

**THE DEVELOPMENT OF A LATENT HEAT THERMAL ENERGY STORAGE
SYSTEM USING A PHASE CHANGE MATERIAL FOR SOLAR ENERGY
APPLICATION**

by

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A dissertation submitted to the Faculty of Engineering in partial fulfillment of the academic requirements for the Master of Science degree: Environmental Engineering in the Department of Civil Engineering, University of KwaZulu-Natal, Howard College.

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The work presented in this dissertation was carried out in the Department of Chemical Engineering, Mangosuthu University of Technology, from August 2006 to August 2008, under the supervision of Prof D.R. Arnold (UKZN) and co-supervisor Mr Y.D. Attah (MUT).

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ABSTRACT

This investigation forms part of an attempt to provide an alternative to conventional power generation technologies that use fossil fuels which have impact on global warming. The field of this investigation covers the development of a latent heat thermal storage system which has a potential of conserving available solar energy. The advantages of using thermal energy storage that have been found previously include reduced energy cost, energy consumption, equipment size and pollutant emissions, also increased flexibility of operation, efficiency and effectiveness of equipment utilization.

Traditionally, available heat has been stored in the form of sensible heat (typically by raising the temperature of the energy storage medium) for later use. Latent heat storage on the other hand, is a young and developing technology which has found considerable interest in recent times due to its advantages over sensible heat storage which include smaller temperature swing, smaller size and lower weight per unit of storage capacity. It has been demonstrated that, for the development of a latent heat thermal energy storage system, the choice of the phase change material (PCM) as well as the heat transfer mechanism in the PCM play important roles. In this study, a suitable phase change material and an appropriate heat transfer enhancement technique are identified for utilization in a proposed latent heat thermal energy storage system. Also included, is the design of the proposed heat storage system.

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LIST OF SYMBOLS**Nomenclature**

A_c	Cross-sectional area, [m ²]
A_s	Surface area, [m ²]
C_p	Specific heat capacity, [J/kgK]
D	Diameter, [m]
G	Mass velocity, [kg/m ² s]
g	Gravitational acceleration, [m/s ²]
h	Heat transfer coefficient, [W/m ² K]
j_H	Colburn j factor for heat transfer
k	Thermal conductivity, [W/m.K]
L	Characteristic length, [m]
m	Mass, [kg]
\dot{m}	Mass flow rate, [kg/s]
N_T	Number of tubes
Q	Rate of heat flow, [W]
R_f	Fouling factor, [m ² .K/W]
T_m	Mean temperature, [°C]
T_∞	Fluid temperature, [°C]
T_s	Surface temperature, [°C]
ΔT	Temperature difference, [K or °C]
t	Time, [s]
u	Fluid velocity, [m/s]
U	Overall heat transfer coefficient, [W/m ² K]

Dimensionless groups

Gr Grashof number, $g\beta(T_s - T_\infty)L^3/\nu^2$

Nu Nusselt number, hL/k_f

Pr Prandtl number, $C_p\mu/k_f$

Ra Rayleigh number, $Gr.Pr$

Re Reynolds number, $\rho u D/\mu$

Greek letters

β Volumetric thermal expansion coefficient, [K^{-1}]

ε_{fin} Fin effectiveness

η_{fin} Fin efficiency, [%]

μ Dynamic viscosity, [kg/s.m]

ν Kinematic viscosity, [m^2/s]

ρ Mass density, [kg/m^3]

σ Standard deviation

σ^2 Variance

Abbreviations

PCM Phase change material

PTSC Parabolic trough solar collector

RT6 Rubitherm phase change material melting at 6 °C

RT27 Rubitherm phase change material melting at 28 °C

RT35 Rubitherm phase change material melting at 35 °C

RT100 Rubitherm phase change material melting at 99 °C

CHAPTER 1

THE PROBLEM AND ITS SETTING

1.1 Introduction

All major conservation bodies urgently need to conserve fuel and power resources as a result of shrinking fossil fuel resources, growing global energy demands and the impact of global warming. Therefore, the way in which power is generated and used needs to be reassessed. Renewable energy technologies such as solar energy, wind energy, hydropower and biomass conversion have the potential for conservation of fuel and power resources by providing an alternative to conventional power generation technologies that use fossil fuels [8]. The process of introducing renewable energy is still in its infancy and the opportunity cost is only now becoming clear.

Solar thermal energy systems remain among the most promising of the renewable energy technologies. The parabolic trough system, the central receiver and the solar chimney are some of the technologies that offer enormous potential for electricity production in South Africa, a country with abundant levels of solar irradiance. Of these three technologies, only the parabolic trough system has been commercialized, giving it a clear advantage. Parabolic trough system is a cost-effective solar technology with potential for significant cost reduction and has an advantage over many other solar energy collectors in that it can be augmented with thermal energy storage, allowing it to provide power on demand [12, 13]. Much of the research on renewable energy is done at academic institutions, for example Mangosuthu University of Technology. Against a backdrop of heightened interest in solar thermal power generation, the continued development of Mangosuthu University of Technology's solar thermal research programme is motivated by the desire to further develop South Africa's capacity in alternative energy systems, in general, and solar energy in particular.

The major problem with solar energy is that the availability of collected solar energy is unpredictable, intermittent and is often subject to interruption due to changes in weather. As a result, a form of thermal energy storage is required to match the supply with the demand. Energy storage plays important roles in conserving available energy and improving its utilization, since many energy sources are intermittent in nature. The successful application of thermal energy storage in the conservation of energy depends to a large extent on the method of energy storage used. Thermal energy storage can either be achieved by:

1. Using sensible heat storage where energy is stored by raising the temperature of a storage medium or
2. Latent heat storage where energy is stored by changing the physical state of the storage medium.

The latent heat method of storage which uses a phase change material as a heat storage medium provides a feasible means of storing solar thermal energy. It comprises significantly smaller volumes and higher energy storage density with a smaller temperature swing as compared to alternative materials storing only sensible heat.

1.2 The Problem Statement

The main objective of this investigation is to evaluate selected phase change materials in terms of their characteristics for storing thermal energy for the purpose of identifying phase change materials with the potential of conserving available solar energy and to explore their utilization.

1.3 Hypothesis

If the relationship between the selected phase change materials and the characteristics for storing thermal energy can be demonstrated then the potential for conserving available solar energy can be explored and methods to utilize the stored energy can be investigated.

1.4 Assumptions

For this investigation it is also assumed that the chemical analyses of the materials included in the investigation are as reported on the data sheets provided.

1.5 Delimitations

This study will only investigate characteristics of phase change materials that have a bearing on thermal energy storage potential.

1.6 The Importance of the Study

Not all phase change materials are suitable for thermal energy storage. Some materials may have excellent heat absorption characteristics with poor capacities to release the energy to the environment. Some materials have good heat storage capacities but exhibit problems such as phase segregation and super-cooling which could negatively affect the performance of the energy storage system. Therefore there is a need to investigate the capability of different phase change materials to store and release thermal energy when required with the purpose of developing a storage system which has a potential of conserving available solar energy.

1.7 Outline of Chapters

The research and findings are presented in the following chapters of the dissertation:

Chapter 1: Introduction to the problem and its setting.

Chapter 2: focuses on the review of related literature.

Chapter 3: presents the general procedure used in carrying out the research work. This includes the research methodology, description of data, methodology and statistical processing of the results.

Chapter 4: presents the experimental results and discussion for the identification of the suitable phase change material.

Chapter 5: presents the results and discussion for the selection of the appropriate heat transfer technique. This chapter also includes the result for the design of the proposed thermal energy storage system.

Chapter 6: concludes the dissertation by providing a summary of the findings and final comments on the results presented in chapters 4 and 5.

CHAPTER 2

REVIEW OF RELATED LITERATURE

2.1 Conservation of fuel

Most electricity generating power plants use fossil fuels as a source of thermal energy. At the 1992 Conference on Climate Change, the United Nations Inter-Governmental panel concluded that a 60% reduction in the use of fossil fuel would have to be made in order to reduce the level of CO₂ emissions by the year 2005 [1]. This process would make a major contribution to the conservation of fuel by enforcing the use of alternative and renewable energy sources. This has tremendous implications in the residential building sector as they account for over half of the fuel consumed, with 60% of emissions being attributed to lighting and heating buildings [1].

The amount of solar energy reaching the earth's surface in a year is approximately 1000 times that obtained from burning all fossil fuels extracted during the same period [2]. Consequently, the use of solar power in residential buildings has enormous potential in the conservation of fossil fuels.

2.2 Global Warming

The latest research on climate change from the scientific community worldwide predicts that we are entering a period of global warming brought about by anthropogenic emissions of greenhouse gases such as carbon dioxide, methane, and others [3]. They are called greenhouse gases because they trap heat in the atmosphere just as greenhouse glass traps heat in a greenhouse.

In order to maintain a constant environmental temperature, the earth has to radiate back to space the same amount of radiated energy from the sun. This radiation goes up to the atmosphere, where a range of molecules, most importantly CO₂, forms a blanket which reduces reflected radiation, resulting in warming the surface of the earth. This blanket works like a glass, whereby it is somewhat transparent to high energy sunlight yet opaque to the lower energy heat escaping from the earth. This process is referred to as global warming [3].

It is important to distinguish between normal and high levels of greenhouse gases. The normal levels help to keep the earth at its natural temperature while high levels make the earth warmer. This high levels global warming has a negative impact on our economy, human health and loss of a wide range of plant and animal species. Therefore if we are to sustain a healthy environment and economy over long term, an understanding of how man contribute to the high levels global warming and what needs to be done about it is of crucial importance.

There is increasing evidence that the measured atmospheric increase in heat trapping gases, principally CO₂, is related to the burning of fossil fuels [4]. The majority of scientists agree that global warming caused by the burning of fossil fuels will continue to raise global average temperature by 1.8 to 6.3°C over the next hundred years. They addressed global warming from both economic and environmentally responsible point of view by recommending elimination of fuel subsidies and increased support for renewable energy technologies such as solar thermal energy.

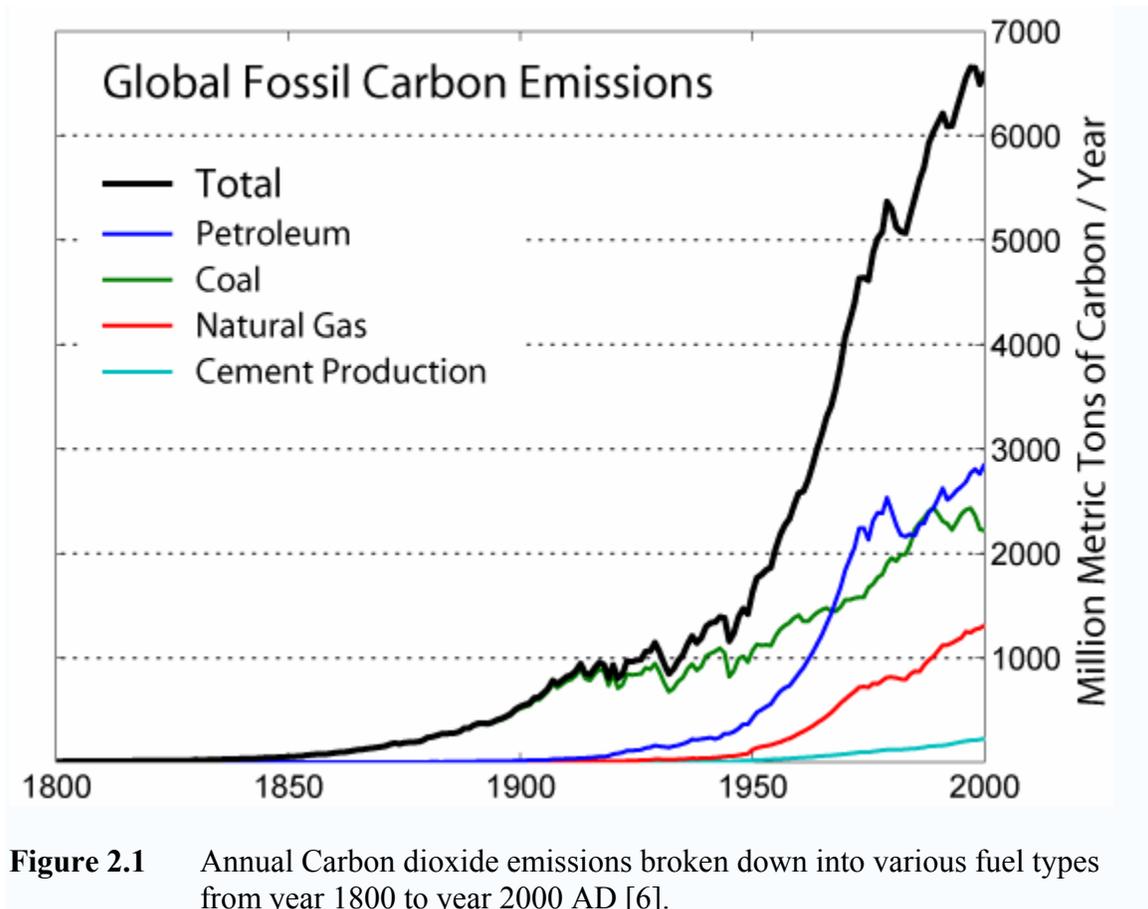
The importance of being able to develop a system which can harness the thermal energy of the sun is therefore obvious.

