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Solar thermal energy storage in power generation using phase change material with heat pipes and fins to enhance heat transfer.

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Abstract

Phase change materials absorb or otherwise release heat at close to a constant temperature during its melting and solidification phases. This is a very sought after property in power generation, where a high temperature heat source is required within a narrow temperature range as heat input for the turbine. Solar tower technology provides a high temperature heat source, but unfortunately it is time dependent. A sufficient amount of this heat may be stored in a phase change storage system which can deliver dispatchable heat. In such a storage system the phase change material needs to be exposed to a sufficient heat transfer area to melt or solidify at sufficient rates. In this study this is achieved with heat pipes with metallic fins. The analysis of this design included testing an experimental module during heat absorption and heat removal cycles, as well as a numerical analysis to model the storage module. To determine the parameters for a specific phase change storage system in a high temperature solar tower application the validated numerical thermal response simulation is incorporated. Certain solar input conditions and load cases are applied to the phase change storage system model and the size and geometry of the solar thermal storage system are determined from this analysis.

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Keywords: Phase change material; solar thermal energy; heat transfer enhancers; heat pipes; metallic fins

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1. Introduction

Advances in solar thermal systems have made it possible to achieve a high temperature heat source from solar irradiation. This high temperature heat needs to be stored to achieve dispatchable power. There are some sensible

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two tank molten salt systems under construction and in operation around the world [1]. This kind of system stores heat in a sensible form, for example, the solar power plant Crescent Dunes in Tonopah, Nevada, USA will heat a large amount (32 000 tons) of molten salt from 288°C to 565°C during its heat absorption phase. It will deliver 110 MW of electricity for 10 hours during a full heat removal cycle [2]. The larger the temperature difference the larger is the heat storage, and a very large quantity of molten salt is required. Alternatively heat may be stored in latent form by melting a PCM salt from solid to liquid form. The latent heat of PCM salts vary between 60 kJ/kg to 1700 kJ/kg depending on the salt. For example, the latent heat absorbed or removed from table salt (NaCl) is 482 kJ/kg at a melting temperature of 801°C. Phase change materials absorb or release heat at a close to constant temperature during its melting and solidification phases. In this study experimental tests were conducted using paraffin wax melting at 59 °C and having a latent heat of fusion of 200 kJ/kg, and for the CSP power plant test facility a numerical simulation model that uses the properties of a salt containing 45% KCl and 55% KF on a molar basis and melting at 605 °C and having a latent heat of fusion of 407 kJ/kg [3].

The immediate advantages of using such a PCS system is that only one storage tank is required, which reduces containment costs and a smaller size tank will be required because of the high energy density of the phase change material. Also the container need not withstand high pressures, because the volume change is such that the container can be kept at atmospheric pressures. A further advantage is that by using a phase change material as storage medium a large amount of latent heat is available at a close to constant temperature during solidification when heat is extracted from the storage material. This high temperature heat storage system may be able to deliver reliable heat to the heat transfer fluid which in turn can supply heat to another heat exchanger, which boils high pressure water that power the turbine until the PCS system has delivered all its useful heat. However many PCMs have a low thermal conductivity. To remove all the absorbed heat from the PCM it needs to be exposed to a sufficient heat transfer area of the heat exchanger surfaces because of its low thermal conductivity. In this study this is achieved with heat pipes and metallic fins.

In this article the objectives are determined and the relevant literature reviewed. Following these sections a modular PCS concept is described. Following that the experimental and numerical work based on this test module, which uses paraffin wax as the PCM which melts at low temperatures, is summarised. Furthermore, a numerical model is developed based on the validated PCS system's numerical model for a high temperature PCS system using PCM salts and which incorporates a solar tower as solar input. The generated results will be described in the results section. A discussion and conclusion will follow.

Nomenclature

Symbols	
$\dot{Q}$	Power
Q	Energy
T	Temperature
X	Fraction
Subscripts	
Al	Aluminium
b	Bottom
c	Condenser
E	Experimental
e	Evaporator
ext	Extracted
hp	Heat pipe
i	Inner
N	Numerical
l	Left
r	Right
t	Top
S	Storage
salt	Phase change salt
V	Volume
w	Wall
wax	Paraffin wax
Abbreviations	
CSP	Concentrating Solar Power
HTE	Heat Transfer Enhancers
HTF	Heat Transfer Fluid
PCM	Phase Change Material
PCS	Phase Change Storage

2. Objectives

The objective of this study was to design, build and test a phase change storage module. This characterized module will be used as a building block in a phase change storage system.

The analysis objectives are to set up numerical models of the storage systems, both of the low temperature storage module to validate it with the experiments, as well as in a CSP power plant test facility to determine its predicted performance.

3. Literature study

Work is underway to investigate the inherent potential that phase change storage systems may hold for solar thermal energy storage systems [4]. PCMs exhibit high energy densities during the phase change process between solid and liquid states and contain significant heat capacity during sensible heat up and cool down processes. The container may be kept at atmospheric pressures and this reduces containment cost compared to using high pressure steam as PCM.

