamic standard formalism.

At current time exergoeconomics, concept of exergy price and exergy accounting are relevant concept in the field of thermoeconomics. The inflow of physical resources is converted into equivalent exergy form by exergy accounting. Having a homogeneous exergetic base helps the investigators to have a better evaluation in energy and mass transfer that is transferring between different sectors of society and makes a clear view for irreversible losses to be quantified more understandable (Pu et al., 2010; Sciubba, 2001; Sciubba et al., 2008).

In Xiang et al. (2010) perspective, exergy cost is a concept which shows the used external resources units in production cycle of a product. However, this idea does not exist in the current economic prices. In another research Valero (2006) expresses a reasonable chain of concepts to connect economics with physics. He mentioned that cumulative exergy consumption or exergetic cost actually is the same with the embodied exergy. In the view point of exergy, the production of a process is different from energy aspect.

Some analyses have done by Hepbasli (2008) in which, specific monetary prices are calculated by the concept of exergy prices or exergetic prices instead of their energy concept.

Moreover in another study for converting exergy to its equivalent money Rosen et al. (2008) mentioned some ways to make it possible and explained that the environment can have relation with the exergy in three ways of exergy order destruction, exergy resource degradation and waste exergy emissions. The order destruction is environmental destruction and basically entropy measure of disorder. So, a system with higher entropy is more disordered than the one with low entropy and relatively a system with higher exergy is the more ordered one system. For the resource degradation part two general solutions exist. The first one is increasing efficiency and the second one is usage of external exergy resources like solar energy which is considered as a great external resource for the earth. When wastes from a process are not in balance with the environment they have the ability to make some damage on it, so the price to remove this wastes and pollutants should be considered when the price of exergy is going to be calculated (Rosen et al., 2008).

Dincer (2002) in his paper mentioned that in different resources the price of exergy is different from the energy price because of the different percentage of converting to the work. For instance he mentioned that for electricity the price of exergy and energy is equal because the all of energy can be converted to the work. For our investigation because the network electricity is the source of energy the price of exergy considered the same as the price of electricity in the investigated country.

1.6 Scope of the study

This study concentrates on the energy and the exergy efficiency of thermal energy storage which is investigating different designs by different melting temperatures of a specified manufactured type of PCM in a designated range. By clearance effect of exergy analyses on the environment, calculation of this value and its equalization with money is a good way to have more efficient design.

1.7 Significance of the study

Exergy is a wage concept and its practical effects with the environment are not sensible like energy. In this study for the first time the equivalent money for exergy used to made the system designing more efficient in a holistic view of the great system of environment. This study gives a better investigation for environment and predicts more hidden costs which are not considered in previous investigation that considered energy as the only effective factor for their design.

1.8 Objective of the study

- To calculate energy and exergy efficiency of the system with different melting temperature of PCM.
- To calculate the price of solar energy and exergy.
- To calculate life cycle cost of the system with different melting temperature of PCM by considering price of energy, exergy and PCM.
- To find the most economical PCM type which can be used in the system by comparing total life cycle costs.

1.9 Organization of the study

In this study an extensive review on energy and exergy efficiency of thermal energy storages is presented in chapter 2. The functional methodology which described usable equation for our investigation is illustrated in chapter 3. The calculated results are shown in chapter 4 and in the final section the conclusion and recommendation for future jobs are mentioned in chapter 5.

2 Chapter Two: Literature review

2.1 Studies conducted on energy analysis of latent heat storage

Calculation of efficiency and other similar parameters for Latent Heat Thermal Storage (LHTS) units has been investigated by many researches. Some of these investigations concentrate on each section of charging, storage and discharging separately and the others have taken the whole system’s working cycle. In a certain condition a system will receive to the maximum capable efficiency and designers are eager to catch these certain conditions.

Storage efficiency of LHTS in solar water heater is investigated by Adine and El Qarnia (2009) and the ratio of the stored latent heat in the PCM to the total radiation of solar is considered as the storage efficiency. In this research higher efficiency is catchable by using more tubes in the heat exchanger. In another similar research by Kaygusuz (2003) energy efficiency for a solar heat pump is calculated and found that by increasing the mass flow rate of Heat transfer fluid (HTF), the storage efficiency will increase. Moreover, it noted that inlet temperature of HTF have less effect on storage capacity of the storage tank.

Thermal efficiency analyses of shell and tube Latent Heat Thermal Storage (LHTS) is investigated by Seeniraj et al. (2002) and reported that higher performance for the unit is achievable by higher mass flow rate of HTF. It mentioned that, smaller size unit has a higher storage performance compared to the larger one.

Efficiency or effectiveness is a well-known parameter which is used for evaluation of thermal system performance. In reality, efficiency is the measure of how effectively heat or cold energy stored or recovered in a thermal system. In another word, value of efficiency shows that by having an obvious amount of energy and after storage and recovering, how much of that energy is available for use. Hence, the efficiency can be defined for all processes separately including charging, storage and discharging or for overall process. In a heating system charging and discharging terms indicated as melting and solidification of the storage tank, respectively.

In some processes in which the charging or discharging is more important than the other one just one of them is investigating and the other one is neglected. In a research by Gumus (2009), a cycle for preheating of air before start of the engine is designed, and the efficiency is calculated during discharging process and during melting of the PCM. In this process the ratio of energy earned by the engine and the total heat stored in the heat storage unit is defined as efficiency term.

MacPhee and Dincer (2009) have carried out some calculations for efficiency term and they used some assumptions to make their calculation more logical and clear.

- All kinetic and potential effects are neglected.
- All piping losses and viscous dissipation losses assumed negligible.
- The storage tank is cylindrical, with diameter equal to height.
- The thermal energy stored in the HTF is negligible
- All thermal energy is stored in the water/ice medium.
- Tank is considered to be of constant temperature, changing according to the specified system process.
- All thermo-physical properties are assumed constant at their prescribed values.

An energy balance and the total energy efficiency on the entire process clearly can be shown by the equations below:

$$\Delta E_{sys} = E_{in} - E_{out} \tag{2.1}$$

MacPhee and Dincer (2009) for the charging, storage and discharging cycles defined the energy efficiency as ratio of the desired energy to the required energy which used in a cooling system analyses which can be modified to be used in heating application.

$$\eta = \frac{E_{des}}{E_{req}} \tag{2.2}$$

Mawire and Mcpherson (2008) have defined charging and discharging efficiencies separately for solar cookers system and can be used for all solar heating systems because of their working similarity. The energy efficiency in two steps of charging and discharging cycles can be shown as below. However, each one of these steps has their own analyzes which should be done separately:

$$\eta_{char} = \frac{Total\ energy\ stored\ in\ the\ unit}{Total\ enrgy\ supplied\ by\ HTF} \tag{2.3}$$

$$\eta_{dis} = \frac{Total\ energy\ absorbed\ by\ the\ HTF}{Total\ energy\ stored\ in\ the\ unit} \tag{2.4}$$

By multiplying two above equations the total equation can be calculates as:

$$\eta = \eta_{char} \times \eta_{dis} = \frac{Total\ energy\ absorbed\ by\ the\ HTF}{Total\ energy\ supplied\ by\ HTF} \tag{2.5}$$

In all the equations which are mentioned here they are the average temperature and all the flow masses are calculated as average of mass flow rate. Ezan et al. (2010)

made the process a little more realistic and used the integration during the total period of charging and discharging. Their equations are showed as below:

$$\eta_{char}(t) = \frac{E_{PCM}(t) - E_{PCM,i}}{E_{HTF}(t)} \qquad (2.6)$$

$$E_{HTF}(t) = \int_{t=0}^{t} \dot{m}\,(t) C_{HTF}[T_{in}(t) - T_{out}(t)]dt \qquad (2.7)$$

$$\eta_{dis} = \frac{E_{HTF}(t)}{E_{PCM}(t) - E_{PCM,i}} \qquad (2.8)$$

Koca et al. (2008) cleared these equations especially for solar usage and mentioned below equation for calculating the energy efficiency of the net:

$$\eta_{net} = \frac{Transfered\ heat\ to\ the\ water}{Solar\ energy\ input} \qquad (2.9)$$

At the final step by considering all above equations the below equation is useful for our investigation for calculation energy efficiency which sows the ratio of the transferred heat from the PCM during discharging cycle to the transferred heat to the PCM during charging cycle:

$$\eta = \frac{\dot{m}_2\ C_{HTF}[T_{in} - T_{out}]}{\dot{m}_1 C_{HTF}\ [T_{in} - T_{out}]} = \frac{Transfed\ heat\ from\ the\ PCM\ during\ discharging\ cycle}{Transfered\ heat\ to\ the\ PCM\ during\ charging\ cycle} \qquad (2.10)$$

2.2 Studies conducted on exergy analysis of latent heat storage

In the exergy analyzes unlike the energy one, the second law of thermodynamic is used which is about the quality of energy. The quality of energy is evaluated by comparing the system situation with the surrounding condition. Exergy is the maximum quantity of work that a system could produce as it receives to the balance with surrounding. It means that exergy is the potential to make change because of unbalance with the surrounding condition. It is important to know that exergy cannot be preserved only can be used up or destroyed.