2.3 Power Sources

2.3.1 Fossil fuels

Coal, oil and gas are called fossil fuels because they have been formed from fossilized remains of prehistoric plants. They provide about 66% of the world's electrical power while contributing 95% to the world's total energy supply [5]. This shows that large amount of power is generated using fossil fuels. Although a large amount of energy can be generated using fossil fuels, the by-product of its use is their contribution to the high level of pollution in the environment. The burning of fossil fuels is the largest source of CO₂ emissions, which causes the greenhouse effect.

The increased rate of fossil fuels consumption and the increased rate of CO₂ emissions between years 1800 and 2000 are illustrated in Figure 2.1.



The use of fossil fuels depends upon their availability because they are finite resources. The fossil fuels, once they are burned, cannot be renewed and therefore their availability is decreasing. The principle of supply and demand suggests that as fossil fuels supplies diminish, prices will rise. Therefore higher prices will lead to increased usage of alternative energy sources because it will become more affordable. The significant employment of alternative energy sources such as renewable energy sources and scientific advances would reduce the dependency on fossil fuels [6].

A global movement toward the generation of renewable energy is therefore underway to help meet the increased global energy needs and to reduce the level of pollution in the environment.

2.3.2 Renewable Energy Sources

About two billion of the world's population still does not have access to the power grid which gives rise to an ever increasing global energy demand [7]. In order to be able to meet this demand, more attention to the source of energy is needed because it has a significant impact on the environment and on the health of millions of people, plants and animals. Therefore, cleaner power sources should be used in order to reduce pollution and thereby ensuring reduction in the level of global warming. Renewable energy sources present us with the potential to progress without threatening our future. In theory it is possible to cut down the energy use in half by using cost effective renewable energy sources available today. A 50% reduction in fossil fuel energy use resulting from the use of renewable energy translates into a 50% reduction in pollution [3].

Renewable energy sources such as solar energy, wind energy, water power, geothermal energy and biomass conversion are very important alternatives for addressing climate change, as well dwindling energy supplies and rising world energy consumption. They all offer potential for replacing conventional fossil fuels power plants, though not yet on the same scale.

Table 2.1 Comparison between the current use and future utilization potential of different renewable energy sources [8]

The Renewable Energy Resource Base (GW)			
	Current use (2001)	Technical potential	Theoretical potential
Hydropower	285	1,586	4,661
Biomass energy	1,586	>8,752	91,958
Wind energy	3.8	20,294	190,259
Solar energy	3.2	>49,943	123,668,189
Geothermal energy	19	--	--
Ocean energy	not estimated	not estimated	234,652
Total	1,903	>57,078	>126,839,168

Table 2.1 summarizes the energy that can be produced using renewable sources globally. It is shown that solar energy has the highest future utilization potential as compared to the other renewable energy sources. Given South Africa's sunny climate, research into harnessing solar energy is therefore a logical choice. The exploratory work on trough solar energy collector already completed at Mangosuthu University of Technology forms the basis to take the energy trapping process further.

2.4 Solar Energy

Solar energy describes a number of methods of harnessing energy from the sun. Evidence of the desire to harness solar energy can be found in the designs of many traditional building methods for many centuries. Recently the challenge of harnessing solar energy has become of increasing interest in developed countries as the environmental costs and the impact of non-renewable nature of fossil fuels are realized. Solar energy, for example solar panels, is already in widespread use where access to other power supplies is absent, such as in remote locations and in space [9].

Solar power has enormous potential for use because the solar energy that reaches the surface of the earth is approximately 30000 times the amount of energy needed to satisfy human needs [10]. It is also a clean source of energy because it does not produce any CO₂ and it is totally renewable. However there are several major problems with harvesting solar energy because its availability is unpredictable, intermittent and is often subject to changes in the weather. Due to the harvesting problems and the fact that for approximately half of the 8760 hours per year any location is in darkness, the importance of being able to store solar thermal energy for use when the sun is not shining, is critical.

2.4.1 Solar energy harvesting methods

2.4.1.1 Parabolic trough collector

The parabolic trough is the most successful and cost-effective concentrated solar power system design at present [12, 13]. It uses a curved trough which reflects sunlight onto a hollow tube running along above the trough as shown in Figure 2.2.



Figure 2.2. Parabolic trough solar collector with glass-shielded receiver during operation at Mangosuthu University of Technology [13]

The whole trough tilts through the course of the day so that light remains focused on the hollow tube. A fluid passes through the tube and becomes heated. Full-scale parabolic trough systems consist of many parabolic troughs laid out in parallel over a large area of land. A solar thermal system using this principle is in operation in California in the United States. It produces approximately 330 MW of power which is currently the largest operational solar thermal energy system [11].

Other parabolic trough systems are under development, which create steam directly in the tubes. This concept is thought to lead to cheaper overall designs. A small scale commercial parabolic trough solar collector has been designed and constructed at Mangosuthu University of Technology in Durban, KwaZulu-Natal for the purpose of investigating the problems associated with harnessing and storing solar energy [13].

2.5 Thermal Energy Storage

Energy storage is a fundamental requirement of all solar energy systems. It plays important roles in conserving available solar energy and improving its utilization, since many energy sources are intermittent in nature. Because solar energy is available only during the day an efficient thermal energy storage system is a critical requirement to ensure that energy is available during the night. Therefore in a conventional power generation station, more efficient power production can be achieved by load shifting the stored thermal energy. The success of load shifting will depend to a large extent upon the method of energy storage used. The designs of heat storage units, the sensible heat and latent heat systems are well described in textbooks [14, 15]. These concepts will be discussed separately.

2.5.1 Sensible heat storage

Thermal energy storage can take the form of sensible heat storage where energy is stored by raising the temperature of a storage medium. This is the most commonly used method of thermal storage e.g. in solar heating system, water is used for heat storage in liquid based systems. Rock beds are used for air based systems. [18].

There are two major drawbacks of using sensible storage, namely:

1. the volume of the storage medium is heavy and bulky
2. energy cannot be stored or released at a constant temperature, and
3. this method is also inefficient as it takes less energy to raise the temperature of a material than it requires to change a solid into a liquid. Consequently to store the same amount of energy, significantly large quantities of storage medium are required for sensible heat storage in comparison to latent heat storage method.

These disadvantages of sensible heat over latent heat are illustrated in Table 2.2. The sensible heat using a rock bed and water is compared to the latent heat using organic and non-organic compounds. The advantage of the latent heat is clear from the comparison of the volume and mass of the storage unit required for storing a certain amount of heat.

Table 2.2 Comparison between the different methods of heat storage [28]

Property	Rock	Water	Organic PCM	Inorganic PCM
Density, kg/m ³	2240	1000	800	1600
Specific heat, kJ/kg.K	1.0	4.2	2.0	2.0
Latent heat, kJ/kg	-	-	190	230
Latent heat, kJ/m ³	-	-	152	368
Storage mass for 10 ⁶ J, kg	67000	16000	5300	4350
Storage volume for 10 ⁶ J, m ³	30	16	6.6	2.7
Relative storage mass	15	4	1.25	1.0
Relative storage volume	11	6	2.5	1.0

Figure 2.3 also illustrates a comparison between latent heat and sensible heat systems. It is shown that the storage potential of the latent heat system is more efficient. The sensible heat capacity of concrete is approximately 1.0 kJ.kg⁻¹[19], compared with calcium chloride which during phase transition can store or release 190 kJ.kg⁻¹[21]. In order for concrete to store the same amount of energy i.e. 190 kJ, concrete has to be heated up to 190°C, otherwise large amount of concrete is required. Due to the large volume of material required, sensible heat storage is not suitable for large applications because it will take up a lot of space which may have major cost implications and could attract unfavourable criticism from environmentalists.

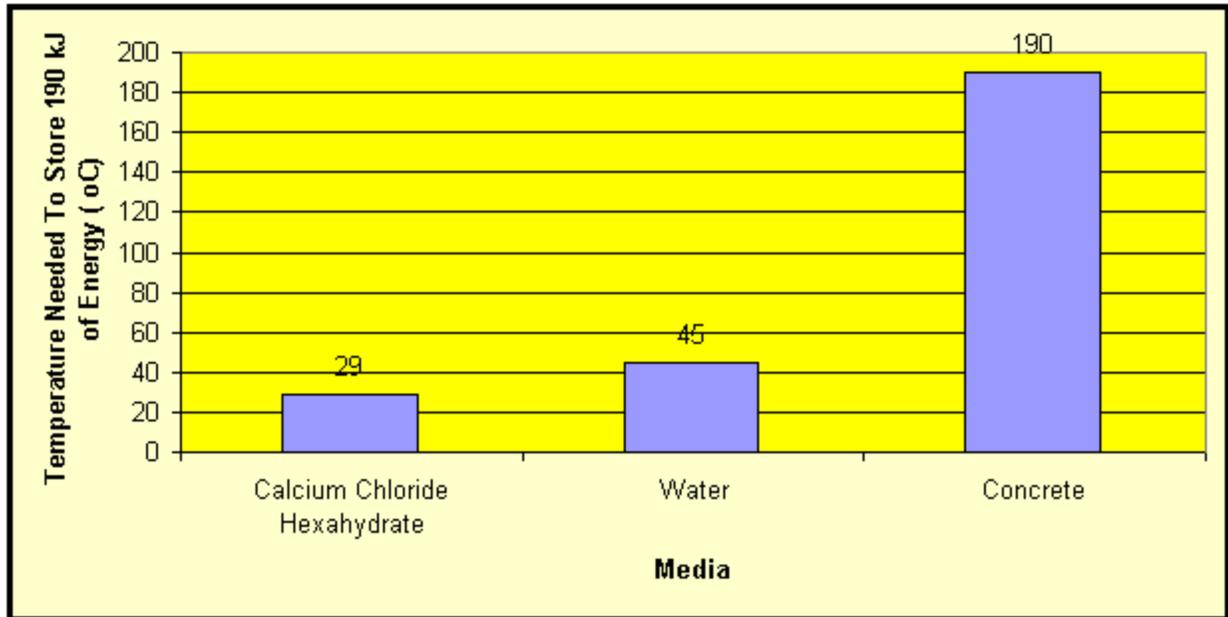


Figure 2.3 Comparison between the temperature required to store 190 kJ of energy as latent heat and that required to store the same amount as sensible heat [17]

2.5.2 Latent heat

2.5.2.1 Theory

Latent heat is the amount of energy in the form of heat released or absorbed by a substance during a change of phase (i.e. solid, liquid or gas). There are different phase transitions that exist:

- solid to liquid (melting) = heat of fusion
- liquid to solid (freezing) = heat of fusion
- liquid to gas (evaporation) = heat of vaporization
- gas to liquid (condensation) = heat of vaporization
- solid to gas (sublimation) = heat energy added
- gas to solid (deposition) = heat energy removed [16]

These different phase transitions are illustrated in Figure 2.4.

