STUDIES ON IMPROVING HEAT TRANSFER IN SOLAR APPLICATIONS

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ABSTRACT

Solar thermal technologies' commercial viability and economic viability are dependent on the creation of efficient and reasonably priced thermal storage systems. Due to its isothermal behaviour during charging and discharging and huge heat storage capacity, thermal storage units that use latent heat storage materials have gained more attention in recent years. For any application involving latent heat thermal storage (LHTS), heat transfer augmentation techniques are necessary, as the thermal conductivity of most high energy storage density phase-change materials (PCM) is unacceptable.

Enhancing heat transfer in a thermal storage device made up of a cylindrical vertical tube with an arrangement of longitudinal fins inside it is studied. Following is a full mathematical and analytical model created using the enthalpy formulation to look into how non-dimensional factors affect the LHTS unit's performance. The current work creates a broad H-T relationship that works for materials that have either constant phase change temperatures or a range of them. Finding solutions to phase change problems using numerical methods is easier because of this link. What makes the computer model special is that it considers the flow of heat around the edge of the container. For a useful range of Biot numbers and other geometrical and physical factors, the need for fins and the need to think about the circumferential heat flow are scrutinised. This article explains how the experimental findings can be used to validate the numerical model. On a practical range of parameters, the temperature distribution along the radial direction in the fin, along the circumferential direction in the boundary wall and within the PCM region, the location of the interface in the PCM region, the surface heat flux, and the frozen volume fraction are all shown and talked about. This paper shows the effect of Biot and Stefan number, fin improvement factor, and subcooled factor when put together.

Keywords: Enhancement Factor (EF), cylindrical glass jar, thermocouples, transportation
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1. INTRODUCTION

Solar power and other renewable energy sources are becoming more important worldwide. The use of renewable energy sources and the improvement of energy efficiency are two crucial components of all national initiatives in the areas of agriculture, industry, transportation, and homes. Scientists and engineers are very interested in solar energy since it is pure, endless, and does not pollute. Extensive studies on the potential of solar energy have been conducted, including both technical and economic feasibility analyses. The majority of solar thermal energy applications were first focused on home hot water systems. Solar energy has many more potential uses, such as in refrigeration, drying, cooking, green house heating, desalination, electricity generation, space power, and cooling. Zvirin and Zamkow (1993) found that Israel uses more solar energy per capita than any other country in the world. Over three percent of Israel's overall energy consumption comes from solar sources, mostly SDHWSs.

1.1 THERMAL STORAGE: AN ABSOLUTE REQUIREMENT

Solar energy is time dependent, which is a crucial consideration despite its many uses. While solar energy does fluctuate in phase and pattern, the time-dependent nature of energy demands for many diverse uses is distinct. Therefore, it is essential that devices and utilities that rely on solar energy be dynamically matched at both the source and the application points.

1.2. POWER RETENTION FOR SOLAR USE

Many new units are being built that use solar energy to meet the thermal demands of residential and commercial businesses, and there is now a lot of research going on about this. The thermal energy storage units used have a significant impact on how well these systems work.

1.3 STORAGE SYSTEMS TYPES

The sensible heat, latent heat, or chemical reaction of a substance can be used to store thermal energy, as can the sensible heat of a liquid or solid. The quantity of energy that needs to be stored per unit of weight or volume of the medium, as well as the temperature range that the medium must be suitable for, determine the choice of storage media. The heat capacity per volume of sensible heat storage systems that use pebble beds, water, or oil is extremely low. In contrast, the LHTS unit's isothermal behaviour while charging and discharging, along with its large energy storage capacity, make it an attractive option.

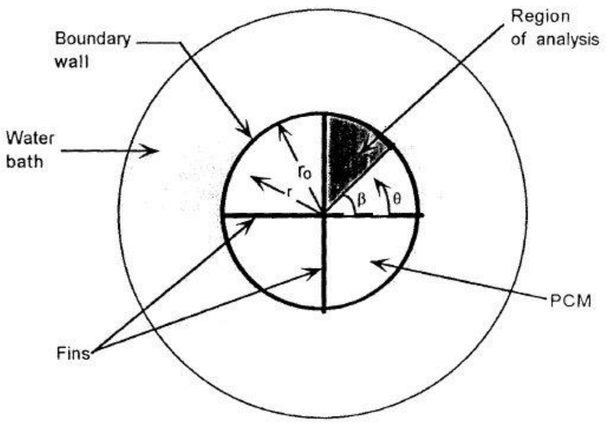
1.4 ENHANCING HEAT TRANSFER FOR LHTS UNITS: A NECESSITY

The sensible heat storage system is more commonly used for residential solar hot water and space heating applications than LHTS systems, despite the fact that LHTS systems have desirable qualities including a high energy density and isothermal behaviour. The primary cause is the challenge of heat charging and discharging from the storage system. As the LHTS unit goes through a phase shift, the contact between the solid and liquid phases moves away from the surface that transfers heat convectively.

Natural convection happens in the melt layer during melting, which typically speeds up the heat transfer rate in comparison to solidification, whereas conduction is the only transport mode during solidification. Natural convection in the liquid PCM also slows the pace of freezing during solidification, which happens when the PCM temperature is initially higher than the fusion value. Natural convection in a superheated liquid can decrease the rate of freezing or perhaps stop it altogether, as demonstrated by Sparrow et al. (1979). Since PCMs often have a relatively low thermal conductivity, when they solidify, they stick to the heat transfer surfaces and function as an insulator.