Rosen (1992) clearly indicated that even though energy efficiency is widely used in storage systems, exergy efficiency could be calculated and used to show that the system is working in the highest possible amount of exergy efficiency. Like the energy part, the exergy efficiency can be calculated separately in the charging and discharging period.

In the exergy efficiency analyses section unlike the energy efficiency one, the temperature of the surrounding and the temperature in which PCM is melting are very important and quality of energy is showing its effect on the calculations dramatically. In the exergy analyses, clearer picture of system behavior can be seen thermodynamically (Kousksou et al., 2007).

Green energy is another issue that discussed simultaneously by exergy concept. Rosen et al. (2008) believed that exergy better than energy can show the environmental benefits and economics of technologies in energy field. Exergy can bring more information about the sources of provided energy. Thus for utilization of green energy technologies, undoubtedly, exergy can take a prominent role.

Catching the maximum efficiency is not a final goal in practice and concentrating on only efficiency normally leads to unpractical outcomes. Efficiency analyses is useful when it helps to receive another benefits like meeting applicable emissions standards, reducing life cycle cost and mitigating natural resources wastes in a system.

Some useful formula which introduced by researchers is discussed here. In the charging period part of the exergy which is supplied by the heat thermal fluid (HTF) is stored in the PCM and exergy efficiency is declares as produced by Watanabe and Kanzawa (1995).

$$\psi_{char} = \frac{Exergy\ stored\ in\ the\ PCM}{Exergy\ supplied\ by\ the\ HTF} \qquad (2.11)$$

Latent heat transfer system is a time dependent system and the above equation can be shown as below.

$$\psi_{char} = \frac{Rate\ of\ the\ exergy\ stored\ in\ the\ PCM}{Rate\ of\ the\ exergy\ supplied\ by\ the\ HTF} \qquad (2.12)$$

Rosen and Dincer (2003) indicated that because the heat pump power which is used to flow the HTF is comparatively significant and it should come into calculation as pump work. The equation which used pump work into exergy efficiency can be found in (Öztürk, 2005) and below.

$$\psi_{char} = \frac{Rate\ of\ the\ exergy\ stored\ in\ the\ PCM}{Rate\ of\ the\ exergy\ supplied\ by\ the\ HTF + Power\ input\ to\ compressor\ or\ pump} \tag{2.13}$$

In the above equation the supplied exergy can be calculated by using the different between inlet and outlet temperature together with the environmental temperature. One problem of the previous equation is that, it cannot show the maximum exergy which is provided by HTF and this deficit can be solve by the modifying the previous exergy equation by using Gong and Majumdar (1997) and equation which given as:

$$\psi_{char} = \frac{Rate\ of\ exergy\ stored\ in\ the\ PCM}{Exergy\ rate\ possessed\ by\ the\ HTF\ before\ contact\ with\ the\ PCM} \tag{2.14}$$

Demirel and Ozturk (2006) also have the same viewpoint in this field.

In the calculation of exergy the different between inlet and environment temperature is coming into account rather than the different between inlet and outlet temperature of HTF. This new equation shows that how much exergy can be saved in PCM from the maximum potential which is available for work.

The same phrase can be acquired for the discharging process. In the discharging process the output exergy is the change of exergy between inlet and outlet fluid and the available exergy is the exergy existed in the PCM. So the exergy of discharging can be shown as:

$$\psi_{dis} = \frac{Exergy\ gained\ by\ the\ HTF}{Initial\ exergy\ available\ with\ the\ PCM} \tag{2.15}$$

This equation uses the total amount of exergy and the maximum of the available exergy. For making this equation dependent from time the equation below can be expressed (Ramayya & Ramesh, 1998):

$$\psi_{dis} = \frac{Rate\ of\ the\ exergy\ gainred\ by\ the\ HTF}{Rate\ of\ the\ exergy\ released\ by\ the\ PCM} \qquad (2.16)$$

The total process contains of storing energy process and removal energy process and if this characteristic is not considered the significant error will occur (Krane, 1987). The overall exergy efficiency can be calculated by the following equation (Ramayya & Ramesh, 1998).

$$\psi_{overall} = \psi_{char} \times \psi_{dis} \qquad (2.17)$$

And by combining all the process the following equation can cover all the previous ones (Sari & Kaygusuz, 2000).

$$\psi_{overall} = \frac{Exergy\ extracted\ from\ the\ PCM\ by\ the\ HTF\ during\ discharging}{Exrgy\ input\ to\ the\ PCM\ during\ charging} \qquad (2.18)$$

Ezan et al. (2010) mentioned another equation for calculating exergy during charging and discharging period by considering ice as the PCM and water as the heating fluid which are mentioned below:

$$\psi_{char} = \frac{Ex_{PCM}(t) - Ex_{PCM,i}}{Ex_{HTF}(t)} \tag{2.19}$$

$$\psi_{dis} = \frac{Ex_{HTF}(t)}{Ex_{PCM}(t) - Ex_{PCM,i}} \tag{2.20}$$

In (Jegadheeswaran et al., 2010) some simple and usable formula for the calculation of exergy efficiency mentioned as below:

During charging period, the rate of exergy supplied by HTF is defined by Demirel and Öztürk (2006) and expression as below equation:

$$\dot{E}x_{input} = \dot{m}_{HTF,in} \times C_{HTF}\left[\left(T_{HTF,in} - T_{HTF,out}\right) - T_o \ln\left(\frac{T_{HTF,in}}{T_{HTF,out}}\right)\right] \tag{2.21}$$

Equation (2.21) declares the input exergy from mass flow rate of HTF which comes from solar collector and translates to the storage tank. By taking the environment as the equivalence for the base this exergy content here shows the minimum useful energy when it receive to equivalent with the state of environment.

By taking time integration of previous equation, the total exergy input to the PCM can willingly achieved. By determining the energy balance the immediate heat transfer rate can be acquired. In charging mode of operation instantaneous heat transfer rate is used to calculate stored exergy at any time. Thus the rate of exergy stored in PCM is given as:

$$\dot{E}x_{stored} = \dot{m}_{HTF}C_{HTF}\left(T_{HTF,in} - T_{HTF,out}\right)\left[1 - \left(\frac{T_o}{T_{PCM}}\right)\right] \tag{2.22}$$

In this equation the value of T_{PCM} is the same with melting temperature of the PCM and it is assumed that PCM is melting in the fixed melting temperature completely and sensible heat for PCM is neglected. It is important to know that, in practice PCM is not melting in a fixed point and there is a small range in which PCM is melting but in theory because the temperature of PCM changes in a linear manner, the average temperature of PCM between the initial and final state during melting or solidification is computed to be used as T_{PCM}. Moreover, at different location and different time, temperature of PCM is not constant because of solid and liquid interface. This issue is done by Gong and Mujumdar (1997). However, Farid and Kanzawa (1989) noted that sensible heat contributes significantly in the energy calculation. This issue is because they believed that the temperature of the PCM may changes dramatically before receiving to the melting temperature of the PCM and in this period PCM is in the solid or liquid phase and in all formulas the sensible heat should be used instead of by latent heat and the temperature of PCM should be replaced by temperature of the PCM at that moment.