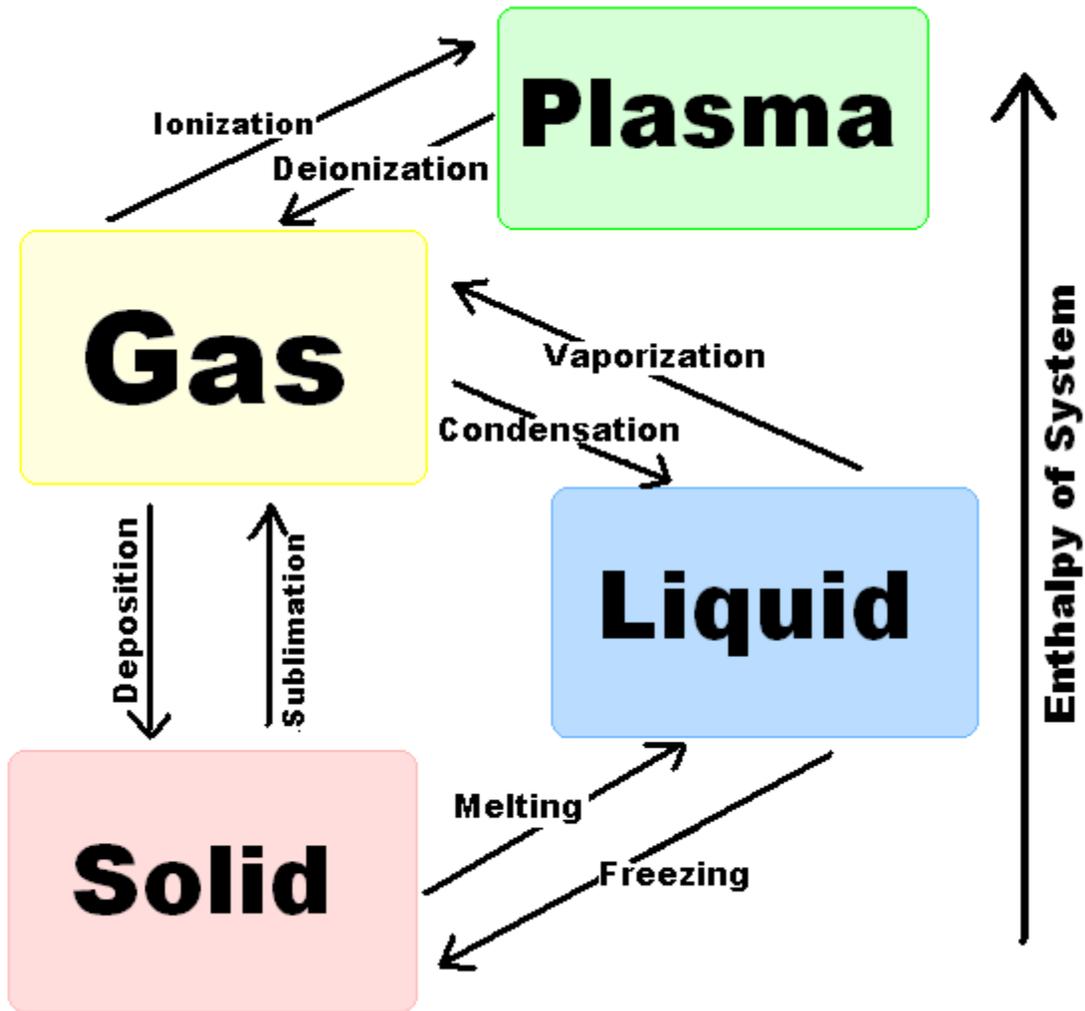


Figure 2.4 Illustration of different phase changes [16]

In this study, latent heat refers to the latent heat of fusion (melting/freezing), as latent heat of vaporization is not practical due to large volume change associated with it.

2.5.2.2 Latent heat storage

Heat storage materials absorb heat through the standard heat transfer mechanisms such as conduction, convection and radiation. They use chemical bonds to store and release heat. Latent heat is the large quantity of energy which needs to be absorbed or released when a material changes phase from the solid to the liquid state (melting) or from the liquid to the solid state (crystallization). These phase changes take place at constant temperature and for

certain materials the process of melting and solidification can be repeated over an unlimited number of cycles with no change to the physical or chemical properties of the material.

When a solid phase change material is subjected to a heat source causing the temperature to rise resulting in melting, the phase change material will store heat. Alternatively, when a liquid phase change material is cooled to the point of crystallization, the phase change material will discharge heat.

2.5.2.3 The use of latent heat storage

The use of latent heat storage is ideally suitable as large amounts of energy can be stored per unit volume and is stored under isothermal conditions which means energy can be delivered or stored at a constant temperature. The use of latent heat storage is especially suitable for solar energy storage where it can result in high solar collection efficiency and consequently the solar collector area can be reduced by 30% [21].

Although, latent heat storage is preferred it has some practical difficulties which include

- low thermal conductivity for heat transfer,
- density change,
- stability of properties under extended cycling and
- phase segregation and
- sub-cooling of the storage medium.

The latent heat storage system uses phase change material as a storage medium.

2.6 Phase Change Materials (PCM)

Phase change materials are compounds which melt and solidify at certain temperatures and in doing so are capable of storing or releasing large amounts of energy. Phase change materials can be incorporated into a thermal storage system in order to store daytime solar energy to be used at night.

In order to explain the characteristics of phase change materials, water is used as an example. When water in a liquid state is cooled to the point of crystallization (0°C) it will discharge heat and collect it when melting. This process is similar at the other phase change of water at temperatures of 100°C . Boiling of water result in heat storage and condensing result in heat discharge.

Materials to be used for phase change thermal energy storage must have a large latent heat capacity, high thermal conductivity and high storage density. They should have a melting point that is in the practical range of operation, melt congruently with minimum sub-cooling and be chemically stable, low in cost, non-toxic and non-corrosive. Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and inorganic compounds [18]. These materials are classified into three most common groups: organic compounds, inorganic compounds and eutectics.

2.6.1 Organic phase change compounds

Organic phase change compounds are based on paraffin, where the melting point of the paraffin varies in relation to the amount of carbon atoms it possesses. Pure paraffins contain 14-40 carbon atoms, whereas paraffin waxes contain 8-15 carbons [20]. Organic phase change materials offer several advantages in that they:

- possess a wide range of melting points,
- are non-toxic,
- are non-corrosive,
- are non-hygroscopic,
- are chemically stable,
- are compatible with most building materials,
- have a high latent heat per unit weight,
- melt congruently and
- most importantly exhibits negligible super-cooling which has plagued some inorganic compounds [21].

Some disadvantages of organic phase change materials are: high costs [22], low density, and low thermal conductivity in comparison to inorganic compounds. These limitations have led some researchers to investigate the potential of technical grade organic phase change materials as alternatives. The problem of low thermal conductivity can be addressed by the addition of a filler with a high thermal conductivity or the use of matrixes [23]. Organic phase change materials also are subject to substantial changes in volume upon melting and flammability is also a potential disadvantage.

2.6.2 Inorganic phase change materials

Inorganic compounds mainly consist of compounds such as hydroxides or oxides, which have been diluted in an acid solution and are termed as salt hydrates or molten salt. The advantages of inorganic compounds in comparison with organic phase change materials are:

- low cost
- high latent heat per unit mass and volume,
- high thermal conductivity and
- wide range of melting points from 7-117°C [24].

However, they can suffer from loss of water when subjected to long-term thermal cycling due to vapour pressure. This can be prevented by using air tight containerization. Problems with corrosion have also been experienced with salt hydrates. The major drawback with salt hydrates is that they can degrade over time due to decomposition. When this happens the PCM melts incongruently and produces two irreversible phases, an aqueous phase and a solid phase. Each phase possesses different densities, consequently the denser solid phase settles at the bottom of the container [18].

Attempts at addressing the problem of salt hydrate decomposition have centred around using thickening agents with varying degrees of success. However it was observed that Glauber's salt, for example, when thickened with clay withstood thermal cycling better than an unthickened salt, although its thermal storage capacity declined over time [21].

2.6.3 Eutectics phase change materials

A eutectic PCM is a combination of two or more compounds of either organic, inorganic or both which may have more appropriate melting points than individual and separate compounds. The mixture behaves as salt hydrates. The main problem with eutectic PCMs is the cost which is two or three times greater than the individual organic or inorganic products [18].

2.6.4 Major problems with PCM's

2.6.4.1 Phase segregation

The phase change behaviour of salt hydrate PCMs is more complex than that of organic compounds because hydration/dehydration occurs, rather than simple melting/freezing. Salt hydrates exhibit three general types of phase change behaviour: congruent, incongruent and semi-congruent melting. The desirable behaviour is congruent melting which occurs when the solid phase composition is the same as the liquid phase composition. Semi-congruent melting occurs when a material has two or more hydrate forms with differing solid compositions and melting points. Incongruent melting materials yield two distinct phases upon melting: a saturated solution and a precipitate of insoluble anhydrous salt [26].

The problem of segregation occurs after a certain number of cycles have been completed by the phase change material, during which time the hydration/dehydration process does not appear identical to the melting/freezing process. The material can be transformed into other hydrate form(s) before either complete melting or freezing occurs resulting in a temporary loss in thermal storage capacity.

2.6.4.2 Super-cooling

Several phase change materials exhibit super-cooling characteristics whereby the temperature drops well below the melting point before freezing initiates. Once the freezing process begins, the temperature rises to the melting point and remains until the material is entirely frozen. If super-cooling is excessive it can prevent the withdrawal of heat from the PCM [26]. To minimize super-cooling, nucleation has been tried through: the addition of a chemical nucleating agent to the PCM. Nucleating agents are substances upon which the PCM crystal will deposit with little or no super-cooling [26].

Table 2.3 summarizes the super-cooling range of PCMs which shows a significant reduction in the degree of super-cooling by applying suitable nucleating and thickening agents.

Table 2.3 Super-cooling range of thickened PCMs with different nucleating agents [27]

PCM	Thickener	T_m (°C)	Nucleating agent (size, μm)	Subcooling (°C)	
				w/o nucleator	w/nucleator
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	SAP	32	Borax (20×50–200×250)	15–18	3–4
$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	SAP	36	Borax (20×50–200×250) Carbon (1.5–6.7) TiO_2 (2–200) Copper (1.5–2.5) Aluminum (8.5–20)	20	6–9 0–1 0–1 0.5–1 3–10
$\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$	CMC	46	Na_2SO_4 SrSO_4 Carbon (1.5–6.7)	20	4–6 0–2 4–7
$\text{Na}_2\text{S}_2\text{O}_7 \cdot 5\text{H}_2\text{O}$	CMC	57	K_2SO_4 $\text{Na}_2\text{P}_2\text{O}_7 \cdot 10\text{H}_2\text{O}$	50	0–3 0–2

2.6.4.3 Stability of thermal properties under extended cycling

The most important criteria that have limited widespread use of latent heat storage are the useful life of PCMs-container systems and the number of cycles the PCMs can withstand without any degradation in their properties. Insufficient long term stability of the storage materials result from poor stability of the materials properties and corrosion between the PCM and the container [29]. The PCM containers must be able to demonstrate physical and thermal stability, as the PCMs undergo repetitive cycles of heating/cooling.

The thermal stability PCM containers can be enhanced. Kimura and Kai [30] have used NaCl to improve the stability of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, containing slightly more water than the stoichiometric composition. The salt was found to be very stable following more than 1000 heating/cooling cycles. Gibbs and Hasnain [31] confirmed that the paraffins have excellent thermal stability as neither the cycles nor contact with metals degraded their thermal behaviour.

The density of a PCM is important because it affects its storage effectiveness per unit volume. Low change in volume as the phase changes from solid to liquid or from liquid to solid is desirable because it affects the storage density of the material. Large changes in volume may cause high stresses on the heat exchanger walls. Volume contraction during solidification may not only reduce the heat transfer area but also separate the PCM from the heat transfer surface, increasing the heat transfer resistance dramatically. The change of volume with the phase transition when in the order of 10%, represents a minor problem [32].

2.6.4.4 Low thermal conductivity

Most phase change materials have unacceptably low thermal conductivities which negatively affect the rates of heat flow during their applications. This problem has limited the use of organic type phase change materials for thermal energy storage application. In order to address this problem, the use of heat transfer enhancement techniques and micro-encapsulation methods are required for any latent heat thermal storage application [18].

2.6.5 Heat Transfer Enhancement

Various methods are proposed to enhance the heat transfer in a latent heat thermal storage system. Hasnain [28] used metallic fillers, metal matrix structures, finned tubes and aluminium shavings to improve the thermal conductivities of paraffins. The use of finned tubes in thermal storage systems with different configurations has been reported by Morcos [33], Sadasuke and Naokatsu [34], Costa et al. [35] and Padmanabhan and Murthy [36]. Zhang and Faghri [37] have showed that adding internal fins in a tube is an efficient way to enhance the heat transfer in thermal energy storage systems when a fluid with a low thermal conductivity is used as the transfer fluid. Lacroix [38] studied the effect of external fins in a shell and tube heat exchanger. The study showed an improvement in heat transfer rate.

2.6.5 Encapsulation of phase change materials

There are many benefits of encapsulated PCMs, such as increasing heat transfer area, reducing PCMs reactivity towards the outside environment and controlling the changes in the storage material volume as phase change occurs. Lane [25, 39] has identified over 200 potential phase change heat storage materials melting from 10 to 90 °C to be used for encapsulation. The development of wall and floor panels for microencapsulation of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ in polyester resin was successful. The technical and economic feasibility of using encapsulated PCMs for thermal energy storage in solar driven residential heating applications was also demonstrated. The potential of encapsulating a group of promising phase change heat storage materials in metal or plastic containers was also shown.

Various encapsulation strategies have been explored. Stark [40] investigated the encapsulation of PCMs into the micropores of an ordered polymer film. The product exhibited excellent mechanical stability under cyclic freezing-melting conditions. Felix Regin et al. [41] investigated the thermal performance of phase change material capsules. They also made a comparison between cylindrical and spherical capsule containing PCMs. The results showed that the heat transfer fluid temperature around the capsule, the radius of the capsule and thermal conductivity of PCM has strong effect on the time for complete

solidification and instantaneous heat flux. It was found that the time for complete solidification was increased by the increase of radius of capsule and was decreased by decreasing the heat transfer fluid temperature for the same volume of PCM. It was also observed that the solidification time for cylindrical capsule was 50% higher than the spherical capsule of the same volume and the same heat transfer area. It was therefore concluded that the use of cylindrical capsules for encapsulating PCMs was most preferable.