One of the main drawbacks of many of the PCMs is its low thermal conductivity. The adverse insulating effect is most noticeable during the heat removal phase when the PCM coagulates onto the heat exchanger surfaces. The only mode of heat transfer through the growing solid layer is by conduction. Therefore using such PCMs as storage material results in long heat absorption and especially long heat removal periods of a PCM storage container, because natural convection does not aid the solidification process [4]. An extensive research effort has been directed at shortening the heat absorption and heat removal periods of a PCM container and 28 references are noted by Agyenim *et al.* [5] that investigated heat transfer enhancement by either geometry adaptation or embedding highly conductive material in the PCM. The result of this research effort is that there are various design options available to increase the heat removal rates from a given mass of PCM to some extent, by using many small pipes in a shell and tube configuration at the cost of intricate welding and large pressure losses, or encapsulation of the PCM, or embedding the PCM in highly conductive foams or porous material such as graphite, or using heat pipes and fins. Various geometries of heat transfer enhancers (HTE) have been investigated to heat or cool the PCM, but to reach some form of compromise between storage capacities of the resulting configuration per unit mass, cost of materials utilised and the shortened resulting heat absorption and heat removal rates from the formed mixture of PCM and HTE further analysis is required.

In this study the heat transfer enhancing technique that was selected was to use heat pipes and fins. Other researchers, for example Lui *et al.* investigated a phase change storage system with heat pipes and fins to enhance the heat transfer to and from the PCM [6,7]. It consisted of 5 multipurpose cylindrical heat pipes with horizontal disk fins all along its length. The PCM container was encased in between the hot HTF channel at the lower section of the evaporator and the cold HTF channel at the upper condenser section. The results were only analysed experimentally and no mention was made of the fluid phenomenon inside the storage container. By testing it numerically, improvements in design may be made quickly and cheaply and by understanding the flow phenomena inside the storage container, a more accurate representation can be set-up numerically. Robak *et al.* argues that small laboratory scale tests may be built and analysed with lower melting temperature PCMs before larger systems are constructed and tested at higher temperatures for commercial viability [8]. This may aid initial design decisions and improve geometry layout for a particular application. Robak *et al.* tested three set-ups experimentally: One just with PCM in a cylindrical container heated from below, one with 5 added vertical rods, and one with 5 added heat pipes. The melting and solidification periods were significantly decreased when the heat pipes were incorporated into the PCM, compared to the metal rods and the PCM only test case. Unfortunately no tests were done with finned heat pipes to give an indication of how much the heat absorption and heat removal periods of such a system could be shortened. The low thermal conductivity of the PCM lends itself to finned surfaces to decrease the distance that heat needs to be transferred through the solid PCM. In further studies a decision was made to only use heat pipes to enhance heat transfer, without considering combining the two [9,10].The results are still laboratory set-up specific.

From an economic perspective Robak *et al.* did spearhead a comparison evaluation between a latent heat thermal energy storage system using heat pipes and a two tank molten salt system and found a 15% reduction in cost for a 50 MW parabolic trough plant [9]. Shabgard *et al.* did an analysis on cascaded PCMs between 280-390°C and heat pipes and found that the cascaded system recovers the maximum exergy, or in other words the quality of the heat is retained to a higher degree during a 24 hour charging-discharging cycle [10]. This is mainly due to a more uniform temperature difference between the PCM and the HTF as it passes through the heat exchanger. These analyses lay the ground for further thermodynamic improvements to be made that may lead to cost savings.

In this study the focus is on developing a PCS system for a solar tower application which can reach high temperatures and combining both heat pipes and fins to transfer heat to and from the PCM. In this way fewer heat pipes will be required and a lower temperature difference will be required to melt or alternatively solidify the PCM.

However in a solar thermal energy system it is especially required to have a storage container capable of quick heat removal periods. This limiting characteristic can be circumnavigated by adding heat transfer enhancers to the storage container and embedding the phase change material into it. Different HTE's have been investigated, such as metal foams [11], graphite matrix [12], adding of metal particles, encapsulating the phase change materials and by extending the heat transfer surface of the heat exchangers with fins [13] and short heat pipes [14]. Long heat pipes have also been suggested in thermal storage systems because of high heat transfer rates, and the heat is extracted over a larger distance especially during the critical solidification phase of the phase change material [6-9]. The different materials used to enhance heat transfer consisted of certain metals or graphite with high thermal conductivity. Also, the shape in which these materials were incorporated into the PCM varied widely, for example fins, matrixes, foams, mesh, shavings, brushes, encapsulation of PCM and heat pipes. From these options the designer of a PCS system needs make the decision of what enhancers to employ on the basis of cost and thermal performance. Developing thermal simulation models of the different configurations may act as a simulation tool to make better informed decisions.

Concluding this section, the argument made in this paper is that one can use heat pipes and fins to enhance heat transfer rather than choosing one or the other. In the past, only an experimental model of heat pipes with fins was tested. However, in this article, a numerical model is proposed as well. In the following section the concept development is explained.