The output exergy rate calculates by equation (2.23) as below:

$$\dot{E}x_{output} = \dot{m}_{HTF,in} \times C_{HTF} \left[\left(T_{HTF,out} - T_{HTF,in} \right) - T_o \ln \left(\frac{T_{HTF,out}}{T_{HTF,in}} \right) \right] \qquad (2.23)$$

In the charging and discharging process the inlet temperature is a very important factor. When the melting temperature is fixed the inlet temperature could be controlled for receiving the highest exergy performance. Moreover, the inlet temperature is affected by the surrounding temperature in the discharging cycle and influenced by heat source during charging cycle.

Kouksksou et al. (2008) noted that in PCM capsules system, higher inlet temperature causes higher entropy generation due to higher temperature difference between HTF and PCM. Entropy generation is product of temperature difference, and when this difference is more, higher entropy generation is happening. Thus it can be concluded that for decreasing the entropy generation, the inlet temperature of heat transfer fluid (HTF) for charging cycle should be as low as possible. However, by decreasing the HTF inlet temperature, heat transfer rate and charging rate will be affected. In some systems like heat recovery systems that availability of the heat source is not continues, the charging rate should be as high as possible (Velraj et al., 1999). Thus according to the system's situation choosing the temperature for inlet HTF can change. For instance, in a system like solar thermal applications that higher charging rate may not be very important, the inlet temperature could be as low as possible and higher exergy efficiency would be achieved. During discharging cycle the temperature of PCM have high temperature and for having less entropy generation and reaching higher exergy efficiency, the inlet temperature should be close to the PCM temperature.

In another research by El-Dessouky and Al-Juwayhel has been noted that during discharging process by increasing HTF inlet temperature, entropy generation reduces. They announced that by comparing air and water as heat transfer mass concludes that when water was used instead of air as the HTF, entropy generation was smallest (El-Dessouky & Al-Juwayhel, 1997). This may lead to the conclusion that when the gas is used as HTF the entropy generation is more than the condition in which HTF is liquid. However, in another investigation by Erek and Dincer (2008) has been declared that entropy generation for ethylene glycol as HTF is highly dependent on inlet temperature of HTF. These two previous investigations did not use the same method. In another research which is done by Ramayya and Ramesh (1998) like Erek and Dincer (2008) worked with shell and tube module. In both investigations, during discharging period, significant increase in exergy efficient reported due to increase in inlet HTF temperature. It’s obvious that if higher charging and discharging rate is required, higher temperature difference is required.

Mass flow rate or velocity is another issue which investigated by researches and found to have a high impact of exergy efficiency. The well-known Reynolds dimensionless number generally is employed to examine the effect of mass flow rate on exergy efficiency. Higher velocity will conclude to higher and lower one has lower Reynolds number.

In the field of relation between velocity and exergy efficiency Kousksou et al. (2007) have announced that entropy generation is somehow dependent from the velocity of HTF and this factor have not significant role in exergy efficiency analysis. The reason for this announcement is that in the numerical model, entropy generation due to pressure drop in the system is neglected thus velocity, which is responsible for pressure drop, could not be investigated in entropy generation. But it is obvious that higher velocity results in higher Reynolds number and finally results in higher pressure drop which leads to higher entropy generation.

At higher Reynolds number, because of limitation in time for changing temperature of HTF, the temperature difference between inlet and outlet HTF is less which leads to less entropy generation. At the final step exergy efficiency decreases because of increase in Reynolds number, however, the pressure drop will increase too that have an irreversible effect on entropy generation (Jegadheeswaran et al., 2010).

It is important to know that in all above mentioned researches the works of the pumping power does not included which means that mechanical irreversibility is neglected. But it is obvious that high Reynolds number needs high pumping power to be created. Hence, in the investigation of Reynolds number effect on the entropy generation, pumping power is a prominent factor which should come into account to have a better accuracy. By all of these discussions the effect of inlet temperature of HTF is much higher than the Reynolds number effect on the entropy generation (Jegadheeswaran et al., 2010).

2.3 Studies conducted on economic analysis of latent heat storage

One of the main challenges which exist in front of engineers is large energy demand and finite natural resources. The situation of energy demand somehow can be in a better situation by designing more efficient devices instead of current ones. Understanding the mechanisms of energy degradation will help significantly to receive this goal and reduce environmental impact. Exergy combined with economics prepared a powerful tool for study and optimization of systems in an organized way.

Recent thermoeconomic analyses have been performed by Tozer et al. (1999), Lozano and Valero (1993) leading to the development of the ‘‘Theory of the exergetic cost’’ and its application in operation optimization, cost allocation and the economic optimization of different thermal systems. It is well known that the exergy value of energy represents its quality. Nieuwlaar and Dijk (1993) made use of this fact when he performed a thermodynamic analysis of heating in buildings for the end users of heat. They estimated that for the case of consumption, there are many possibilities for improving energy efficiency. Rosen (1992) also performed an energy and exergy analysis for energy consumption. He estimated that the exergy losses in all branches of industry are relatively high and introduced possibilities for the reduction of these losses.

Some of the researches mentioned Nicholas (1971) as the pioneer and the father of termoeconomic. As mentioned before in the introduction sector, thermoeconomic, exergoeconomic and exergonomic are some names that chosen by previous researchers for the exergy combined with economic. Exergy is related to utility term which is a central concept in macroeconomics. Exergy tax on system designs and production prices is a good example of how exergy can be used as an effective tool in macroecomics.

The concept of exergy is not only critical for efficiency analysis but also it is important in economic analysis and cost accounting. Costs should reflect the real value of something, if the concept of exergy in neglected during cost evaluation, it will lead to inappropriate costing system (Rosen & Dincer, 2003). When the environmental issue became more critical the system of cost evaluation does not have any other choice to escape using exergy as an important tool. Using exergy can be helpful to manage product prices and evaluate real profits and also can assist engineers to make more logical decisions about how one process should operate to be more efficient and cause less environmental impact.

3 Chapter Three: Methodology

The procedure to calculate the energetic, exergetic and cost benefits of utilizing PCM for heating application is presented in this section.

3.1 Deriving equations

According to literature review some equations which are used in this investigation are mentioned below.

3.1.1 Energetic analyzes

In this part, according to the inlet and outlet temperature of the used liquid and the mass flow rate which is estimated by having the required energy, the inlet energy is calculated by using equation below (Jegadheeswaran et al., 2010):

$$Q_{in} = \dot{m}C_{HTF}[T_{in} - T_{out}] \qquad (3.1)$$

where Q_{in} is the energy which translated from the solar collector to the PCM during charging period and stores there by melting all the existed PCM in the storage tank. The outlet energy is calculating by the equation below:

$$Q_{out} = \dot{m}C_{HTF}[T_{in} - T_{out}] \qquad (3.2)$$

where Q_{out} is the energy which collected by heat transfer fluid form PCM during the discharge period and transferred to the building. For showing the total process the equation below can makes a better view of what is happening:

$$\eta = \eta_{char} \times \eta_{dis} = \frac{\dot{m}_2\, C_{HTF}[T_{in} - T_{out}]}{\dot{m}_1 C_{HTF}\, [T_{in} - T_{out}]}$$

$$= \frac{Transfered\ heat\ from\ the\ PCM\ during\ discharging\ cycle}{Transfered\ heat\ to\ the\ PCM\ during\ charging\ cycle} \quad (3.3)$$

3.1.2 Exergetic analyzes

By having all the data in each design by using equations below all the exergy efficiencies are calculated separately (Jegadheeswaran et al., 2010). Equation (3.4) is showing the input exergy during charging period which comes from the solar collector to the storage tank.

$$\dot{E}x_{input} = \dot{m}_{HTF,in} \times C_{HTF}\left[\left(T_{HTF,in} - T_{HTF,out}\right) - T_o \ln\left(\frac{T_{HTF,in}}{T_{HTF,out}}\right)\right] \quad (3.4)$$

The amount of exergy which is stored in the storage tank is calculated by below equation:

$$\dot{E}x_{stored} = \dot{m}_{HTF} C_{HTF}\left(T_{HTF,in} - T_{HTF,out}\right)\left[1 - \left(\frac{T_o}{T_{PCM}}\right)\right] \quad (3.5)$$

And finally the exergy which is coming out from the storage tank is calculated by the below equation:

$$\dot{E}x_{output} = \dot{m}_{HTF,in} \times C_{HTF}\left[\left(T_{HTF,out} - T_{HTF,in}\right) - T_o \ln\left(\frac{T_{HTF,out}}{T_{HTF,in}}\right)\right] \quad (3.6)$$

For calculating the exergy efficiency in the charging part the stored exergy should be divided to the input energy and for calculating the discharging exergy efficiency the output exergy exergy should be divided to the stored exergy in the next step. For calculating the overall exergy efficiency the below equation is used:

$$\psi_{overall} = \psi_{char} \times \psi_{dis} \tag{3.7}$$

3.1.3 Economic analysis

The most important part of the cost analyzes in this research is finding the relation between the melting temperature and the total prices of the system according to the PCMs prices. Finally all the other costs are fixed in all designs and for simplification are not coming into account.