2.7 Incorporation of phase change materials into solar energy applications

There are different ways of incorporating the phase change materials into solar thermal energy storage systems that have been studied. The most used method is an indirect contact latent heat storage with the PCM separated from the heat transfer fluid by a plate wall or a tube wall.

2.7.1 Indirect contact latent heat storage

The PCM is usually contained in a number of thin flat containers, similar to plate type heat exchangers [42-47], as shown in Figure 2.5.

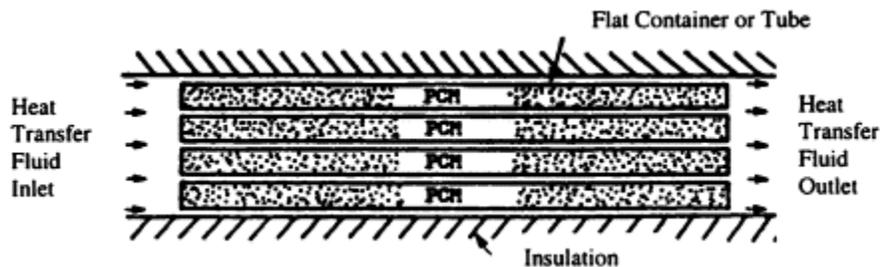


Figure 2.5 Schematic of a latent heat storage unit using flat containers for encapsulating the PCM [47]

Alternatively, the PCM may be contained in small diameter tubes [38, 48-52] with the heat transfer fluid flowing along or across the tubes. The PCM may also be contained in the shell of a shell and tube heat exchanger [38, 53-55].

In an effort to improve heat transfer rates, the idea of using finned tubes in which the PCM was placed between the fins was tested [56-60]. A significant improvement in heat transfer rate was found when a liquid was used as a heat transfer fluid. The effect of using inner fins in the tubes containing the PCM was studied [56], while Lacroix [38] studied the effect of external annular fins in a shell and tube heat storage unit with the PCM placed in the shell. Both studies showed significant improvement in the heat transfer rate due to these enhancement arrangements. Their experimental measurements and theoretical predictions obtained from their numerical analysis for different fin heights and thicknesses showed that the use of fins enhance the heat transfer rate significantly.

2.8 Phase change thermal storage for shifting the peak heating load

Electricity consumption varies during the day and night according to the demand by industrial, commercial and residential activities. The shift of electricity usage from peak periods to off peak periods will provide significant economic benefit. The development of an energy storage system will enable the surplus energy to be stored until such time as it is released when needed. Winter storage heating is a simple application of energy storage that has been used in many countries. The most common domestic storage heater uses ceramic bricks and structural cement [28], which is heated with electrical heating wires or heat transfer fluids (such as hot water) during the night. During the day, the heat is extracted from the heater by natural convection using an electric fan.

A new concept was introduced to the design of heaters by replacing the ceramic bricks with a paraffin wax encapsulated in thin metal containers [42]. Four individual storage units were filled with paraffin wax having a melting temperature of 55°C. An electrical plate heater was fixed at the axis of each storage unit to provide low heat flux but sufficient to melt all the wax within 8 hours. Using a phase change material can lead to a significant weight reduction in domestic storage heaters.

CHAPTER 3

GENERAL PROCEDURE

3.1 Research Methodology

The purpose of the research was to develop a thermal energy storage system for the parabolic trough solar collector at Mangosuthu University of Technology. In view of the storage system the goal was to get a better appreciation of the potential to conserve available solar energy. It has been demonstrated from literature that, for the development of the latent heat thermal energy storage system, the choice of the phase change material (PCM) as well as the heat transfer mechanism in the PCM play important roles [18].

The development sequence of the storage system was divided into three stages:

3.1.1 Stage 1: Identification of the suitable PCM.

It was necessary to identify a suitable PCM with melting and crystallization range within the temperature band for the proposed system operating temperature. This stage involved experimental investigations conducted during a period of 1 year in the Chemical Engineering laboratory at Mangosuthu University of Technology. The experiments were repeated 17 times and the average results were computed for the final results.

3.1.2 Stage 2: Selection of the appropriate heat transfer enhancement technique.

After a suitable PCM was identified, the process of selecting an appropriate heat transfer enhancement technique was initiated. This stage involved using literature to select the appropriate technique and then determining its efficiency in order to check for feasibility of using such a technique.

3.1.3 Stage 3: Design of a proposed thermal energy storage system.

Based on the information regarding a suitable PCM and an appropriate heat transfer enhancement technique, the design of a thermal energy storage system was done.

3.2 Description of experimental data

3.2.1 Primary data:

The data that was collected experimentally during the investigation:

1. **Mass of PCM in grams:** This was used to calculate the rate at which heat is stored.
2. **Mass of water in the cooler box in grams:** This was used to calculate the rate at which heat is discharged by PCM to the water.
3. **Transition time in seconds:** Time taken for energy storage (melting) and time taken for energy discharge (crystallization).
4. **The initial and final temperatures of water in °C:** These were used to calculate the rate at which heat is released by PCM to the water.
5. **The rate of heat flow to the PCM in watts:** The storage mechanism for all solid-liquid PCM is the same. Once melting temperature of a PCM is reached it changes phase from crystallization to fusion. This is called a charge period, as **during this stage considerable quantities of latent heat are stored**. The PCM will continue to store heat all the time it is at or above its melting point, or until its saturation point is reached. When the temperature falls below the melting point of the material it will begin **to discharge the stored latent heat**, which it needs to do in order to crystallize and change phase from liquid to solid. Some materials may have excellent heat storage characteristics but poor capacities to release the energy to the environment. The rate of heat storage and the rate of heat discharge were calculated.
6. **Crystallization temperature in °C:** Several PCMs exhibit super-cooling, the temperature drops well below the melting point before freezing initiates. The temperature at which the PCM re-crystallized was measured.
7. **Congruency:** Observe if there is any phase segregation with the increase of the number of cycles.

3.2.2 Secondary data:

The data that was taken from the literature and supplier's data sheet:

1. **Volumetric storage density in MJ/m³:** High density is important because more heat can be stored in a given volume.
2. **Melting point in °C:** It is essential that the output temperature of heating system is not less than the overall temperature required to melt the PCM, permitting the desired heat transfer to take place. Those materials with the lowest melting points are therefore more desirable.
3. **Volume expansion in %:** Low changes in volume are desirable as a phase changes.
4. **Latent heat of fusion in J/g:** Large latent heat is desirable because more heat can be stored in a given mass of material.
5. **Density in kg/m³:** This was used to calculate the volumetric storage density.
6. **Thermal conductivity in W/m°C:** High thermal conductivity is important to improve the process of heat transfer.
7. **Specific heat capacity of water in J/g°C:** This was used to calculate the rate at which heat is discharged by the PCM to the water.
8. **Safety:** Materials must be non-flammable, non-toxic and disposable.

3.3 Description of experimental test apparatus and procedure

3.3.1 Apparatus

1. **A 250 ml bottle:** A pre-weighed amount of PCM was allowed to melt inside an enclosed bottle.
2. **Hot water bath:** To test the performance of an enclosed PCM as it changes phase during heat storage, it was necessary to supply heat under tightly controlled conditions at 100 °C.
3. **Cooler box:** To measure the behaviour of PCM as it solidifies after melting, it was necessary to cool the sample under controlled conditions at 20 °C.

4. **Balance:** The mass of PCM was measured in order to calculate the rate of heat storage. The mass of water in the cooler box was measured in order to calculate the rate at which heat is discharged by the PCM.
5. **Thermocouples:** It was necessary to determine the phase transition temperature of the PCM. The initial and the final temperatures of water in the cooler box were measured. The crystallization temperature of the PCM was measured.
6. **Stop watch:** It was necessary to measure the phase transition times in order to determine the rate of energy storage and the rate of energy discharge.

A picture of the hot water bath with RT27 and RT35 samples during heat storage is shown in figure 3.1.



Figure 3.1 A picture of a hot water bath used during the experiment

A picture of a balance, a thermocouple, stop watch and a cooler box used during the experiment are shown figure 3.2.



Figure 3.2 A picture showing a cooler box with RT27 and RT35 during heat discharge.

3.3.2 Test procedure for identifying the suitable PCM

The experiment for the identification of the suitable PCM was set up in the Chemical Engineering laboratory at Mangosuthu University of Technology. There were four different PCMs (RT6, RT27, RT35 and RT100) that were supplied by Rubitherm, Germany. Based on the manufacturer's data sheet (Table 4.3), the specifications of only two products, RT27 (28 °C melting point) and RT35 (35 °C melting point) were within the temperature range (15 °C – 90 °C) that could be applied in solar energy applications [18]. As a result, only RT27 and RT35 were tested for the identification of the suitable phase change material.

A 90 g sample of PCM, at room temperature, was enclosed in a 250 ml bottle and placed in a water bath at 100 °C. The sample was then heated up to its melting point. The sample was visually observed for phase transition. The stop watch was timed when the sample began to melt and stopped when it had completely melted. At this stage, the bottle was taken out of the water bath and quickly placed in a cooler box which was filled with 1500 g of water at 20°C. The sample was visually observed for phase transition. The stop watch was timed when the sample began to re-solidify and stopped when it had completely re-solidified. The initial and the final temperatures of water in the cooler box were measured using the thermocouples. As the phase changes, observation of any super-cooling and phase segregation was done. Thermal energy storage is dependent upon the latent heat of melting of a phase change material while energy discharge is dependent upon the rate at which re-solidification of the PCM takes place. The experimental data was used to calculate the heat storage (section 3.3.3.1) and the heat discharge (section 3.3.3.2).

After statistical processing the data for repeatability check, the average results were computed. The results for statistical processing are shown in Tables 4.1 and 4.2. The average results from the experiment are in Table 4.4 and the complete results are in Appendix C. The graphical comparison between the rate of heat storage of RT27 and that of RT35 is shown in Figure 4.1 while the comparison for the rate of heat discharge is in Figure 4.2.

3.3.3 Equations used for the calculations of the rate of heat storage and discharge

The calculations for the rate of heat storage and discharge were based on the following assumptions:

1. The physical properties of the liquid and solid phases of the PCM were the same.
2. Temperature variations normal to the flow direction were ignored.
3. Heat losses to the surroundings were negligible.
4. The heat transfer resistance in the PCM was ignored.

Using these assumptions will result in a constant fluid temperature equal to the melting point of the PCM during both melting and freezing processes.

3.3.3.1 Heat storage equation

$$Q_s = \frac{m_s l_f}{t_s} \quad (3.3.3.1)$$

where, Q_s = rate of heat stored by PCM upon melting in (W)
 m_s = mass of PCM in (g)
 l_f = latent heat of fusion of PCM in ($\text{J}\cdot\text{g}^{-1}$)
 t_s = phase transition time in (s)

3.3.3.2 Heat discharge equation

$$Q_D = \frac{m_D \cdot cp \cdot (T_{wf} - T_{wi})}{t_D} \quad (3.3.3.2)$$

where, Q_D = rate of heat discharge in (W)
 m_D = mass of water in the cooler box in (g)
 cp = specific heat capacity of water in ($\text{J}\cdot\text{g}^{-1}\cdot\text{°C}^{-1}$)
 T_{wf} = Final temperature of water in (°C)
 T_{wi} = Initial temperature of water in (°C)
 t_D = crystallization time of PCM in (s)

3.4 The design method of the heat exchanger

Kern's method for designing finned tube heat exchanger was used. In order to enhance the rate of heat transfer, circular fins were added on the outside surface of the tubes. The effectiveness of adding fins was determined. The key aspects of this heat exchanger that was designed are presented in Tables 5.1. The complete design is presented in Appendix D.

The steps that were followed for design procedure were [65]:

1. The fluid physical properties required were collected: density, viscosity, thermal conductivity.
2. The duty was defined: heat transfer rate, fluid flow rates and temperatures.
3. The log mean temperature difference was determined based on the counter current flow.
4. A trial value for the overall heat transfer coefficient was selected.
5. A provisional value of the surface area required was calculated.
6. A provisional number of tubes was determined.
7. A shell diameter was determined.
8. Individual heat transfer coefficients were calculated.
9. The overall heat transfer coefficient was calculated and compared with the trial value.
10. The heat exchanger pressure drops were determined.
11. The effectiveness of adding fins to enhance the rate of heat transfer was calculated.