4. Concept development and experimental set-up of the modular PCS with enhanced heat transfer capabilities

A storage module is designed and tested to quantify its thermal response. The aimed characteristic of this module is that it should deliver heat across a narrow temperature range. The heat must also be absorbed or delivered at a sufficient rate during the heat absorption and heat removal cycles. Maximum utilisation of the storage system must be achieved during such a heat absorption and heat removal cycle. Because convection does not enhance heat transfer significantly during the cooling of the PCM, and because of the solid layer coagulates on the heat extraction surfaces that reduce the rate of heat transfer from the PCM to the heat removal heat pipes, heat transfer enhancers will be added to increase the effective heat transfer surface area. A PCM is used as heat storage material to enable the development of smaller, more compact thermal energy storage vessels that will not only result in lower environmental losses, but also in cheaper thermal energy storage systems. The aim is to develop a module that overcomes the insulating effect caused by the solidification of the PCM on heat transfer surfaces during heat removal to some extent by adding heat transfer enhancers. This module (shown in Figure 1(a)) comprises heat pipes and rectangular fins as HTEs. This storage module consists of a rectangular fin block with 0.87 kg paraffin wax embedded into it. At the left side of the container is a multichannel rectangular Furukawa micro heat pipe to transfer heat to the storage module and at the right side is a similar Furukawa micro heat pipe to transfer heat from the PCS system. There are several thermocouples placed in the PCS module, and specifically thermocouples T_{S04} or T_{ml} the middle left thermocouple, T_{S05} or T_{mm} the central middle thermocouple and T_{S06} or T_{mr} the middle right thermocouple are used to calculate the heat absorbed and energy of the PCS module.

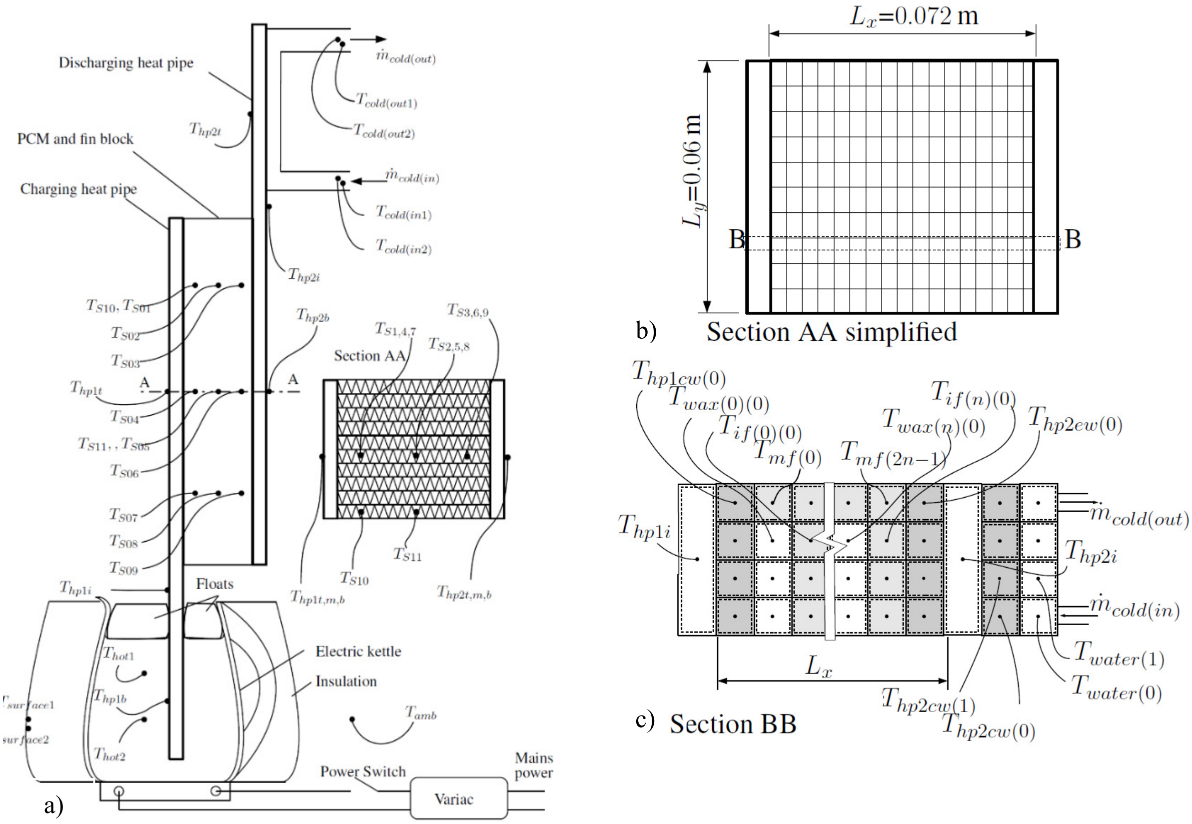

Fig. 1. (a) The experimental set-up of the phase change storage module; (b) The simplified cross section of the PCS module viewed from the top with the solution domain of the storage module; (c) The thermal resistive network of the numerical PCS module.

The fin geometry is composed of rectangular fins connected to the heat pipes. In between these fins additional fins form a zigzag shape to contain the phase change material and form additional heat paths. The PCM cells that are formed when it is melted and poured in between the fins are long and rectangular in shape. When heat is transferred to the PCM cell it may start to melt and the liquid expands. In this setup the molten PCM may expand in the vertical direction. During the heat removal phase heat is transferred from the PCM to the fins, it is then conducted from the fins to the heat pipes, from where it is transferred to the heat exchanger that heats water coming from a constant head tank.