As mentioned in the introduction section energy and price have a clear relation and when energy is wasted it can be seen in the costs directly. Nowadays scientists found that after a long time when one system changes the environment and after a process cannot bring it back to the first situation in the long term some problems will occur. This concept can be shown numerically by Exergy. It means that if the earth and the environment can be taken as a system. Before a system starts to work and after finishing its work some changes will happen in the system. By increasing the exergy efficiency this changes can be reduced. The main question here is how exergy can be shown in money equivalent. It is clear that by minimizing the life cycle cost according to the economic situation the best system can be design but here the cost of environmental effect needs to be added to the life cycle cost which has been seen in exergy analysis. In addition to energy analysis and exergy one the price of PCM is another part which has a segment in the life cycle cost analysis.

The mass of the PCM is calculated by the equation below:

$$m = \frac{Q}{(C_{liquid}\,\Delta T_1 + L + C_{solid}\,\Delta T_2)} \qquad (3.8)$$

For our system for simplicity assumed that temperature is not changing and all of the heat is absorbed by latent heat capacity. So the equation below will be more useful:

$$m = \frac{Q}{L} \qquad (3.9)$$

The total cost for the system during its life cycle is calculated for 40 years.

For calculating the solar energy and exergy price some economic factors are used and interest rate is considered in calculations. For calculating the life cycle of a product, the present value of all expenses must be determined. Present value is the time equivalent value of past, present or future cash flows as of the beginning of the base year. Since most initial expenses occur at about the same time, initial expenses are considered to occur during the base year of the study period. There is no need to calculate the present value of initial expenses because their present value is equal to their actual cost. Equation (3.10) is showing the present value relation with discount factor by the time (Mearig et al., 1999):

$$C_t = \frac{PC}{D} \qquad (3.10)$$

In which C_t is the cost at time t and is used for future predicted price according to special interest rate of I and t is number of the year. The amount of discount factor is introduced in Equation (3.11) as below:

$$D = \frac{1}{(1+I)^{(t-1)}} \tag{3.11}$$

In which D is discount factor I is interest rate and t is the year.

3.2 System description and assumptions

Ramlow and Nusz (2010) mentioned that the amount of 4300 kWh for heating system is required for a common house in North America in one year. The available data in (Henning, 2003) confirms this range for required energy value for a normal house. The heating radiators in the house are designed to work 5 degree centigrade different temperature between T_{bin} and T_{bout} and to work 12 hours a day during cold weather time in the day and uses water with C_{HTF} 4.18 kJ/kg.k as heating transfer fluid. By having these values and using equation (3.1) the amount of mass flow rate in the building ($\dot{m}_2$) is calculated and will be equal to 0.046 kg/sec. The heat exchanger with the PCM container is designed (Shah et al., 2003) to have energy efficiency equals to 97% so by using this amount as energy efficiency in Equation (3.3) the amount of required solar energy in the solar cycle becomes clear. Jagoda et al. (2011) mentioned that the temperature of solar collector in the investigation situation can reach up to 90 ºC (363 ºK) so the solar collector could be designed (Henning, 2003) to collect energy in 6 hours a day. Then for this study, in steady state situation the average temperature for T_{sout} which is assumed as 61 ºC (334 ºK) could reach up to the average temperature of 66 ºC (339 ºK) for T_{sin}. By getting η equal to 0.97 and by assuming different temperature between T_{sin} and T_{sout} as 5 degree centigrade in Equation (3.3) value of 0.097 kg/sec is calculated for mass flow rate for the solar collector ($\dot{m}_1$).

Melting temperature for the storage tank is another issue which should be clear to be used in calculations of exergy efficiency. Because the total amount of PCM should be melted and solidified during charging and discharging process, this temperature should be less than T_{sout} 61 ºC (334 ºK) and higher than T_{bout}. Thus, the temperature range of 32 ºC (305 ºK) up to 58 ºC (331 ºK) is taken as melting temperature range for the PCM. T_{bin} and T_{bout} are chosen to be dependent on melting temperature of PCM and according to our design T_{bout} and T_{bin} are 3 and 8 ºC lower than melting temperature of PCM accordingly. PCMs are chosen from the company products which are ready to be used directly in the storage tank. The price of used PCM per kg is calculated according to negotiation by this company which produces suitable required melting temperature range ("pcm products," 2012) and the mass of used PCM is calculated by Equation (3.9). The schematic of investigated system is shown in Figure 3.1.

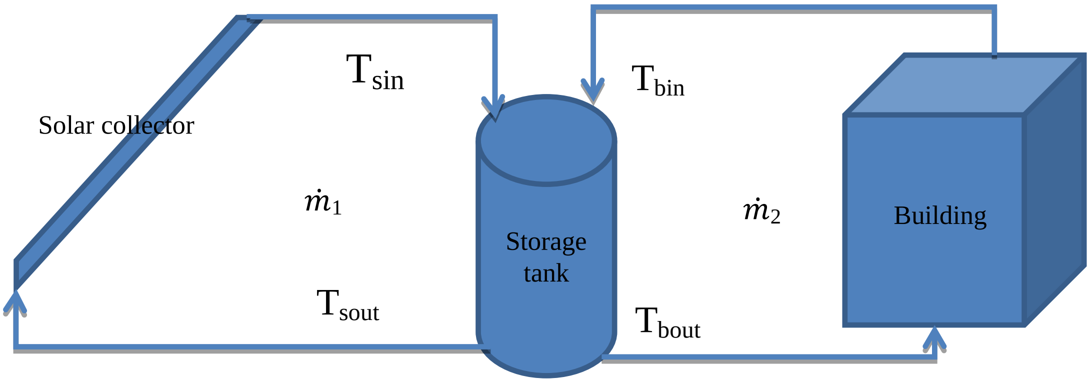

Figure 3.1 Schematic of the investigated system

In Figure 3.1 HTF is heated by solar collector and its temperature increased and this heat is transmitted to the storage tank during the charging cycle by melting all the available PCM and after some times and when it is needed this saved energy is transmitted to the building by the HTF in the discharging cycle. During discharging cycle the PCM is solidifies and releases energy. According to the schematic system and the above explanations, all the details of each design mentioned in table 3.1. In this system the surrounding temperature is assumed 15°C (288 ºK) ("Canada travel," 2012) for a country like Canada and the building should remain at constant temperature of 23°C (296 ºK) (ASHRAE, 1992; Henning, 2003).

Table 3.1 Details of each system's design due to melting temperature of PCMs

PCM type	**T_m ºC (°K)**	**T_{sin} ºC (°K)**	**T_{sout} ºC (°K)**	**T_{bin} ºC (°K)**	**T_{bout} ºC (°K)**
A32	32 (305)	66 (339)	61 (334)	24 (297)	29 (302)
A39	39 (312)	66 (339)	61 (334)	31 (304)	36 (309)
A42	42 (315)	66 (339)	61 (334)	34 (307)	39 (312)
A53	53 (326)	66 (339)	61 (334)	45 (318)	50 (323)
A55	55 (328)	66 (339)	61 (334)	47 (320)	52 (325)
A58	58 (331)	66 (339)	61 (334)	50 (323)	55 (328)

3.3 Input data

3.3.1 Case characteristics

As mentioned in system description section, Table 3.1 is the basic of the calculations.