3.5 Statistical processing of data

On every analysis that was carried out, the necessary precautions were followed. Repeated experimental measurements and analyses were performed and the averages were computed for the final results. The standard deviation and variance were computed as repeatability checks for the analysis. The equations below were used to compute the average, standard deviation and the variance for the analysis [61].

$$\text{Average} = \frac{1}{n} \sum_{i=1}^n x_i \quad (3.4.1)$$

$$\text{variance} = \frac{1}{n} \sum_{i=1}^n (x_i - x)^2 \quad (3.4.2)$$

$$\text{standard deviation} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - x)^2} \quad (3.4.3)$$

where

x_i is value of the analysis data

n is number of observation or data

x is average of the analysis data

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Repeatability Check

Tables 4.1 and 4.2 show the statistical processing of data where the averages, standard deviation and the variance of the heat storage and heat discharge tests data are presented. The data therefore came from a reasonable distribution because for both RT27 and RT35 more than 68% of the data were between $(x - \sigma)$ and $(x + \sigma)$ [61].

Table 4.1 Statistical results of the experimental data for heat storage

PCM	Average (x) n = 17	Standard Deviation (σ)	Variance (σ^2)	$x - \sigma$	$x + \sigma$
RT27	40.25 (W)	2.28	5.19	37.97	42.53
RT35	32.26 (W)	1.83	3.34	30.43	34.09

Table 4.2 Statistical results of the experimental data for heat discharge

PCM	Average	Variance	Standard Deviation (σ)	$x - \sigma$	$x + \sigma$
RT27	2.99 (W)	0.50	0.71	2.28	3.70
RT35	7.68 (W)	1.19	1.09	6.59	8.77

4.2 Identification of the suitable phase change material

4.2.1 Secondary data

The results from the manufacturer's data sheet (secondary data) are presented in Table 4.3. This table shows the secondary data for all of the four materials (RT6, RT27, RT35 & RT100) that were supplied by Rubitherm. Both RT6 and T27 have the highest volumetric storage density (134 MJ/m^3) and high latent heat of fusion. RT100 has moderate volumetric storage density (129 MJ/m^3) and moderate latent heat of fusion. RT35 has the lowest volumetric storage density (119 MJ/m^3) and latent heat of fusion. All of the four PCM's have low volume expansion (10%) which is desirable and low thermal conductivity ($0.2 \text{ W/m}^\circ\text{C}$) which is undesirable and hence, their application would require large heat transfer area which would result from heat transfer enhancement. As far as heat storage capacity is concerned RT6 and RT27 are preferable because of high storage density and latent heat of fusion.

According to Farid et al [18], the suitable PCM should first be selected based on melting point which should be in a practical range of operation. Only RT27 and RT35 were selected for primary data collection because of their melting points which are between 15°C and 90°C and thus applicable for solar energy applications. Although RT27 had a higher storage density than RT35 but it was still not easy to conclude because the primary data such as the rate of heat storage and heat discharge, congruency, crystallization temperature and the transition time had not yet been collected. This data was necessary since some materials may have high storage density but have poor capabilities to release heat to the surrounding as well as exhibit phase segregation and super-cooling.

Table 4.3 Thermophysical properties of four PCMs supplied by Rubitherm [62]

Property	Units	RT6	RT27	RT35	RT100
Melting point	°C	8	28	35	99
Heat of fusion	kJ/kg	174	179	157	168
Density	Kg/m ³	770	750	760	770
Thermal Conductivity	W/m°C	0.2	0.2	0.2	0.2
Volume expansion	%	10	10	10	10
Volumetric storage density	MJ/ m ³	134	134	119	129

4.2.2 Primary data

The primary data for RT27 and RT35 was experimentally collected. From the average results in Table 4.4 and the graphical representation of the rate of heat storage in Figure 4.1, it is shown that RT27 has higher rate of heat storage which is an average of 40.25 W as compared to an average of 32.26 W for RT35. On the other hand, RT35 has a better capability to release heat to the surrounding which is an average of 7.68 W as compared to an average of 2.99 W for RT27 (see Figure 4.2 for graphical representation). This lower rate of heat discharge for RT27 resulted from thermal conductivity being lower in solids which means that the rate of heat transfer decreases during heat rejection process.

The enhancement of heat transfer process would assist in overcoming the problem of poor rate of heat discharge for RT27 which appears to be the better PCM than RT35 (Table 4.5). Both the materials do not exhibit the problems of super-cooling and phase segregation. The overall performance of RT27 (high latent heat, high volumetric storage, low change in volume on phase transition, lowest melting point within a practical range of operation and high rate heat absorption) shows that it is the most suitable PCM to select for further investigation.

Table 4.4 Average experimental tests results of two phase change materials, RT27 and RT35

Property	Units	RT27	RT35
Mass of PCM	g	90	90
Mass of water in the cooler box	g	1500	1500
Transition time for storage	s	402	439
Transition for discharge	s	7115	2627
Initial temperature of water	°C	20.2	20.2
Final temperature of water	°C	23.5	23.4
Rate of heat storage	W	40.25	32.26
Rate of heat discharge	W	2.99	7.68
Super-cooling		None	None
Phase segregation		None	None

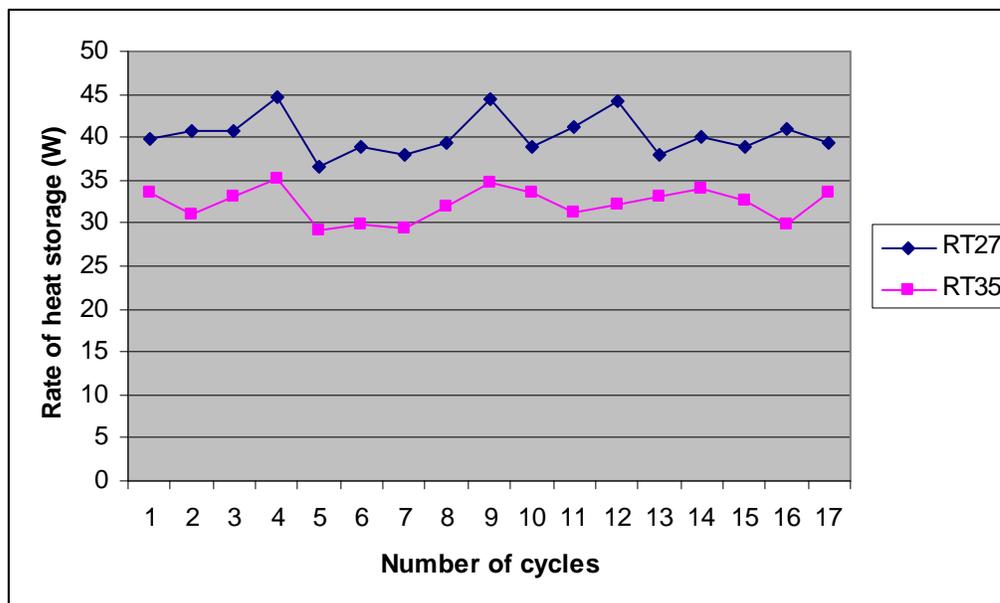


Figure 4.1 Comparison between the rate of heat storage of RT27 & RT35

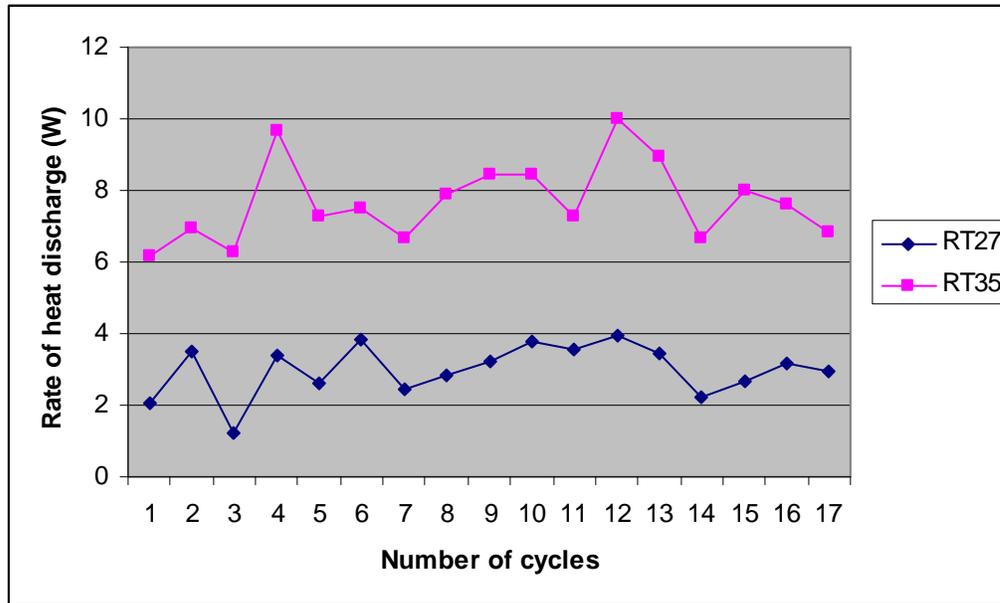


Figure 4.2 Comparison between the rate of heat discharge of RT27 and RT35

Table 4.5 Relative performance of RT27 and RT35

Property	Suitable PCM according to Farid et al [18]	RT27	RT35
Latent heat	High	High (179 kJ/kg)	Low (157 kJ/kg)
Volumetric storage density	High	High (134 MJ/m ³)	Low (119 MJ/m ³)
Thermal conductivity	High	Low (0.2 W/m°C)	Low (0.2 W/m°C)
Heat absorption	High	Higher (40.25 W)	Lower (32.36 W)
Heat discharge	High	Lower (2.99 W)	Higher (7.68 W)
Change in volume	Low	Low (10%)	Low (10%)
Melting point	Lowest in the practical range of operation	Lowest (28°C)	Higher (35°C)
Congruency	Melt congruently	Melt congruently	Melt congruently
Super-cooling	No super-cooling	No super-cooling	No super-cooling
Stability	Chemical stable	Chemical stable	Chemical stable

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Selection of the appropriate heat transfer enhancement technique [63].

The rate of heat transfer from a surface at a temperature T_s to the surrounding medium at T_∞ is given by Newton's law of cooling as:

$$Q_{conv} = hA_s(T_s - T_\infty) \quad (5.1)$$

Where, A_s is the heat transfer area and h is the convection heat transfer coefficient.

When the temperatures T_s and T_∞ are fixed by design considerations, as often the case, there are two ways to increase or enhance the rate of heat transfer:

1. To increase the convective heat transfer coefficient, h .
2. To increase the surface area, A_s .

Increasing h may require the installation of a pump or fan or replacing the existing one with a larger one, but this approach may or may not be practical. Besides, it may not be adequate. The alternative way is to increase the surface area by attaching to the surface extended surfaces called fins made of highly conductive materials such as aluminium. Finned surfaces are manufactured by extruding, welding or wrapping a thin metal sheet on a surface. Fins enhance heat transfer from a surface by exposing a larger surface area to convection and radiation. Finned surfaces are commonly used in practice to enhance heat transfer by rapidly increasing the rate of heat transfer.

It has been demonstrated from literature that finned tubes have been used for PCM thermal storage systems [33, 34, 35, 36, 37, 38]. The use of fins is most effective in applications involving low convective heat transfer coefficient.

5.1.1 Analysis of fins

The following assumptions were used for the analysis of fins:

1. Consider steady operation with no heat generation in the fin.
2. Assume the thermal conductivity of the material to remain constant.
3. Assume the convective heat transfer coefficient h , to be constant and uniform over the entire surface of the fin for convenience in the analysis.
4. Use a minimum number of fins because adding too many fins on a surface may actually decrease the overall heat transfer as this decreases the overall heat transfer coefficient.

5.1.2 Fin efficiency

In an ideal situation, the temperature of the fin will be uniform and it will be at the tube base value. The heat transfer from the fin will be maximum in this case. In reality, the temperature of the fin will drop along the fin, and thus the heat transfer from the fin will be less because of the decreasing temperature difference toward the fin tip. To account for the effect of this decrease in temperature on heat transfer, fin efficiency is defined as

$$\eta_{fin} = \frac{\dot{Q}_{fin}}{\dot{Q}_{fin,max}} = \frac{\text{Heat transfer in reality}}{\text{Ideal heat transfer}} \quad (5.1.2)$$

The fin efficiency decreases with increasing fin length because of the decrease in fin temperature with length. Fin lengths that cause the fin efficiency to drop below 60% usually cannot be justified economically and should be avoided. The efficiency of most fins used in practice is above 90%.

5.1.3 Fin Effectiveness

Fins are used to enhance heat transfer, and the use of fins on a surface cannot be recommended unless enhancement in heat transfer justifies the added cost and complexity associated with the fins. The performance of the fins is judged on the basis of the enhancement in heat transfer relative to the case where fins are not used. Therefore, fin performance is expressed in terms of fin effectiveness which is defined as:

$$\varepsilon_{fin} = \frac{Q_{fin}}{Q_{no\ fin}} \quad (5.1.3)$$

$\varepsilon_{fin} = 1$, indicates that the addition of fins to the surface does not affect heat transfer at all.

$\varepsilon_{fin} < 1$, indicates that the fin acts as an insulator instead of a conductor. This may happen when fins are made of low thermal conductivity materials.