Heat pipes were selected to transfer heat uniformly along the length of the storage container during the heat absorption and heat removal cycles. It is a passive closed loop thermo siphon that makes use of boiling of the fluid at the lower evaporator section and condensation of the vapour at the higher condenser section to transfer heat across even a small temperature range. It may be used effectively in a solar thermal application by penetrating deep into the phase change storage container. Even thin diameter pipes may be used to transfer a large amount of energy to and from the storage container.

The design of the PC storage system was developed with the end design in mind; this end design will consist of many of the test modules. This novel test module is indicated in Figure 1(a). It has a geometry that can be modelled easily numerically; the discretized numerical model is indicated in Figures 1 (b & c). The wax is contained inside long narrow vertical compartments that is heated uniformly from the side with the aid of a heat pipe. This enables the wax to expand and contract in the vertical direction during melting and solidification without building up unnecessary pressure inside the container. The storage module is composed of a rectangular PCM container that has a charging heat pipe connected to the heating side, and a discharging heat pipe connected to the heat extraction side. Fins compartmentalise the phase change material into small rectangular convection suppressed compartments. This configuration leads to effective heat transfer to and from the embedded phase change material, because of the reduced distance that heat needs to be transferred through the insulating solidified phase change material.

4.1. The experimental module

During the current research two experimental modular set-ups were designed, built and tested. One of the modules contained only wax, while the other module contained fins with wax in between the fins. The experimental module comprises two rectangular heat pipes with a rectangular PCM section sandwiched in between as indicated in Figure 1. Paraffin wax melting at 59 °C was melted into the storage section. The test section comprised a rectangular PCS test module with dimensions of 60 mm wide by 72 mm thick by 300 mm high. The reason for this shape was to create a close to two dimensional heat flow by applying heat uniformly to one side with the aid of the charging heat pipe during heat absorption, as well as during heat removal when heat was transferred to the other side with the aid of the discharge heat pipe.

The tests comprised a heat absorption phase by heating up the kettle electrically, and a heat removal phase where the hot water was first extracted from the kettle and cold mains water was then allowed to flow through the top heat exchanger from a constant head tank in order to cool down the wax. Both modules were tested for heat absorption and heat removal cycles. The results of these tests are summarised in Section 5.

4.2. The numerical module

A numerical model was set up to calculate theoretically how the storage system will perform thermally. It makes use of the explicit Euler method [13]. It is a C++ program and it solves the explicit equations at each time step. A time step of $\Delta t = 0.5$ ms was found to give stable results. One hour of real time requires 18 min of CPU time on a 2.3 GHz CPU. It keeps track of the temperature and state. During each time step of the numerical simulation the new state of each control volume is determined. This includes both its temperature and phase, whether it's liquid or solid or a mixture of the two. With the new temperature and phase values the thermophysical properties are evaluated. The model is a two dimensional conduction model. The control volumes of the fins and the phase change material are discretised into long vertical rectangular volumes. The convection currents of the liquid phase change material are deemed to be negligible because of the large aspect ratio between the thickness and the height of the PCM. Also during the heat removal cycle convection does not enhance heat transfer [13].

The numerical model of the test module was set up to be as similar as possible to the physical test module. The geometry was set to be similar with the storage size to be 300 mm long, 60 mm deep and 72mm wide. The fins comprised a volume percentage $X_{V(Al)}$ = 20.6% and is comprised of 1.2mm thick fins spaced 8 mm apart with a zigzag 0.15 mm thick fin placed in between to form the compartments. The heat pipes are rectangular Furukawa micro heat pipes with a geometry 500mm long, 60mm deep and 1 mm wide and was deemed useful in delivering a uniform flux to the storage compartment.

The numerical simulation is set up by taking the minimum required control volumes to capture the temperature distribution inside the storage container. The fins form repetitive sections which are modelled by using thermal symmetry and assuming that heating occurs uniformly along the height of the storage section because uniform saturation temperatures exist all along the length of the heat pipe during normal operation. The numerical model is closely modelled to the physical experimental module to make a reasonable comparison possible between the experimental and numerical module.