3.3.2 Calculation of solar energy price

For calculating the cost of solar energy there are two viewpoints that show this calculation for PV type and solar heaters. Most of the researches (Leckner & Zmeureanu, 2011; Rowlands, 2005; Solangi et al., 2011) have shown the calculated price for electric solar power. In heating section Ramlow and Nusz (2010) have done a simple and very usable calculation method with reliable data. In this book some comparison between electrical, gas heater and solar one has been done. For its calculation the price of $ 9,000 is mentioned for equipment and installation and $ 2 per month for maintenance cost is predicted and the life cycle for this system is 40 years (Ramlow & Nusz, 2010). As mentioned before the annual energy production for this system is 4300 kWh which is the amount of required energy for a common house in Canada, Toronto city. Interest rate of 1% is assumed for Canada ("worldinterestrates," 2012).

Table 3.2 Life cycle cost for solar collector system in 40 years

year	Discount Factor	Present value($)	Cost at t($)	Produced energy(kWh)
1	1.00	9000	9000	4300
2	0.99	24	24	4300
3	0.98	24	24	4300
4	0.97	24	25	4300
5	0.96	24	25	4300
6	0.95	24	25	4300
7	0.94	24	25	4300
8	0.93	24	26	4300
9	0.92	24	26	4300

Table 3.2, continued

year	**Discount Factor**	**Present value($)**	**Cost at t($)**	**Produced energy(kWh)**
10	0.91	24	26	4300
11	0.91	24	27	4300
12	0.90	24	27	4300
13	0.89	24	27	4300
14	0.88	24	27	4300
15	0.87	24	28	4300
16	0.86	24	28	4300
17	0.85	24	28	4300
18	0.84	24	28	4300
19	0.84	24	29	4300
20	0.83	24	29	4300
21	0.82	24	29	4300
22	0.81	24	30	4300
23	0.80	24	30	4300
24	0.80	24	30	4300
25	0.79	24	30	4300
26	0.78	24	31	4300
27	0.77	24	31	4300
28	0.76	24	31	4300
29	0.76	24	32	4300
30	0.75	24	32	4300
31	0.74	24	32	4300
32	0.73	24	33	4300

Table 3.2, continued

year	Discount Factor	Present value($)	Cost at t($)	Produced energy(kWh)
33	0.73	24	33	4300
34	0.72	24	33	4300
35	0.71	24	34	4300
36	0.71	24	34	4300
37	0.70	24	34	4300
38	0.69	24	35	4300
39	0.69	24	35	4300
40	0.68	24	35	4300
Total			10,149	172,000

According to this data the total cost is $ 10,149 and the total energy production is 172,000 kWh. It should be considered that by having 1% interest rate during 40 years the price of energy will change in each year and this price should change according to discount factor value. Here try and error method is used to find the price of solar energy ($/kWh). So by estimating an assumption for the first year price for solar energy, the other year's price according to the assumed price is calculated. Then, by using these values total cost of consumed energy in 40 years will be computed, now the total cost of consumed energy in 40 years should be equal to total solar system cost ($) 10,149and if these two values are not equal, the price of solar energy for the first year should change to receive this equality. In the next step, solar exergy price should be calculated. In this regard, Dincer (2002) mentioned the value of 0.9 for the quality factor which is showing energy price ratio to the exergy price for solar energy. Thus, the price of exergy is calculated by having the price of energy and both of them are tabulated in table 3.3.

Table 3.3 Solar energy and exergy price for each year

year	Solar Energy ($)	Solar Exergy ($)
1	0.048	0.053
2	0.048	0.054
3	0.049	0.054
4	0.049	0.055
5	0.050	0.055
6	0.050	0.056
7	0.051	0.057
8	0.051	0.057
9	0.052	0.058
10	0.052	0.058
11	0.053	0.059
12	0.054	0.060
13	0.054	0.060
14	0.055	0.061
15	0.055	0.061
16	0.056	0.062
17	0.056	0.063
18	0.057	0.063
19	0.057	0.064

Table 3.3, continued

year	Solar Energy ($)	Solar Exergy ($)
20	0.058	0.064
21	0.059	0.065
22	0.059	0.066
23	0.060	0.066
24	0.060	0.067
25	0.061	0.068
26	0.062	0.068
27	0.062	0.069
28	0.063	0.070
29	0.063	0.070
30	0.064	0.071
31	0.065	0.072
32	0.065	0.073
33	0.066	0.073
34	0.067	0.074
35	0.067	0.075
36	0.068	0.076
37	0.069	0.076
38	0.069	0.077
39	0.070	0.078
40	0.071	0.079

3.3.3 PCM properties

PCM types which are used in this research came from PCM Product Company and are available in international market ("pcm products," 2012). According to the design melting temperature from 32 centigrade degree up to 58 are required and the available range in the market are available according to table 4. Moreover, each PCM's property is available in table 3.4.

Table 3.4 PCM details of each type

PCM Type	**T_m ºC (°K)**	**C_p (kj/kgk)**	**L (kj/kg)**	**Density (kg/m$^{3)}$**	**Price ($/kg)**
A32	32 (305)	2.20	130	845	6.5
A39	39 (312)	2.22	105	900	6.5
A42	42 (315)	2.22	105	905	6.5
A53	53 (326)	2.22	130	910	6.5
A55	55 (328)	2.22	135	905	6.5
A58	58 (331)	2.22	132	910	6.5

4 Chapter Four: Result and discussion

4.1 Energy efficiency

The amounts of energy efficiency, inlet energy form the solar collector to the storage tank, the outlet energy from the storage tank to the building, and the amount of lost energy during this process is calculated by using Equations (3.1), (3.2) and are tabulated in table 4.1.

Table 4.1 Energy efficiency, inserted, output and lost energy

PCM Type	Q_{in}(kJ/year)	Q_{out}(kJ/year)	En_{lost}(kJ/year)=[Q_{in}- Q_{out}]
A32	15,958,763	15,480,000	478,763
A39	15,958,763	15,480,000	478,763
A42	15,958,763	15,480,000	478,763
A53	15,958,763	15,480,000	478,763
A55	15,958,763	15,480,000	478,763
A58	15,958,763	15,480,000	478,763

As can be seen here the amount of energy lost for all designs are equal and is not changing because the temperature difference for inlet and outlet temperature was equal and concluding to equal energy analyses. But the price of energy and its amount is showing its effect on the total life cycle cost of the system.

4.2 Exergy efficiency

As explained before, by changing the melting temperature of PCMs the design will change and different exergy efficiencies will exist. In table 6 exergy efficiency in two steps of charging, discharging and total exergy efficiency is tabulated.

The energy efficiency of latent heat thermal storage (LHTS) in an adiabatic cycle is 100% because the total energy recovered during solidification and stored during melting of PCM in the storage, have the same amount and no heat leakage is happening and energy loss is zero. In realistic condition which is included in analysis and is non-adiabatic, destroyed quantity of the energy is not reflected in energy efficiency and just the energy loss comes into calculation. But in the exergy efficiency calculation which is based on second law of thermodynamic, the destroyed quantity as well as lost quantity takes into account. Due to the above reason in all conditions the exergy efficiency is much less than energy efficiency (Jegadheeswaran et al., 2010; MacPhee & Dincer, 2009).

By using Equations (3.4), (3.5), (3.6) and (3.7), amounts of total exergy efficiency and exergy lost are calculated and tabulated in table 4.2.

Table 4.2 Total exergy efficiency lost exergy

PCM Type	**Ex_{in} (kJ/year)**	**Ex_{stored} (kJ/year)**	**Ex_{out} (kJ/year)**	**Ex_{eff} Charging**	**Ex_{eff} Discharging**	**Ex_{eff} Totall**	**Ex_{lost}=[Ex_{in}- Ex_{out}] (kJ/year)**
A32	2,299,897	889,505	594,045	0.39	0.67	0.26	1,705,852
A39	2,299,897	1,227,597	934,033	0.53	0.76	0.41	1,365,864
A42	2,299,897	1,367,894	1,075,034	0.59	0.79	0.47	1,224,863
A53	2,299,897	1,860,224	1,569,453	0.81	0.84	0.68	730,445
A55	2,299,897	1,946,191	1,655,723	0.85	0.85	0.72	644,174
A58	2,299,897	2,073,193	1,783,141	0.90	0.86	0.78	516,756

In this table the amount of lost exergy is very important because it will be used in calculating the life cycle cost in the next step.