$\varepsilon_{fin} > 1$, indicates that fins are enhancing heat transfer from the surface. However, the use of fins cannot be justified unless ε_{fin} is sufficiently larger than 1.

Fins are designed on the basis of maximizing effectiveness for a specified cost or minimizing cost for a desired effectiveness.

5.1.4 Circular Fins around the tube

Lacroix [38] has studied the effect of external circular fins in a shell and tube heat storage unit with the PCM placed in the shell. This study showed significant improvement in the heat transfer rate due to this enhancement arrangement. This arrangement has been selected for the design of the proposed heat storage system in which the PCM fills the annular space

around the finned tubes while the heat transfer fluid flows inside the tube. A sectional view of the externally finned tube is shown Figure 5.1.

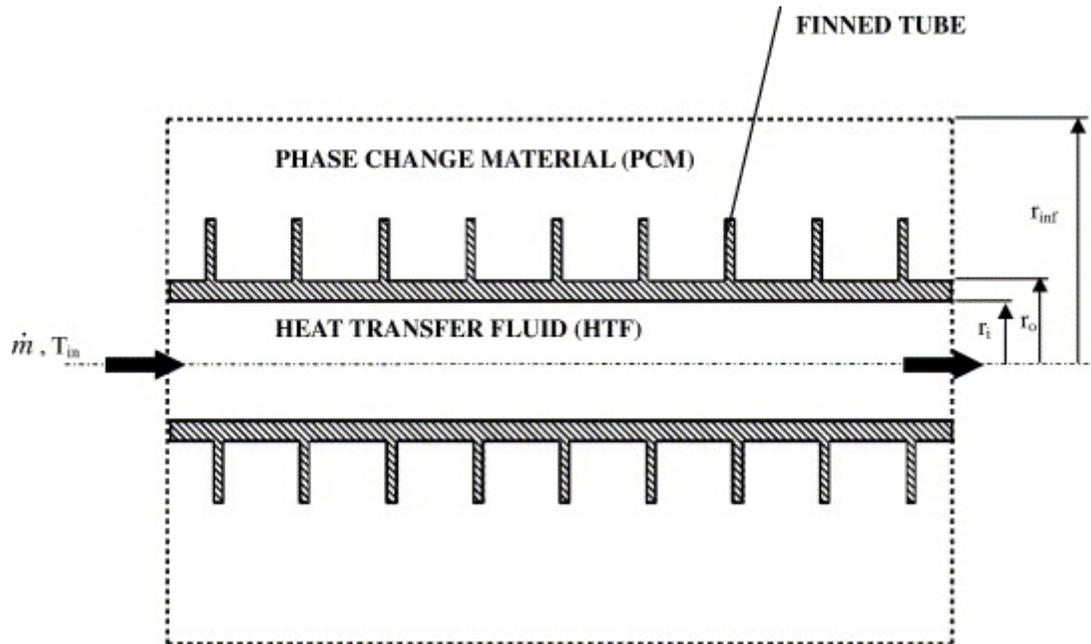


Figure 5.1 A Sectional view of the finned tube [64]

5.2 Design of a proposed thermal energy storage system

Key aspects of the design of a shell and tube heat exchanger which will be used as a thermal energy storage system are briefly described and the results are presented in Tables 5.1.

Circular copper fins were attached to the outside surfaces of the tubes in order to enhance the heat transfer process. It was desired to melt RT27 PCM at 28°C using 300 kg/h of hot water from a parabolic trough solar energy collector. The water was to be cooled from 85°C to 35°C. The water flow rate and temperatures were based on the flow conditions of the fluid circulation system in the existing parabolic trough solar collector. The effectiveness of fins addition was calculated in order to justify the usage of fins for heat transfer enhancement.

Table 5.1 Summary of finned heat exchanger design

	Tube side	Shell side
Heat load (W)	17500	
Mass flow rate (kg/h)	Water = 300	PCM = 352.8
Initial temperature (°C)	85	28
Final temperature (°C)	35	28
Mean Temperature difference (°C)	24	
Area (m ²)	2.5	
Number of tubes	7	
Total number of fins		61
Heat transfer coefficient (W.m ⁻² .°C ⁻¹)	825	218
Overall heat transfer (W.m ⁻² .°C ⁻¹)	293	
Pressure drop (Pa)	46	1460

5.2.1 Fin effectiveness

$$\varepsilon_{fin} = \frac{Q_{fin}}{Q_{no\ fin}} = \frac{2305.52}{808.96} = 2.85$$

The rate of heat transfer was increased by a factor of almost 3, as a result of adding fins. This justifies the use of finned surfaces since an effectiveness of $\varepsilon_{fin} > 1$ indicates that fins are enhancing heat transfer from the surface, as they should.

The finned tube heat exchanger presented in Table 5.1 will be incorporated into the existing parabolic trough solar collector for further investigation.

5.3 Proposed thermal energy storage system

Figure 5.3 presents a PCM latent heat storage system in which solar energy is collected by a parabolic trough collector that uses a curved trough to reflect sunlight onto a hollow tube running along the trough. The whole trough tilts through the course of the day so that light remains focused on the hollow tube. The water passes through the tube and it is heated up. The heated water then enters the tube side of the shell and tube heat exchanger. The PCM is fed into the shell side of the heat exchanger which has circular fins on the outside surfaces of the fins. The heat transfer process takes place between the hot water and the PCM whereby the PCM is heated up to its melting point. As a result heat is stored in the PCM upon melting. The cold water leaving the heat exchanger is re-circulated. To discharge the stored heat, cold water from the main supply is passed through the thermal energy storage unit and this result in reheating of the water.

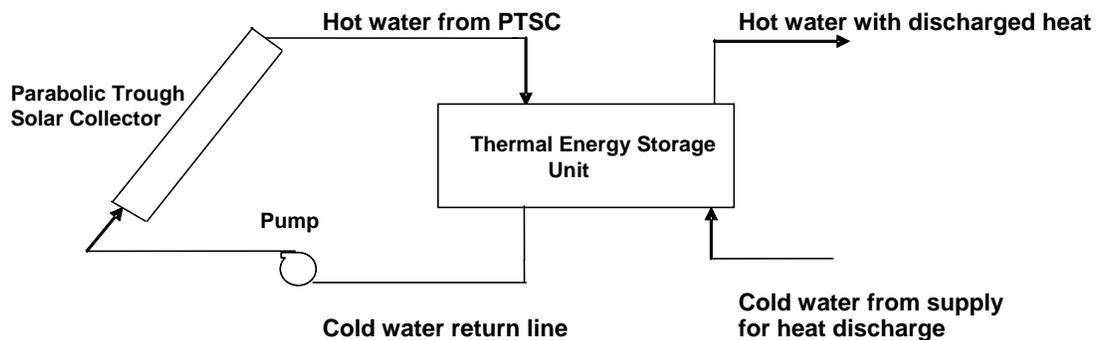


Figure 5.3 Proposed PCM latent heat storage system.

CHAPTER 6

CONCLUSION

The field of this investigation covered the development of a latent heat thermal storage system which has a potential of conserving available solar energy. The advantages of using thermal energy storage that have been found previously include reduced energy cost, energy consumption, equipment size and pollutant emissions, also increased flexibility of operation, efficiency and effectiveness of equipment utilization.

It has been demonstrated from literature that, for the development of a latent heat thermal energy storage system, the choice of the phase change material (PCM) as well as the heat transfer mechanism in the PCM play important roles [18]. In this study, a suitable phase change material and an appropriate heat transfer enhancement technique were selected for utilization in a proposed latent heat thermal energy storage system. A heat exchanger which is compatible with the existing parabolic trough solar energy collector was designed.

The RT27 PCM has been selected as a suitable material for utilization in the development of a latent heat storage system for solar energy application. This choice has been based on the following aspects:

- large latent heat,
- high volumetric energy storage density,
- low volume change with transition, which is in order of 10%,
- low melting point which is in the practical range of operation,
- melts congruently with minimum super-cooling
- no phase segregation
- has good heat absorption characteristics

Although RT27 PCM has these outstanding characteristics, it has some disadvantages that may limit its application, namely:

- low thermal conductivity

- lower rate of heat discharge than RT35 PCM

The enhancement of the heat transfer process using fins that are added on the outside surface of the heat exchanger tubes would overcome the problems of low thermal conductivity and low rate of heat discharge. The result from the calculation of the effectiveness of using fins on the outside surface of the tube was found to be 2.85 which is greater than 1. Therefore, the use of fins to alleviate the problems of low thermal conductivity and low heat discharge rate is justified.

The development of reliable and practical thermal energy storage systems still faces some major uncertainties such as long term thermal behaviour and the small number of PCMs suitable for room temperature applications. Therefore a need for further investigation to explore the potential for conserving available solar energy still exists.

REFERENCES

1. Association of conservation of Energy briefing notes. 1994. No.13 climate change pp1. paragraph 1.
2. SEIA. Solar: Clean and Healthy [Online]. Solar Energy Industries Association. Available from: www.seia.org. Accessed: 15/07/05
3. The Energy Guy. [Online]. *Comprehensive Energy Solutions for a sustainable future*. Available at: www.theenergyguy.com/climate_change.html. Accessed: 03/08/05
4. Intergovernmental Panel on Climate Change. [Online]. 1995. Available at: <http://www.ipcc-wg2.org>. Accessed: 14/08/05
5. Darvill, A. Energy Resources: Fossils fuels [Online]. Available at: www.darvill.clara.net/altenerg/fossil.htm. Accessed: 16/08/05
6. Fossil fuel. In: *Wikipedia free encyclopedia*. [Online]. Available at: http://en.wikipedia.org/wiki/Fossil_fuel. Accessed: 06/04/06.
7. Get energized [Online]. Green Treks network, Inc. Available at: www.greentreks.org/allprograms/getenergized/index.asp. Accessed: 01/09/05
8. Renewable energy. In: *Wikipedia free encyclopedia*. [Online]. Available at: http://en.wikipedia.org/wiki/Renewable_energy. Accessed: 14/08/08
9. Solar Power. In: *Wikipedia free encyclopedia*. [Online]. Available at: http://en.wikipedia.org/wiki/Solar_power. Accessed: 28/03/06

10. Weider, S., 1982. *An Introduction to Solar Energy for Scientists and Engineers.*, New York: John Wiley & Sons.
11. FPL Energy SEGS viii. [Online]. Available at: http://www.fplenergy.com/portfolio/contents/segs_viii.shtml. Accessed: 06/04/06.
12. Solar Paces. [Online]. *Parabolic Trough Systems*. Available at: www.solarpaces.org/publications/sp99_tec.htm,1999. Accessed: 07/04/06.
13. Brooks, M.J. 2005. Performance of a Parabolic Trough Solar Collector. MSc. Eng. dissertation, University of Stellenbosch.
14. Duffie, J.A. & Beckman, W.A. 1980. *Solar energy thermal processes*. New York, USA: John Wiley.
15. Garg, H.P., Mullick, S.C. & Bhargava, A.K. 1985. *Solar thermal energy storage*. Holland: Reidel Publishing Company.
16. State of matter. In: *Wikipedia free encyclopedia*. [Online]. Available at: http://en.wikipedia.org/wiki/states_of_matter. Accessed: 26/08/08.
17. Phase Change Materials Home Page. [Online]. Available at: <http://freespace.virgin.net/m.eckert/index.htm>. Accessed: 01/09/05
18. Farid, M.M., Khudhair, A.M., Razack, S.A.K., Al-Hallaj, S. 2004. *A review on phase change energy storage: materials and applications*. (Energy Conversion and Management 45): p.1597-1615.
19. CIBSE. *Guide A3 Thermal Properties of Building structures*. 1986. London: The Chartered Institution of Building Services Engineers.

20. Abhat, A. 1983. *Low temperature latent heat thermal energy storage: Heat storage materials*. Solar Energy 30(4): p.313-332.
21. Lane, G.A. 1983. *Solar Heat Storage: Latent Heat Materials Volume I* (Background and Scientific Principles. Vol.1). Florida: CRC Press, Inc.
22. Ghoneim, A.A. & Klein, S.A. 1989. *The effect of phase change material properties on the performance of solar air based heating systems*. (Solar Energy 42: p.441-447).
23. Hoogendoorn, C.J., & Bart, G.C.J. 1992. *Performance and modeling of latent heat stores*. (Solar Energy 48:p.53-58).
24. Lane, G.A. 1983. *Solar Heat Storage: Latent Heat Materials Volume II: Technology*. Florida: CRC Press Inc.
25. Lane, G.A. 1980. *Low temperature heat storage with phase change materials*. (The international journal of ambient energy Vol. 1:p.155-168).
26. Eissenberg and al. 1980. *What's in store for phase change thermal storage materials for active and passive solar applications*. (p.12-16).
27. Lane, G.A. 1991. *Phase change materials for energy storage nucleation to prevent subcooling*. (Solar Energy Mater Solar Sells 27:p.135-60).
28. Hasnain, S.M. 1998. *Review on sustainable thermal energy storage technologies, Part 1: Heat storage materials and techniques*. (Energy Conversion and Management 39: p.1127-38).