4.3. Numerical system analysis

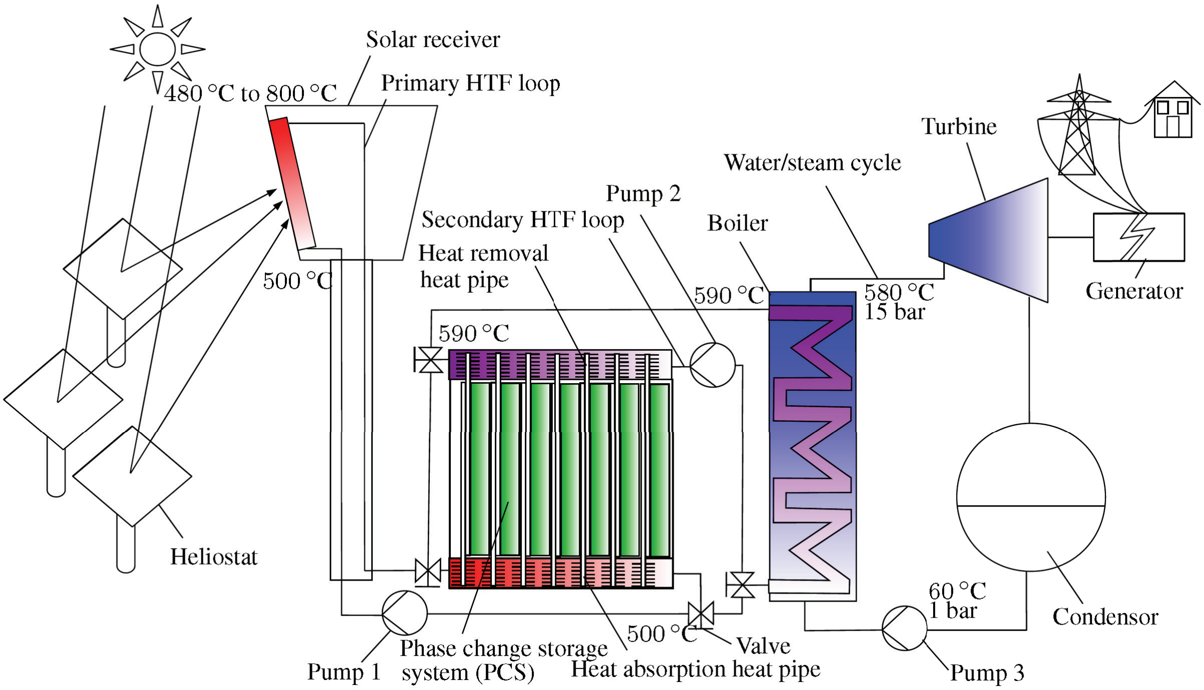

Fig. 2. The solar thermal system used in the numerical model.

The numerical module simulation will be compared to the experimental module in Section 5 and when it compares well it will be adapted to suit a particular solar thermal energy storage system. The numerical model is adapted to simulate a solar tower test facility being built on a farm in Meerendahl near Stellenbosch in South Africa. This is called the *Helio 100* project. The envisioned final system layout is shown in Figure 2. The receiver receives solar irradiation on a 1 m² aperture from 440 m² of heliostat mirrors. 3 300 kg of salt is used in the storage container and it is composed of 45% KCl and 55% KF on a molar basis and it melts at 605 °C and has a latent heat of fusion of 407 kJ/kg [3]. There is the problem with corrosion associated with this PCM, but hopefully this challenge can be overcome by coatings or designing for corrosion in the future and PCMs with a suitable melting temperature and latent heat of fusion may be used.

The solar thermal system model is shown in Figure 2 and operates in the following manner: Solar radiation reflected from the heliostat field is absorbed in the solar receiver. This causes the solar receiver tubes to heat up and transfer heat to the heat transfer fluid. This HTF would operate at low pressures and could be molten glass which must be kept above 450 °C to avoid freezing in the pipes. As a final option sodium may be used, but it is known for its flammable reactivity to water or even the moisture in the air and therefore holds a safety risk. The HTF is pumped either to the storage container where it transfers its heat to the charging heat pipes, which in turn transfers heat and melts the storage material, or the PCS system is bypassed and it directly heats and boils water in the boiler. When additional heat is required by the boiler because of intermittent solar irradiation, and the storage has heated up sufficiently the second pump is switched on. The storage material now transfers its absorbed heat to the discharge heat pipes that finally transfers it to the HTF. The water in the water/steam loop is first pumped to high pressures in the range of 10-15 bar before entering the boiler. It is then superheated in the boiler and from there it is passed to the turbine. Thin steel fins of 0.15 mm thickness were used in the analysis to save on material cost of the fins. The modules were grouped into a cylindrical shape in order to limit heat loss to the environment. The solar receiver was modelled by using a quart glass pane in front of the receiver tubes. Also the receiver tubes were coated with a selective coating in order to limit losses to the environment by radiation. One metre thick insulation with a thermal conductivity of 0.026 W/m K was used with galvanised iron sheeting as cover material around all tanks and piping having an emissivity of 0.2 and a solar absorptivity of 0.7. Temperature data from the nearby University weather station was used to calculate typical ambient and sky temperatures as well as wind conditions from which the convection and radiation losses were calculated for each time step.

Thus far, the concept of an enhanced heat transfer storage module has been described and the numerical models relating to this concept have been discussed. The results of the experiment will be discussed in the following section.

5. Results

5.1. Experimental and numerical results of the PCS module

In the current experimental research aluminium fins and rectangular heat pipes were utilised to enhance heat transfer into and out of a paraffin wax PCM. The reason for this was that the heat transfer into and out of the phase change material was much slower when no fins were used than when fins were used during heat absorption and heat removal cycles. For example during the heat absorption cycle of the storage module only containing wax and no fins, it took three times as long to melt compared to the storage section with fins. During the heat removal cycle over a period of 1 hour 15 minutes, five times more energy was extracted from the finned configuration than from the wax only configuration. This was in spite of the wax only storage module containing 20% more wax. The wax only case was thus unable to extract the absorbed latent heat trapped inside the PCM, because the solid layer that forms during the solidification process on the heat extraction heat pipe insulates the still liquid wax from transferring its latent heat to the heat extraction heat pipe. This gives an indication of the potential for using heat pipes as well as finned PCS systems where all the heat may be extracted within a reasonable amount of time, across a small temperature range.