The data from total exergy efficiency are graphed in Figure 4.1and clearly shows that the amount of exergy efficiency is increasing by enlarging of melting temperature.

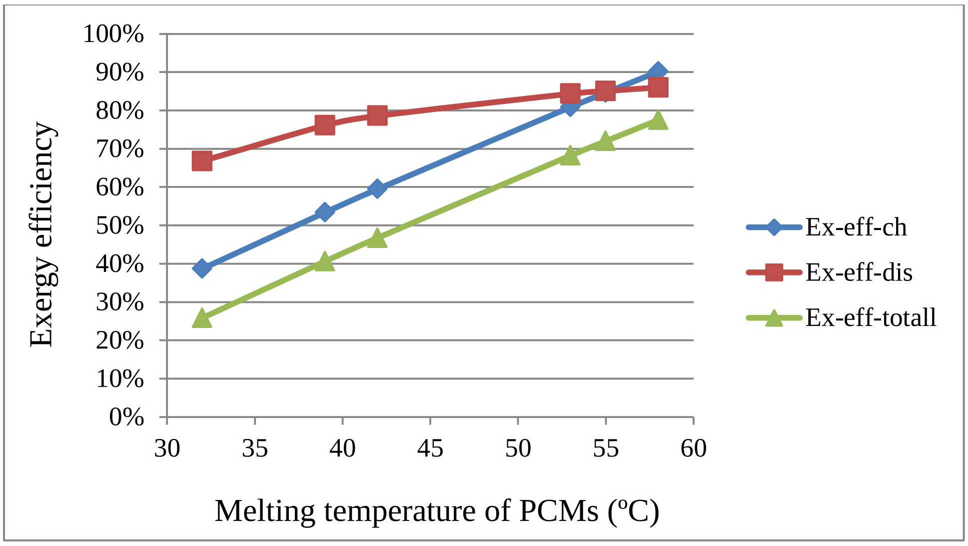

Figure 4.1 Exergy efficiency value in charging, discharging and total cycle

It clearly shows that the higher melting temperature will conclude to higher exergy efficiency. But according to the available designs this temperature range is limited.

4.3 Economic analyzes

In analyzes and designs of energy systems, technical discipline as thermodynamic view and economical view are came together to find the optimum design (Rosen et al., 2008). All of the previous calculations have been done to be used in this important section.

4.3.1 Correlation between energy and economy

Here energy associated with economy can be shown by the price of energy calculated for total life cycle of the system. Table 4.3 shows the costs of lost energy for each PCM type in 40 years.

Table 4.3 Total price of lost energy for 40 years

PCM Type	Total price of lost energy for 40 years ($)
A32	1,123,439
A39	1,123,439
A42	1,123,439
A53	1,123,439
A55	1,123,439
A58	1,123,439

As can be seen here the amount of 1,123,439 $ is calculated for all the losses for all types of PCM and is equal for all and is dependent from melting temperature of the PCM.

4.3.2 Correlation between exergy and economy

The amounts of the total price of exergy lost in the whole life cycle for each PCM is shown in table 4.4 in the next page.

Table 4.4 Total price of lost exergy for each PCM type in 40 years

PCM Type	Total price of exergy lost for 40 years ($)
A32	4,446,622
A39	3,561,181
A42	3,193,553
A53	1,904,470
A55	1,679,538
A58	1,347,324

As can be seen here the amount of exergy lost price is decreasing by increasing the melting temperature. The minimum exergy life cycle cost is for A58 type and is 1,347,324 $ in 40 years.

4.3.3 Total view of energy exergy and PCM price

By using Equation (3.9), the mass of used PCM (kg) is calculated and by having the price for 1 kg of PCM in table (3.4) the price of total used PCM for each melting temperature is computed. Table 4.5 shows the weight calculation, unit price and total price of PCM which has been used in the system.

Table 4.5 Weight calculation, unit price and total price of PCM

PCM Type	PCM weight (kg)	Unit price ($)	PCM price ($)
A32	336	6.5	2,186
A39	416	6.5	2,707
A42	416	6.5	2,707
A53	336	6.5	2,186
A55	324	6.5	2,105
A58	331	6.5	2,153

By addition of energy, exergy and PCM price the total life cycle cost is calculates and is tabulated in table 4.6.

Table 4.6 Total life cycle cost for each type of PCM

PCM Type	Total life cycle cost ($) (Energy, Exergy and PCM)
A32	5,573,248
A39	4,687,327
A42	4,319,699
A53	3,030,095
A55	2,805,082
A58	2,472,916

As can be seen here the price will decrease from the amount 5,573,248 for A32 type to the amount 2,472,916 for the A58 type and undoubtedly A58 is the bests type of PCM which can be used in the investigated system.

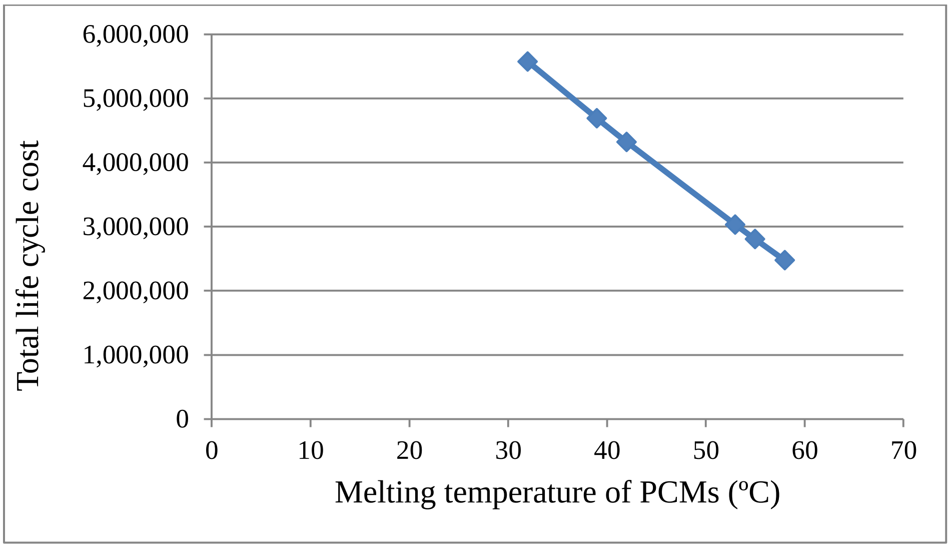

Figure 4.2 Total life cycle cost for each type of PCM

It is very important to know that which section have the biggest share in the total life cycle cost to show the importance of each part and Figure 4.3 drawn to make this important point more clear.

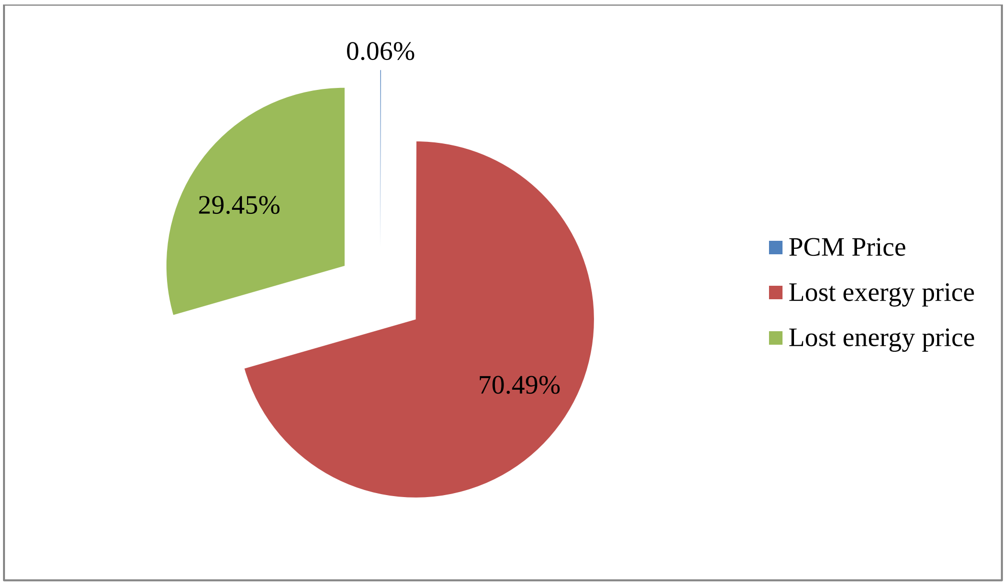

Figure 4.3 lost exergy, lost energy and PCM price share in total life cycle costs

As can be seen here exergy has higher impact in life cycle costs about three times of energy life cycle cost. This brilliant conclusion shows the emphasized impact of exergy amount in the efficient design of a system.