29. Zalba, B., Marin, J., Cabeza, L., Mehling, H. 2003. *Review on thermal energy storage with phase change: materials, heat transfer analysis and applications*. (Appl. Therm. Eng. 23: p.251-83).
30. Kimura, H. & Kai, J. 1984. *Phase change stability of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$* . (Solar Energy 33:p.557-63).
31. Gibbs, B. & Hasnain, S. 1995. *DSC study of technical grade phase change heat storage materials for solar heating applications*. (In: Proceedings of the 1995 ASME/JSME/JSEJ International Solar Energy Conference, Part 2).
32. Dincer, I. & Rosen, M.A. 2002. *Thermal energy storage: system and applications*. (England: John Wiley and Sons).
33. Morcos, V.H. 1990. *Investigation of a latent heat thermal energy storage system*. (Solar Wind Technology 7: p.197-202).
34. Sadasuke, I. & Naokatsu, M. 1991. *Heat transfer enhancement by fins in latent heat thermal energy devices*. (Solar Energy ASME: 223-8).
35. Costa, M., Buddhi, D. & Oliva, A. 1998. *Numerical simulation of a latent heat thermal energy storage system with enhanced conduction*. (Energy Conversion Management 39: p. 319-30).
36. Padmanabhan, P.V. & Murthy, M.V. 1986. *Outward phase change in a cylindrical annulus with axial fins on the inner tube*. (Int. J Heat Mass Transfer 29: p. 1855-68).
37. Zhang, Y. & Faghri, A. 1996. *Heat transfer enhancement in latent heat thermal energy storage system by using the internally finned tube*. (International Journal of Heat and Mass Transfer, Volume 39: p.3165-73).

38. Lacroix, M. 1993. *Numerical simulation of a shell and tube latent heat thermal energy storage unit*. (Solar Energy 50: p.357-67).
39. Lane, G.A. 1976. *Encapsulation of heat of fusion storage materials*. (In: Proceedings of 2nd Southeastern Conference on Application of Solar Energy: p. 442-50).
40. Stark, P. 1990. *PCM-impregnated polymer microcomposites for thermal energy storage*. (SAE, Soc Automotive Eng, Trans 99: p. 571-88).
41. Felix Regin, A, Solanki, S.C. & Saini J.S. *Thermal performance analysis of phase change material capsules*. (Indian Institute of Technology Roorkee, India).
42. Farid, M.M. & Husian, R.M. 1990. *An electrical storage heater using phase change method of heat storage*. (Energy Conversion Management 30: p. 219-30).
43. Farid, M.M., Hamad, F.A. & Abu-Arabi, M. 1998. *Phase change cool storage using dimethyl-sulfoxide*. (Energy Conversion Management 39: p. 819-26).
44. Morrison, D.J. & Abdul Khalik, S.I. 1978. *Effect of phase change energy storage on the performance of air-based and liquid based solar heating systems*. (Solar Energy 20:p. 57-67).
45. Marshall, R. & Dietsche, C. 1982. *Comparisons of paraffin wax storage subsystem models using liquid heat transfer media*. (Solar Energy 29: p. 503-11).
46. Wakilaltojjar, S.M. & Saman, W. 2001. *Analysis and modeling of a phase change storage system for air conditioning applications*. (Appl Therm Eng. 21: p. 249-63).

47. Bailey, J.A., Mulligan, J.C., Liao, C.K., Guceri, S.I., Reddy, M.K. 1976. *Research on solar energy storage subsystem utilizing the latent heat of phase change of paraffin hydrocarbons for the heating and cooling of buildings*. (Report to the National Science Foundation for Grant GI – 4438, North Carolina State University, USA).
48. Farid, M.M. & Kanzawa, A. 1989. *Thermal performance of a heat storage module using PCM's with different melting temperature-mathematical modeling*. (Trans ASME, J Solar Energy Eng. 111:p. 152-7).
49. Farid, M.M., Kim, Y. & Kanzawa, A. 1990. *Thermal performance of heat storage module using PCM's with different melting temperatures-experimental*. (Trans ASME, J Solar Energy Eng. 112:p.125-31).
50. Kamimoto, M., Abe, Y., Kanari, K., Swata, S., Tani, T. & Ozawa, T. 1986. *Heat transfer in latent heat thermal storage units using pentarythritol slurry, thermal energy storage*. (World Congress of Chemical Engineering, Tokyo, Japan).
51. Dietz, D. 1984. *Thermal performance of a heat storage module using calcium chloride hexahydrate*. (Trans ASME, J Solar Energy Eng. 106).
52. Farid, M.M., Kim, Y., Honda, T. & Kanzawa, A. 1989. *The role of natural convection during melting and solidification of PCM in a vertical cylinder*. (Chem Eng Commun 84:p. 43-60).
53. Abe, Y., Takahashi, Y., Kanari, K., Kamimoto, M., Sakamoto, R. & Ozawa, T. 1986. *Molten salt latent thermal energy storage for load following generation in nuclear power plants*. (In: Proceedings of 21st Intersociety Energy Conversion Engineering Conference, San Diego, California, USA: p. 856-61).
54. Riahi, M. 1993. *Efficiency of heat storage in solar energy systems*. (Energy Convers Mgmt 34:p. 677-85).

55. Ismail, K.A.R. & Concalves, M.M. 1999. *Thermal performance of a PCM storage unit*. (Energy Convers Mgmt 40: p. 115-38).
56. Velraj, R. Seeniraj, R.V., Hafner, B., Faber, C. & Schwarzer, K. 1999. *Heat transfer enhancement in a latent heat storage system*. (Solar Energy 65:p. 171-80).
57. Kamimoto, M. & Tani, T. 1980. *Effect of conduction promoters and fins on heat transfer in latent storage unit*. (Bul Electrotech Lab 44:p. 278-368).
58. De Jong, A.G. & Hoogendoorn, C.J. 1980. *Improved of heat transport in paraffin for latent heat storage systems*. (In: Proceedings of TNO Symposium on Thermal Storage of Solar Energy, Amsterdam, Holland: p. 99-110).
59. Eftekhar, J., Haji-Sheikh, A. & Lou, D.Y.S. 1984. *Heat transfer in paraffin wax thermal storage system*. (J Solar Energy Eng 106:p. 299-306).
60. Ismail, K.A.R., Alves, C.L.F. & Modesto, M.S. 2001. *Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder*. (Appl Therm Eng 21:p. 53-77).
61. Melville, S. & Goddard, W. 1996. *Research Methodology*. (An Introduction for Science and Engineering students: p. 51).
62. Rubitherm. 2005. *Rubitherm RT Products Data Sheet*. Germany.
63. Cengel, Y.A., *Heat transfer, a practical approach*, (2nd Edition. Mcgraw-Hill: p.156 -169).

64. Kemal, E., Aytunc, E., & Ibrahim, D. 2007. *Heat transfer analysis of phase change process in a finned tube thermal energy storage system using artificial neural network*. (International Journal of Heat and Mass Transfer Volume 50: p. 3163-3175).

65. Sinnott, R.K. *Chemical Engineering Design*. (Coulson and Richardson's Chemical Engineering Volume 6, 3rd Edition: p634-764).

66. Shell and tube heat exchanger. In: *Wikipedia free encyclopedia*. [Online]. Available at: http://en.wikipedia.org/wiki/Shell_and_tube_heat_exchanger. Accessed: 23/08/08.

APPENDIX A

Rubitherm Phase Change Materials

RUBITHERM[®] RT



Figure A.1 Phase change materials based on n-Paraffins and Waxes [62]

APPENDIX B

PCM Secondary data (supplied by Rubitherm)



APPENDIX B.1

RUBITHERM® RT 6

Property	Unit	Typical Values
Melting Point (approx.)	°C	8
Congealing Point (PCM)	°C	6
Heat storage capacity <i>Temperature -3°C to 12°C</i>	kJ/(kg)	174
Density solid <i>at 15°C</i>	kg/l	0.86
Density liquid <i>At 15°C / 70°C</i>	kg/l	0.77/0.73
Volume expansion	%	10
Volume expansion <i>without phase change</i>	l/K	0.001
Specific heat capacity	kJ/(kg.K)	1.8/2.4
Thermal conductivity	W/(mK)	0.2
Kinetic viscosity @ 40°C	mm ² /s	2.5
Flash point (PCM)	°C	122
Corrosion		Chemically inert
Water hazard		Water hazard class (WGK)1



APPENDIX B.2

RUBITHERM® RT 27

Property	Unit	Typical Values
Melting Point (approx.)	°C	28
Congealing Point (PCM)	°C	26
Heat storage capacity <i>Temperature -3°C to 12°C</i>	kJ/(kg)	179
Density solid <i>at 15°C</i>	kg/l	0.87
Density liquid <i>At 15°C / 70°C</i>	kg/l	0.75
Volume expansion	%	10
Volume expansion <i>without phase change</i>	l/K	0.001
Specific heat capacity	kJ/(kg.K)	1.8/2.4
Thermal conductivity	W/(mK)	0.2
Kinetic viscosity @ 40°C	mm ² /s	4.5
Flash point (PCM)	°C	164
Corrosion		Chemically inert
Water hazard		Water hazard class (WGK)1



APPENDIX B.3

RUBITHERM® RT 35

Property	Unit	Typical Values
Melting Point (approx.)	°C	35
Congealing Point (PCM)	°C	36
Heat storage capacity <i>Temperature -3°C to 12°C</i>	kJ/(kg)	157
Density solid <i>at 15°C</i>	kg/l	0.88
Density liquid <i>At 15°C / 70°C</i>	kg/l	0.76
Volume expansion	%	10
Volume expansion <i>without phase change</i>	l/K	0.001
Specific heat capacity	kJ/(kg.K)	1.8/2.4
Thermal conductivity	W/(mK)	0.2
Kinetic viscosity @ 40°C	mm ² /s	3.3
Flash point (PCM)	°C	178
Corrosion		Chemically inert
Water hazard		No Water endangering substance



APPENDIX B.4

RUBITHERM® RT 100

Property	Unit	Typical Values
Melting Point (approx.)	°C	99
Congearing Point (PCM)	°C	102
Heat storage capacity <i>Temperature -3°C to 12°C</i>	kJ/(kg)	168
Density solid <i>at 15°C</i>	kg/l	0.94
Density liquid <i>At 15°C / 70°C</i>	kg/l	0.77
Volume expansion	%	10
Volume expansion <i>without phase change</i>	l/K	0.001
Specific heat capacity	kJ/(kg.K)	1.8/2.4
Thermal conductivity	W/(mK)	0.2
Kinetic viscosity @ 40°C	mm ² /s	18.5
Flash point (PCM)	°C	312
Corrosion		Chemically inert
Water hazard		No Water endangering substance

APPENDIX C

EXPERIMENTAL TESTS DATA

TABLE C.1 RT 27 Experimental Results

Date	Mass of PCM (g)	Mass of H₂O (g)	Melting period (s)	Cryst. Period (s)	Init. H₂O Temp (°C)	Final H₂O temp (°C)	Rate of heat storage (W)	Rate of disch. (W)	Super-cooling	Phase Seg.
22/08/07	90	1500	405	7740	21	23.5	39.78	2.03	No	No
29/08/07	90	1500	395	5400	19.9	22.9	40.78	3.49	No	No
12/09/07	90	1500	396	11700	22.7	25.0	40.68	1.23	No	No
19/09/07	90	1500	360	6300	20.2	23.6	44.75	3.39	No	No
26/09/07	90	1500	441	7200	20	23	36.53	2.62	No	No
03/10/07	90	1500	415	5700	20	23.5	38.82	3.86	No	No
10/10/07	90	1500	425	5940	20	22.3	37.91	2.43	No	No
17/10/07	90	1500	410	7020	20	23.2	39.29	2.86	No	No
31/01/08	90	1500	362	6000	20	23.1	44.50	3.24	No	No
12/02/08	90	1500	415	6000	20	23.6	38.82	3.77	No	No
21/02/08	90	1500	390	6720	20	23.8	41.31	3.55	No	No
28/02/08	90	1500	365	6840	20	24.3	44.14	3.95	No	No
20/03/08	90	1500	424	7500	20	24.1	37.99	3.43	No	No
03/04/08	90	1500	403	8400	20	23.0	39.98	2.24	No	No
10/04/08	90	1500	415	9600	20	24.1	38.82	2.68	No	No
17/04/08	90	1500	394	7200	20	23.6	40.89	3.14	No	No
24/04/08	90	1500	410	5700	20	22.7	39.29	2.97	No	No
Average	90	1500	402	7115	20.2	23.5	40.25	2.99	No	No