The experimental and numerical results of the finned storage module are compared in Figures 3-5. First the temperature response is given for both the heat absorption and heat removal test in Figure 3, then the heat absorbed and heat removed is depicted in Figure 4. From Figure 4 it is noted that the 3 representative thermocouples can closely resemble the heat absorbed and removed during a heating and cooling test when compared to the numerical model of the heat absorbed and removed from the storage. Finally the total energy stored and the energy removed from the PCS module is depicted in Figure 5. From Figure 5 it is noted that the energy response is very similar between the experimental and numerical analysis for the heat absorption phase in terms of the magnitude of energy available, but for the heat removal phase the period of heat removal is different because different flow rates were used. Overall the temperatures of the numerical model compares well with the discreet thermocouple measurements, and the power and energy response of the numerical model is verified by this comparative analysis.

When considering Figure 3 in more detail the temperature of the storage module increases quickly from the cold start-up condition as can be seen in Figure 3(a), but when it starts to melt the rate of temperature increase decreases significantly as can be seen looking at the fin power absorption in Figure 4(a). Then when all the wax is melted completely, the rate of temperature increase increases before finally slowing down at the end of the heat absorption phase when the storage section reaches thermal equilibrium. In the heat removal test shown in Figures 3(b),4(b) and 5(b) the reverse happens. First, the rate of temperature change is high and the temperature decreases fast, mostly because the temperature difference is large. Secondly, it decreases slower when the phase change material solidifies and when it is completely solidified the PCM cools down further, until almost no heat is transferred anymore and the heat removal cycle is complete.

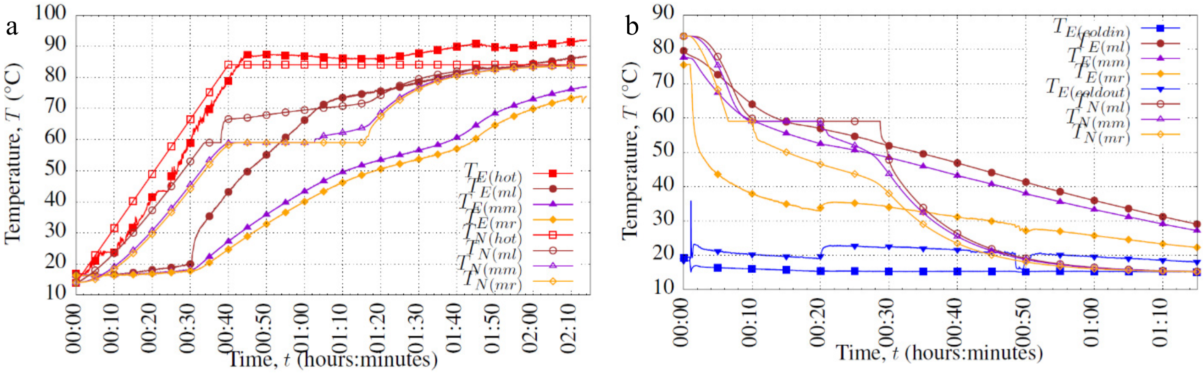

Fig. 3. (a) The temperature response during heat absorption phase; (b) The temperature response during heat removal phase.

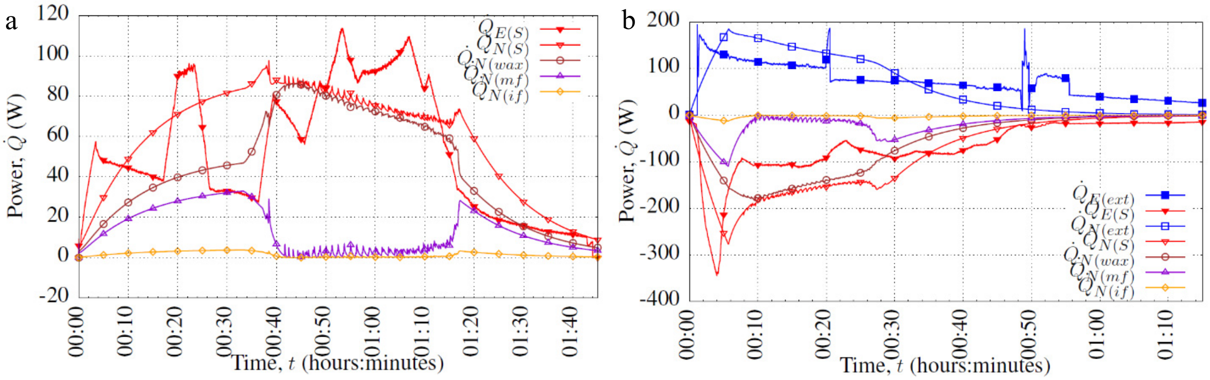

Fig. 4. (a) The absorbed power during the heat absorption phase; (b) The extracted power during the heat removal phase.

The power transferred to the storage section during the heat absorption cycle, indicated in Figure 4(a), increases steadily because the temperature in the kettle is continually raised. Then when the temperature difference stays the same during the phase change to liquid form, the power absorbed decreases very slightly. Subsequently when the PCM is completely melted, the rate decreases until thermal equilibrium is reached. The energy stored indicated in Figure 5(a) is similar between the experimental and numerical results both in shape, magnitude and time period from onset of the heat absorption test to the completion of the heat absorption. The fins act as heat conduits that pass heat from the hot source to the PCM during the test.