5 Chapter Five: Conclusions and recommendations

This chapter summarizes general conclusions that can be drawn from the results of this project and suggests areas where additional research or refinement is needed.

5.1 Conclusions

In this investigation the following conclusions are received:

- Energy and exergy efficiency of the system with different melting temperature of PCM is calculated.
- The price of solar energy and exergy are computed.
- Life cycle cost of the system with different melting temperature of PCM by considering price of energy, exergy and PCM are calculated.
- The most economical PCM type which can be used in the system by comparing total life cycle costs is chosen.

The most important finding here is that all the calculations show that the role of exergy in each melting temperature is more important than energy and price of PCM. The amount of average exergy share is about 70.49%, average energy is about 29.45% and average PCM price share is about 0.06%. It shows that for having a more optimum design the exergy concept should be considered extremely in system designs and policy makings. The concept of exergy, because of its vast area of impact, should be used as a brilliant tool for policy makers to put new rules against companies which design inefficient exergetic systems and help them to improve their diagram to achieve more efficient models by using this concept.

This work shows the equivalent money effect on the environment and could be support by green movements which are trying to show the importance of natural resources for future generations.

5.2 Recommendations for future work

The price of solar energy for heat usage is not calculated clearly and needs more investigation especially by considering the interest rate in each country, because the amount of interest rate is very critical for the solar heating price.

The concept of quality factor must be updated and investigated for showing the ratio of energy price to the exergy, which is not calculated clearly in publications.

For calculation of exergy price for each resource is seems that there is lack of data and has not been done for many sources.

Bibliography

Adine, H. A., & El Qarnia, H. (2009). Numerical analysis of the thermal behaviour of a shell-and-tube heat storage unit using phase change materials. *Applied Mathematical Modelling, 33*(4), 2132-2144.

Aghbalou, F., Badia, F., & Illa, J. (2006). Exergetic optimization of solar collector and thermal energy storage system. *International journal of heat and mass transfer, 49*(7), 1255-1263.

ASHRAE, A. S. (1992). Standard 55-1992 "Thermal Environmental Conditions for Human Occupancy". *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA*.

Bakenhus, B. H. (2000). Ice storage project. *ASHRAE journal, 42*(5), 64-66.

Barkmann, H. G., & Wessling, F. (1975). *Use of buildings structural components for thermal storage*.

Bruno, F., & Saman, W. (2002). *Testing of a PCM energy storage system for space heating*.

Buddhi, D., & Sahoo, L. (1997). Solar cooker with latent heat storage: design and experimental testing. *Energy conversion and management, 38*(5), 493-498.

Calmac International. (2011).

Canada travel. (2012). Retrieved 27 Aug 2012, from http://gocanada.about.com/od/canadatravelplanner/tp/temperatures_canada.htm

Cassedy, E. S. (2000). *Prospects for sustainable energy: a critical assessment*: Cambridge Univ Pr.

Demirel, Y., & Öztürk, H. H. (2006). Thermoeconomics of seasonal latent heat storage system. *International journal of energy research, 30*(12), 1001-1012.

Deng, J., Wang, R., Wu, J., Han, G., Wu, D., & Li, S. (2008). Exergy cost analysis of a micro-trigeneration system based on the structural theory of thermoeconomics. *Energy, 33*(9), 1417-1426.

Dincer, I. (2002). The role of exergy in energy policy making. *Energy Policy, 30*(2), 137-149.

Dincer, I., & Rosen, M. (2010). *Thermal energy storage: systems and applications*: Wiley.

Edgerton, R. H. (1982). Available energy and environmental economics.

El-Dessouky, H., & Al-Juwayhel, F. (1997). Effectiveness of a thermal energy storage system using phase-change materials. *Energy conversion and management, 38*(6), 601-617.

Erek, A., & Dincer, I. (2008). An approach to entropy analysis of a latent heat storage module. *International Journal of Thermal Sciences, 47*(8), 1077-1085.

Ezan, M. A., Ozdogan, M., Gunerhan, H., Erek, A., & Hepbasli, A. (2010). Energetic and exergetic analysis and assessment of a thermal energy storage (TES) unit for building applications. *Energy and Buildings, 42*(10), 1896-1901.

Farid, M. M., & Kanzawa, A. (1989). Thermal performance of a heat storage module using PCM's with different melting temperatures: mathematical modeling. *Journal of solar energy engineering, 111*, 152.

Gong, Z. X., & Mujumdar, A. S. (1997). Thermodynamic optimization of the thermal process in energy storage using multiple phase change materials. *Applied thermal engineering, 17*(11), 1067-1083.

Gumus, M. (2009). Reducing cold-start emission from internal combustion engines by means of thermal energy storage system. *Applied thermal engineering, 29*(4), 652-660.

Hawes, D., Feldman, D., & Banu, D. (1993). Latent heat storage in building materials. *Energy and buildings, 20*(1), 77-86.

Henning, H. (2003). Solar Assisted Air Conditioning in Buildings–A Handbook for Planners.

Hepbasli, A. (2008). A study on estimating the energetic and exergetic prices of various residential energy sources. *Energy and buildings, 40*(3), 308-315.

Inaba, H., & Tu, P. (1997). Evaluation of thermophysical characteristics on shape-stabilized paraffin as a solid-liquid phase change material. *Heat and Mass Transfer, 32*(4), 307-312.

Ismail, K., & Henríquez, J. (2001). Thermally effective windows with moving phase change material curtains. *Applied thermal engineering, 21*(18), 1909-1923.

Ismail, K., & Henríquez, J. (2002). Parametric study on composite and PCM glass systems. *Energy conversion and management, 43*(7), 973-993.

Jagoda, K., Lonseth, R., Lonseth, A., & Jackman, T. (2011). Development and commercialization of renewable energy technologies in Canada: An innovation system perspective. *Renewable energy, 36*(4), 1266-1271.

Jegadheeswaran, S., Pohekar, S., & Kousksou, T. (2010). Exergy based performance evaluation of latent heat thermal storage system: A review. *Renewable and Sustainable Energy Reviews, 14*(9), 2580-2595.

Kaygusuz, K. (2003). Phase change energy storage for solar heating systems. *Energy sources, 25*(8), 791-807.

Koca, A., Oztop, H. F., Koyun, T., & Varol, Y. (2008). Energy and exergy analysis of a latent heat storage system with phase change material for a solar collector. *Renewable Energy, 33*(4), 567-574.

Kotas, T. (1995). The exergy method of thermal power plants: Malabar, FL: Krieger Publishing Company.

Kousksou, T., El Rhafiki, T., Arid, A., Schall, E., & Zeraouli, Y. (2008). Power, Efficiency, and Irreversibility of Latent Energy Systems. *Journal of thermophysics and heat transfer, 22*(2), 234-239.

Kousksou, T., Strub, F., Castaing Lasvignottes, J., Jamil, A., & Bedecarrats, J. (2007). Second law analysis of latent thermal storage for solar system. *Solar energy materials and solar cells, 91*(14), 1275-1281.

Kowata, H., Sase, S., Ishii, M., & Moriyama, H. (2002). *Cold water thermal storage with phase change materials using nocturnal radiative cooling for vegetable cooling*.

Krane, R. J. (1987). A second law analysis of the optimum design and operation of thermal energy storage systems. *International journal of heat and mass transfer, 30*(1), 43-57.