TABLE C.2 RT 35 Experimental Results

Date	Mass of PCM (g)	Mass of H₂O (g)	Melting period (s)	Cryst. Period (s)	Init. H₂O Temp (°C)	Final H₂O temp (°C)	Rate of heat storage (W)	Rate of disch. (W)	Super-cooling	Phase Seg.
22/08/07	90	1500	420	2040	21	23	33.64	6.16	No	No
29/08/07	90	1500	455	2702	20	23	31.05	6.97	No	No
12/09/07	90	1500	427	3000	22.0	25.0	33.09	6.28	No	No
19/09/07	90	1500	402	2150	20.9	24.2	35.15	9.64	No	No
26/09/07	90	1500	486	2940	19.7	23.1	29.07	7.26	No	No
03/10/07	90	1500	472	2520	20	23	29.94	7.48	No	No
10/10/07	90	1500	480	2460	20	22.6	29.44	6.64	No	No
17/10/07	90	1500	442	2460	20	23.1	31.97	7.91	No	No
31/01/08	90	1500	407	2600	20.3	23.8	34.72	8.45	No	No
12/02/08	90	1500	420	2836	20	23.8	33.64	8.42	No	No
21/02/08	90	1500	452	2590	20	23	31.26	7.27	No	No
28/02/08	90	1500	440	2580	20	24.1	32.11	9.98	No	No
20/03/08	90	1500	426	2520	20	23.6	33.17	8.97	No	No
03/04/08	90	1500	415	3120	20	23.3	34.05	6.64	No	No
10/04/08	90	1500	433	2752	20	23.5	32.63	7.99	No	No
17/04/08	90	1500	473	2720	20	23.3	29.87	7.62	No	No
24/04/08	90	1500	420	2673	20	22.9	33.64	6.81	No	No
Average	90	1500	439	2627	20.2	23.4	32.26	7.68	No	No

APPENDIX D

HEAT EXCHANGER DESIGN

D1. DESIGN OF A PROPOSED THERMAL ENERGY STORAGE SYSTEM

A shell and tube heat exchanger, with circular copper fins attached to the outside surfaces of the tubes was designed using Kern,s method. It was desired to melt RT27 PCM at 28°C using 300 kg/h of hot water from a parabolic trough solar energy collector. The water was to be cooled from 85°C to 35°C. The water flowrate and temperatures were based on the flow conditions of the fluid circulation system in the existing parabolic trough solar collector. The effectiveness of fins addition was calculated in order to justify the usage of fins for heat transfer enhancement.

Dimensions were as follows:

Tube dimensions: I.D. = 0.016 m (d_1)

O.D.= 0.020 m (d_2)

Length of tubes: L = 1.83 m

Fin dimensions: Fin height, $h_f = 0.015$ m

Fin thickness, $t_f = 0.005$ m

Spaces between fins, $S = 0.030$ m

Total number of fins = 61

Properties of streams:

Property	PCM at 28°C	Water at 60°C
Heat capacity (kJ/kg.K)	2.4	4.2
Latent heat of fusion (kJ/kg)	179	-
Thermal conductivity (W/mK)	0.2	0.6
Viscosity (Pa.s)	0.004	0.00047
Density (kg/m ³)	840	995

Assumptions

1. Steady state conditions exist.
2. Uniform heat transfer coefficient over the entire fin surfaces.
3. Constant thermal conductivity.
4. Natural convection exists in the shell side.
5. Radiation is negligible.

Heat load

$$Q = \frac{mcp\Delta T}{t} = \frac{300 \times 4200 \times (85 - 35)}{3600} = 17500 \text{ W}$$

Melting rate of the PCM

$$\frac{m}{t} = \frac{17500}{179000} \times 3600 = 352.8 \text{ kg/h}$$

Log Mean Temperature Difference

$$\Delta T_{lm} = \frac{(85 - 28) - (35 - 28)}{\ln \frac{(85 - 28)}{(35 - 28)}} = 24^\circ \text{C}$$

Provisional area

From Figure 12.1 [65], the estimated value of heat transfer coefficient is $U = 600 \text{ W/m}^2\text{C}$

$$A = \frac{17500}{600 \times 24} = 1.22 \text{ m}^2$$

Surface area of one tube:

$$\begin{aligned}
 A_{\text{fin}} &= 2\pi(r_f^2 - r_2^2) + 2\pi r_f t_f \\
 &= 2\pi[0.025^2 - 0.01^2] + 2\pi \times 0.025 \times 0.005 \\
 &= 0.0033 + 0.000785 \\
 &= 0.004085 \text{ m}^2
 \end{aligned}$$

Unfinned portion of the tube:

$$A_{\text{unfin}} = \pi D_2 S = \pi \times 0.020 \times 0.025 = 0.00157 \text{ m}^2$$

$$\text{Total no of fins} = \frac{\text{Tube length}}{\text{Fin pitch}} = \frac{1830}{30} = 61 \text{ fins}$$

$$\text{Total area} = 61 (0.004085 + 0.00157) = 0.345 \text{ m}^2$$

Number of tubes

$$\text{Number of tubes} = \frac{1.22}{0.345} = 4 \text{ tubes}$$

Shell diameter, d_s

Use 1.25 triangular pitch.

$$\text{Bundle diameter, } D_b = 50 \left(\frac{4}{0.319} \right)^{\frac{1}{2.142}} = 162.82 \text{ mm}$$

Optimum tube length to shell diameter falls within the range of 5 to 10 [65].

$$\text{Shell diameter, } d_s = \frac{1830}{9} = 203 \text{ mm}$$

Tube-side coefficient, h_i

$$\text{Cross-sectional area of one tube} = \frac{\pi(0.016)^2}{4} = 2.01 \times 10^{-4} \text{ m}^2$$

$$\text{Tube-side flow area} = 4 \times 2.01 \times 10^{-4} = 8.04 \times 10^{-4} \text{ m}^2$$

$$\text{Mass velocity of water} = \frac{300}{3600 \times 8.04 \times 10^{-4}} = 103.65 \text{ kg/m}^2 \text{ s}$$

$$\text{Mean water temperature} = \frac{85 + 35}{2} = 60^\circ\text{C}$$

Density of water at 60°C is 985 kg/m^3 :

$$\text{Water linear velocity, } u = \frac{103.65}{985} = 0.105 \text{ m/s}$$

Viscosity of water at $60^\circ\text{C} = 0.47 \text{ mNs/m}^2$

Thermal conductivity of water = $0.651 \text{ W/m}^\circ\text{C}$

$$\text{Re} = \frac{0.016 \times 0.105 \times 985}{0.47 \times 10^{-3}} = 3520.85$$

$$\text{Pr} = \frac{4184 \times 0.47 \times 10^{-3}}{0.651} = 3.02$$

Neglect $\left(\frac{\mu}{\mu_w}\right)$

$$\frac{L}{d_i} = \frac{1.83 \times 10^3}{16} = 114.38$$

$$j_H = 4 \times 10^{-3} \text{ (From Figure 12.23 [65])}$$

$$h_i = \frac{k_f Nu}{d_e} = \frac{0.651}{0.016} \times 4 \times 10^{-3} \times 3520.85 \times 3.02^{0.33} = 825 \text{ W/m}^2\text{ }^\circ\text{C}$$

Shell-side coefficient, h_s

$$\text{Baffle spacing} = \frac{203}{5} = 40 \text{ mm}$$

$$\text{Tube pitch} = 1.25 \times 20 = 25 \text{ mm}$$

$$\text{Cross flow area, } A_s = \left(\frac{25 - 20}{25}\right) \times 203 \times 40 \times 10^{-6} = 0.00162 \text{ m}^2$$

$$\text{Mass velocity, } G_s = \frac{0.098}{0.00162} = 60.49 \text{ kg/sm}^2$$

$$\text{Equivalent diameter, } d_e = \frac{1.1}{20} (25^2 - 0.917(20)^2) = 14.4 \text{ mm}$$

Mean shell side temperature = 28°C

PCM density at $28^\circ\text{C} = 840 \text{ kg/m}^3$

Viscosity = $4 \times 10^{-3} \text{ Ns/m}^2$

Heat capacity = 2.4 kJ/kg.°C

Thermal conductivity = 0.2 W/m.°C

$$\text{Re} = \frac{G_s d_e}{\mu} = \frac{60.49 \times 14.4 \times 10^{-3}}{4 \times 10^{-3}} = 218$$

$$\text{Pr} = \frac{C_p \mu}{k_f} = \frac{2.4 \times 10^3 \times 4 \times 10^{-3}}{0.2} = 48$$

For laminar flow conditions:

$$\text{Nu} = 1.86(\text{Re Pr})^{0.33} \left(\frac{d_e}{L} \right)^{0.33} \left(\frac{\mu}{\mu_w} \right)^{0.14} = 1.86(218 \times 48)^{0.33} \left(\frac{14.4}{1830} \right)^{0.33} = 7.97$$

$\left(\frac{\mu}{\mu_w} \right)^{0.14}$ was neglected.

$$h_s = \frac{\text{Nu} k_f}{d_e} = \frac{7.97 \times 0.2}{14.4 \times 10^{-3}} = 111 \text{ W/m}^2 \cdot \text{°C}$$

Overall coefficient

Thermal conductivity of copper = 83 W/m°C

Scales resistances will be taken as 0.00025 m².°C /W for water and 0.00020 m².°C /W for PCM.

$$\frac{1}{U_o} = \frac{1}{E_f} \left(\frac{1}{h_f} + R_f \right) \frac{A_o}{A_f} + \frac{d_o \ln \left(\frac{d_o}{d_i} \right)}{2k_w} + \frac{d_o}{d_i} \times R_i + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right)$$

$$A_o = \frac{\pi d_o^2}{4} = \frac{\pi (0.020)^2}{4} = 0.000314 \text{ m}^2$$

$$A_f = \frac{\pi (0.050)^2}{4} = 0.00196 \text{ m}^2$$

Typical effectiveness, $E_f = 0.95$ [65]

$$\frac{1}{U_o} = \frac{1}{0.95} \left(\frac{1}{110.69} + 0.00020 \right) \frac{0.000314}{0.00196} + \frac{0.020 \ln \left(\frac{0.020}{0.016} \right)}{2 \times 83} + \frac{0.020}{0.016} \times 0.00025 + \frac{1}{825} \left(\frac{0.020}{0.016} \right)$$

$$U_o = 293.10 \text{ W/m}^2 \cdot \text{°C}$$

Pressure drop**Tube side**

Re = 3520.85 from figure 12.24 [65]:

$$j_f = 6.5 \times 10^{-3}$$

Neglecting the viscosity correction:

$$\begin{aligned} \Delta P_t &= \left[8 \times 6.5 \times 10^{-3} \left(\frac{1830}{16} \right) + 2.5 \right] \frac{985 \times (0.105)^2}{2} \\ &= \mathbf{45.87 \text{ Pa}} \end{aligned}$$

Which is low, permitting a possible increase in the number of tube passes.

Shell side

$$\text{Linear velocity} = \frac{G_s}{\rho} = \frac{60.49}{840} = 0.0720 \text{ m/s}$$

From Figure 12.30 [65], at Re = 218:

$$j_f = 1.3 \times 10^{-1}$$

$$\begin{aligned} \Delta P_s &= 8 \times 1.3 \times 10^{-1} \left(\frac{203}{14.4} \right) \left(\frac{1830}{40} \right) \frac{840 \times (0.0720)^2}{2} \\ &= \mathbf{1460.4 \text{ Pa}} \end{aligned}$$

This is lower than 70 kPa, which is acceptable.

Actual heat transfer area

$$A = \frac{Q}{U\Delta T} = \frac{17500}{293.10 \times 24} = 2.5 \text{ m}^2$$

Actual number of tubes

$$N_t = \frac{2.5}{0.345} = 7 \text{ tubes}$$

Actual shell diameter

$$\text{Bundle diameter, } d_B = 50 \left(\frac{7}{0.319} \right)^{\frac{1}{2.142}} = 211.43 \text{ mm}$$

$$\text{Shell diameter, } d_S = 211.43 + 50 = 260 \text{ mm}$$

Fin Effectiveness**Finned tubes:**

Assuming fin efficiency of 0.95 [65].

$$Q_{fin} = \eta_{fin} Q_{fin.max} = \eta_{fin} UA_{fin} \Delta T = 0.95 \times 0.345 \times 293.1 \times 24 = 2305.52 \text{ W}$$

Unfined tubes:

$$A_{no\ fin} = \pi DL = \pi \times 0.02 \times 1.83 = 0.115 \text{ m}^2$$

$$Q_{no\ fin} = UA\Delta T = 293.1 \times 0.115 \times 24 = 808.96 \text{ W}$$

$$\varepsilon_{fin} = \frac{Q_{fin}}{Q_{no\ fin}} = \frac{2305.52}{808.96} = 2.85$$

The rate of heat transfer was increased by a factor of almost 3, as a result of adding fins. This justifies the use of finned surfaces since an effectiveness of $\varepsilon_{fin} > 1$ indicates that fins are enhancing heat transfer from the surface, as they should.