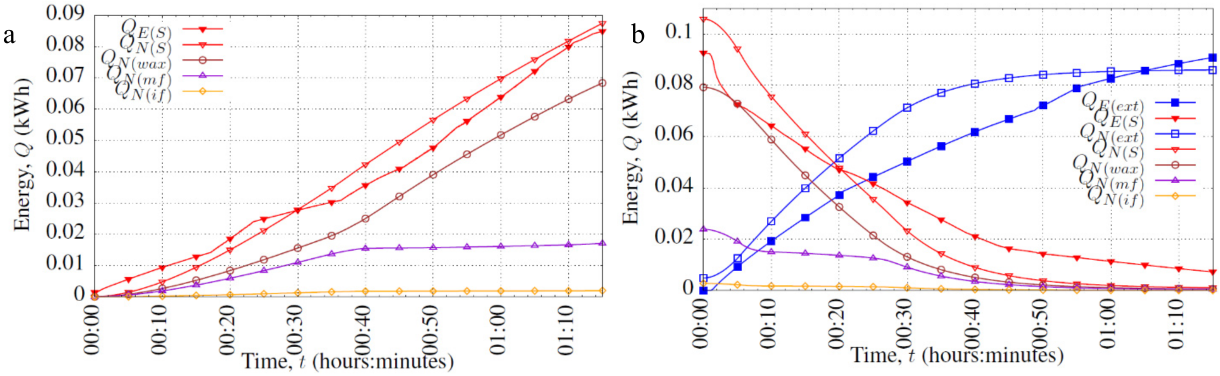

Fig. 5. (a) The absorbed power during the heat absorption phase; (b) The extracted power during the heat removal phase.

During the heat removal test water is passed through the heat exchanger and its thermal response is given in blue in Figures 3(b), 4(b) and 5(b). Initially the temperature difference is large and the heat extraction rate is high, then the rate steadily decreases until it starts to solidify and the power extracted stays close to constant until all PCM is solidified and then the power extracted diminishes to zero. The numerical and experimental results are similar in shape, but not in magnitude and time period to remove its absorbed heat. This may be because the flow rates did not completely match up and therefore the numerical model cooled quicker than the experimental module where the flow rate had to be kept to a slower rate to have a measurable temperature difference across the heat exchanger.

The results of the total energy absorbed into the storage module compare very well both in magnitude and in time period to completion of the heat absorption cycle. It is noted that the system absorbs heat at a close to constant power level during the heat absorption cycle when melting occurs. Also during the heat removal cycle heat is transferred very effectively out of the storage material. This indicates that heat transfer was enhanced in the test and very quick heat transfer rates can be achieved with this system.

The numerical model thermal response calculation is validated with this comparison to the experimental module. By comparing the numerical model to the experimental tests, it is clear that the numerical model, at least for the test module geometry, has been verified.

This model that models the test set-up module may now be adapted with a higher level of confidence to simulate a higher temperature application that will typically be experienced in a concentrating solar thermal application.

5.2. Results of the numerical model of Helio 100 with PCM salt storage

For this analysis the initial conditions of the control volumes were set to 350°C and the start time was set to 09:00. The reason for starting at solid cold state is that this is the chosen initial condition to see the transient response during heat up, but after a day of simulation it was found that the system becomes cyclic if the draw off conditions stays similar as well as the solar input between the different days. From that point in simulation time the storage system was allowed to be heated up from the heat absorbed by the solar receiver. It was found that some of the salt could be melted on the first day without extracting any heat to the power block, and it was possible to melt all the PCM on the second day as can be seen in Figure 6. The liquid salt in the cold heat exchanger that delivers its absorbed heat to the boiler experiences an unstable flow/no flow condition during cut off, because heat is delivered from the hotter to the colder side of the storage which cause the pump to switch on again. In a real power plant the pump would stay off when the storage becomes too cold.

The energy that was absorbed was successfully transferred to the power block at a time period between 15:00 and 24:00 as can be seen in Figures 7 and 8. The mass flow rate was kept constant at 0.435 kg/s and the heat delivered to the boiler started at 130 kW and steadily decreased to 100 kW as the storage system cooled down. The power graph in Figure 7 indicates that a high amount of incident solar radiation could be absorbed into the storage system and that the system will be able to deliver heat to the power block for a reasonable amount of time. During evening periods the storage system cools by delivering heat to the power block.

The energy graph in Figure 8 indicates the total energy incident during the two days of simulation, as well as the total energy absorbed by the receiver, stored in the PCS system and extracted to the power block. The system will be able to deliver heat to a small turbine and deliver heat at close to constant temperature during the heat removal cycle, as can be seen in Figure 6. The temperature loss that occurs during 21 December in the instant when the cold heat transfer fluid is initially passed through the top heat exchanger is the following, from the solar collector tubes that are at 700 °C, the PCS system is heated to 675 °C at the hottest heat absorption side, to 600 °C at the cold side. Also the heat transfer fluid T_{cold} enters the top heat exchanger at 400 °C and exits at between 550 °C at onset of heat extraction to 500 °C at completion of the heat removal cycle when the PCM has completely solidified. The environmental losses of the system are quite high, because the temperatures are excessively high and the insulation could be improved to further limit the environmental losses of the storage system.