Lane, G. A. (1983). Solar heat storage: latent heat materials.

Leckner, M., & Zmeureanu, R. (2011). Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. *Applied Energy, 88*(1), 232-241.

Li, Y. Q., He, Y. L., Wang, Z. F., Xu, C., & Wang, W. (2012). Exergy analysis of two phase change materials storage system for solar thermal power with finite-time thermodynamics. *Renewable Energy, 39*(1), 447-454.

Lozano, M., & Valero, A. (1993). Theory of the exergetic cost. *Energy, 18*(9), 939-960.

MacPhee, D., & Dincer, I. (2009). Performance assessment of some ice TES systems. *International Journal of Thermal Sciences, 48*(12), 2288-2299.

MacPhee, D., & Dincer, I. (2009). Thermodynamic analysis of freezing and melting processes in a bed of spherical PCM capsules. *Journal of solar energy engineering, 131,* 031017.

Mawire, A., & McPherson, M. (2008). Experimental characterisation of a thermal energy storage system using temperature and power controlled charging. *Renewable Energy, 33*(4), 682-693.

Mearig, T., Coffee, N., Morgan, M., & Section, A. D. o. E. S. S. F. (1999). *Life Cycle Cost Analysis Handbook: Draft*: State of Alaska, Department of Education and Early Development, Education Support Services/Facilities.

Mehling, H., Cabeza, L., Hippeli, S., & Hiebler, S. (2002). *Improvement of stratified hot water heat stores using a PCM-module*.

Mehling, H., Cabeza, L., Hippeli, S., & Hiebler, S. (2003). PCM-module to improve hot water heat stores with stratification. *Renewable energy, 28*(5), 699-711.

Mehling, H., Krippner, R., & Hauer, A. (2002). *Research project on PCM in wood-lightweight-concrete*.

Moran, M., & Sciubba, E. (1994). Exergy analysis: principles and practice. *Journal of Engineering for Gas Turbines and Power, 116,* 285.

Moran, M. J. (1982). Availability analysis: a guide to efficient energy use.

Morikama, Y., Suzuki, H., Okagawa, F., & Kanki, K. (1985). *A development of building elements using PCM*.

Nicholas, G. R. (1971). The entropy law and the economic process. *Cambridge, Mass./London: Harvard UP*.

Nieuwlaar, E., & Dijk, D. (1993). Exergy evaluation of space-heating options. *Energy, 18*(7), 779-790.

Omer, S., Riffat, S., & Ma, X. (2001). Experimental investigation of a thermoelectric refrigeration system employing a phase change material integrated with thermal diode (thermosyphons). *Applied thermal engineering, 21*(12), 1265-1271.

Öztürk, H. H. (2005). Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating. *Energy Conversion and Management, 46*(9), 1523-1542.

Pasupathy, A., Velraj, R., & Seeniraj, R. (2008). Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renewable and Sustainable Energy Reviews, 12*(1), 39-64.

pcm products. (2012). Retrieved 5/8/2012, 2012, from http://www.pcmproducts.net/

Pu, J., Liu, G., & Feng, X. (2010). Application of the cumulative exergy approach to different air conditioning systems. *Energy and buildings, 42*(11), 1999-2004.

Ramayya, A. V., & Ramesh, K. (1998). Exergy analysis of latent heat storage systems with sensible heating and subcooling of PCM. *International journal of energy research, 22*(5), 411-426.

Ramlow, B., & Nusz, B. (2010). *Solar Water Heating: A comprehensive guide to solar water and space heating systems*: New Society Pub.

Riffat, S., Omer, S., & Ma, X. (2001). A novel thermoelectric refrigeration system employing heat pipes and a phase change material: an experimental investigation. *Renewable energy, 23*(2), 313-323.

Rosen, M. (1992). Appropriate thermodynamic performance measures for closed systems for thermal energy storage. *ASME Journal of Solar Energy Engineering, 114*, 100-105.

Rosen, M. (1992). Evaluation of energy utilization efficiency in Canada using energy and exergy analyses. *Energy, 17*(4), 339-350.

Rosen, M., & Dincer, I. (2003). Exergy–cost–energy–mass analysis of thermal systems and processes. *Energy conversion and management, 44*(10), 1633-1651.

Rosen, M., & Dincer, I. (2003). Exergy methods for assessing and comparing thermal storage systems. *International journal of energy research, 27*(4), 415-430.

Rosen, M. A., Dincer, I., & Kanoglu, M. (2008). Role of exergy in increasing efficiency and sustainability and reducing environmental impact. *Energy Policy, 36*(1), 128-137.

Rowlands, I. H. (2005). Solar PV electricity and market characteristics: two Canadian case-studies. *Renewable Energy, 30*(6), 815-834.

Safarik, M., Gramlich, K., & Schammler, G. (2002). *Solar absorption cooling system with 90 C–latent heat storage*.

Salyer, I. O., & Sircar, A. K. (1990). *Phase change materials for heating and cooling of residential buildings and other applications*.

Sari, A., & Kaygusuz, K. (2000). Energy and exergy calculations of latent heat energy storage systems. *Energy sources, 22*(2), 117-126.

Sciubba, E. (2001). Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. *Exergy, an international journal, 1*(2), 68-84.

Sciubba, E., Bastianoni, S., & Tiezzi, E. (2008). Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy. *Journal of environmental management, 86*(2), 372-382.

Seeniraj, R., Velraj, R., & Lakshmi Narasimhan, N. (2002). Thermal analysis of a finned-tube LHTS module for a solar dynamic power system. *Heat and Mass Transfer, 38*(4), 409-417.

Shah, R. K., Sekulić, D. P., & ., K. (2003). *Fundamentals of heat exchanger design*: Wiley Online Library.

Shapiro, M., Feldman, D., Hawes, D., & Banu, D. (1987). Thermal storage in drywall using organic phase-change material. *Passive Sol. J.;(United States), 4*(4).

Sharma, A., Tyagi, V., Chen, C., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*(2), 318-345.

Sokolov, M., & Keizman, Y. (1991). Performance indicators for solar pipes with phase change storage. *Solar energy, 47*(5), 339-346.

Solangi, K., Islam, M., Saidur, R., Rahim, N., & Fayaz, H. (2011). A review on global solar energy policy. *Renewable and Sustainable Energy Reviews, 15*(4), 2149-2163.

Telkes, M. (1975). *Thermal storage for solar heating and cooling*.

Tozer, R., Valero, A., & Lozano, M. A. (1999). SYMPOSIUM PAPERS-CH-99-23-Second Law Studies of Systems and Processes-Thermoeconomics Applied to HVAC Systems. *ASHRAE Transactions-American Society of Heating Refrigerating Airconditioning Engin, 105*(1), 1247-1255.

Vakilaltojjar, S., & Saman, W. (2001). Analysis and modelling of a phase change storage system for air conditioning applications. *Applied thermal engineering, 21*(3), 249-263.

Valero, A. (2006). Exergy accounting: Capabilities and drawbacks. *Energy, 31*(1), 164-180.

Valero, A., Serra, L., & Lozano, M. (1993). Structural theory of thermoeconomics. *ASME, NEW YORK, NY,(USA). 30*, 189-198.

Velraj, R., Anbudurai, K., Nallusamy, N., & Cheralathan, M. (2002). *PCM based thermal storage system for building air conditioning at Tidel Park, Chennai*.

Velraj, R., Seeniraj, R., Hafner, B., Faber, C., & Schwarzer, K. (1999). Heat transfer enhancement in a latent heat storage system. *Solar energy, 65*(3), 171-180.

Watanabe, T., & Kanzawa, A. (1995). Second law optimization of a latent heat storage system with PCMs having different melting points. *Heat Recovery Systems and CHP, 15*(7), 641-653.

worldinterestrates. (2012). Retrieved 23 Aug. 2012, 2012, from http://www.worldinterestrates.info/

Xiang, J., Zhao, J., & Qin, N. (2010). Exergetic cost analysis of a space heating system. *Energy and buildings, 42*(11), 1987-1994.

Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. [doi: 10.1016/S1359-4311(02)00192-8]. *Applied Thermal Engineering, 23*(3), 251-283.