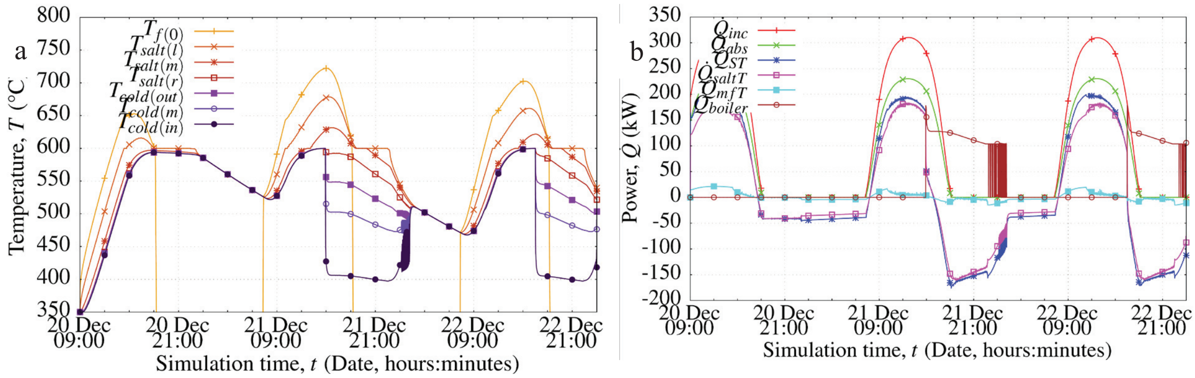

Fig. 6 The temperature (a) and power (b) response of the solar thermal storage system, during three days of numerical testing.

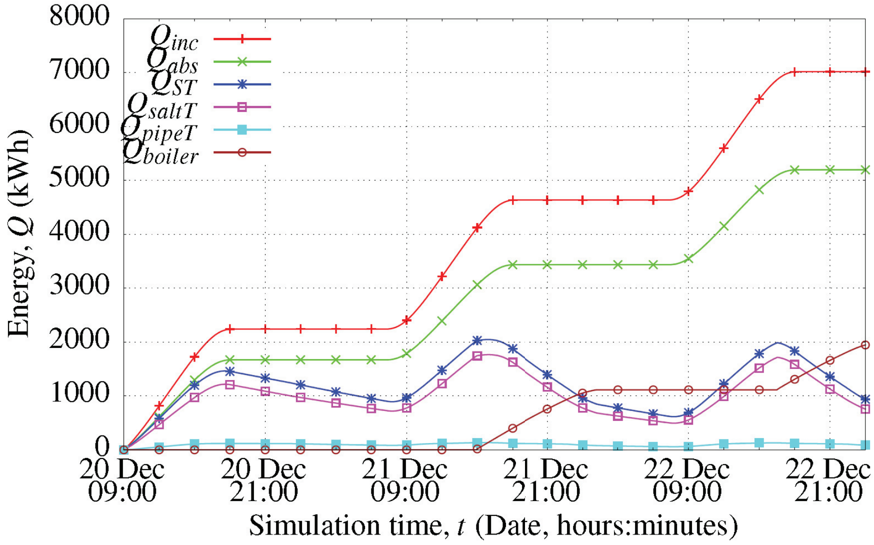

Fig. 7. The energy response of the solar thermal storage system, during three days of testing.

In the next section of this paper, a brief discussion and conclusions will be given.

6. Discussion and conclusions

A modular PCS system utilising heat pipes with fins is suggested in the current research to improve heat transfer to and from the storage material. Such a storage system would only require one storage tank, and a smaller amount of storage material would be necessary because of its high energy density. The experiments of a test module give an indication of how a phase change material will melt and solidify in this particular geometry. The developed numerical model calculates how the system would perform thermally, paying specific attention to the phase change inside the control volumes. The validated numerical model is also adapted to suit a high temperature application which would contain many modules and use a high melting temperature salt such as 45% KCl and 55% KF on a molar basis melting at 605 °C and having a latent heat of fusion of 407 kJ/kg and a fin material such as steel. Further research is required to find either compatible materials, or using inert coatings on the fins and heat pipes to manage corrosion [3]. The numerical model calculated how such a system may perform physically and gives further insight into system design and operation procedures. For example, this modular system was applied in a solar tower test facility application to deliver heat at a high temperature to a turbine and it was capable of delivering heat in a narrow temperature range for a time period of 9 hours The power delivered to the boiler started at 125 kW and the heat output decreased proportionally to 100 kW when heat transfer to the boiler was ceased. During such a heat removal cycle 1 100 kWh was delivered to the boiler. This system is not yet optimised and further thermodynamic improvements can be achieved, for example, with a cascaded PCM system. This could result in higher efficiencies and better usage of the solar energy.

The accurate evaluation of the PCS system is of great importance for the solar thermal power system, because the capacity and thermal performance of the PCS system must be closely linked to the available solar resource and the turbine used, as well as the ideal times to deliver energy to the grid. The designed modular storage system can be used in any solar thermal energy application. The system layout may be determined by using the validated numerical thermal response simulation and the systems thermal performance may be calculated with the numerical model. It is recommended that Stellenbosch University further investigate enhanced heat transfer phase change storage systems for solar power generation.

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