2.THE ENTHALPY MODEL FOR THE INTERNALLY FOUND LHTS UNIT

The enthalpy formulation is used to create the model. The study's chosen phase change material, paraffin, has a narrow temperature range for its phase shift, therefore the model is tailored to work with materials with a similar range. In order to account for materials with a range of phase change temperatures, this vortex modifies a generalised enthalpy-temperature equation that Date (1991) derived for materials with a constant phase change. The solution technique is made simpler by this generalised relationship.



The Physical Model's Cross-Section Revealing the Fin-Tube Layout

A vertical tube is used to enclose the PCM. Along the tube's circumference, there are 'n' longitudinal fins that are internally attached and lie parallel to the tube's axis. At room temperature, the PCM-finned tube assembly approaches the phase change temperature, if not slightly over it.

This analysis is based on the following assumptions:

- Thermophysical characteristics of PCM in both its liquid and solid forms are identical, with the exception of density. With regard to temperature, none of the characteristics change.
- Float force resulting from volume change as a result of phase transition is disregarded. Conduction is the primary heat transfer mechanism in PCM due to its tiny bulk.
- Because it was not observed in the trials, spontaneous convection in the melt layer is disregarded.
- Both the fin and the wall have one-dimensional heat conduction, with the former having a radial pattern and the latter a circumferential one.
- The analysis does not take into account the expected negligible variation in the surface heat transfer coefficient due to temperature variations in the boundary wall.
- The axial temperature change within the paraffin tube is ignored since the fluid surrounding it is kept at a constant temperature.

Assuming a linear H-T connection during phase change is the case for PCM, which undergoes phase shift over a temperature range.

2.1 SIMPLIFIED TUBE MODEL

Numerical model optimisation yields the plain tube configuration as a limiting case when derivatives with respect to co and fin thickness are set to zero. After first validation using London and Seban's exact solution (1943), this model is considered solid. The model's full solidification time and the actual solution's time are compared for various Biot values. For the chosen grid size and time step in the numerical model, the findings remain within ± 2% of each other, indicating a substantial agreement**.**

Improving factor:For the purpose of studying the impact of heat transfer enhancement configuration, a parameter called Enhancement Factor (EF) is defined, which is similar to the term "effectiveness" in extended surface heat transfer.

3. A STUDY THAT USES EXPERIMENTS TO LOOK INTO HOW TO IMPROVE HEAT TRANSFER

The created theoretical model is tested by doing experiments. This paper describes in depth how the experiment was set up and how it was carried out. Using a plain tube model (one without fins) to find the value of the heat transfer coefficient 'h' on the tube surface is described through experiments. Furthermore, two more methods for improving heat transfer are researched, and this paper goes into more depth on them. Using one of these methods, an experimental setup with a 50-liter volume is also made and studied.

3.1 EVALUATING NUMERICAL MODELS THROUGH EXPERIMENTATION

Setup For an Experiment

An experimental setup is built using one vertical tube, which is typical of a storage unit, to validate the theoretical concept. The storage unit is illustrated schematically in Figure 1 and photographically in Figure 2. The component parts are a 60-centimeter-long active section and a 6-centimeter-wide and 5.4-centimeter-deep aluminium cylindrical storage tube. Encased in a well-insulated cylindrical glass jar of 25 cm diameter and identical height to the tube, water is contained within. To keep the coolant water moving, a pump is included.

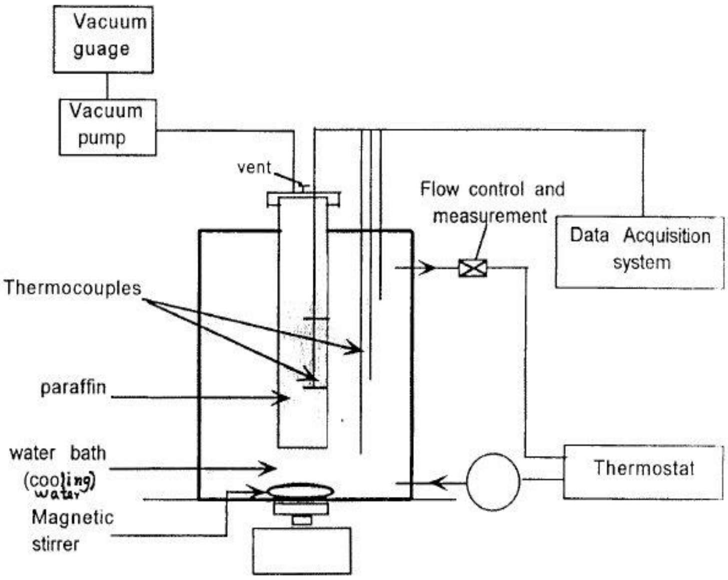


Figure 1: Experimental Set-Up

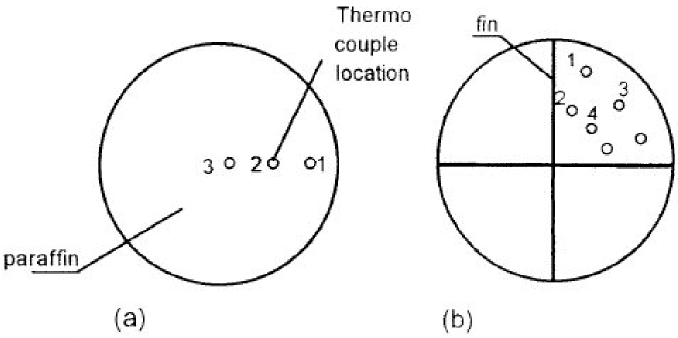


Figure 2: The Designs' Paraffin Storage Tube Cross-Sections and TC Positions (a) Plain Tube, and (b) A Fin-Equipped Plain Tube

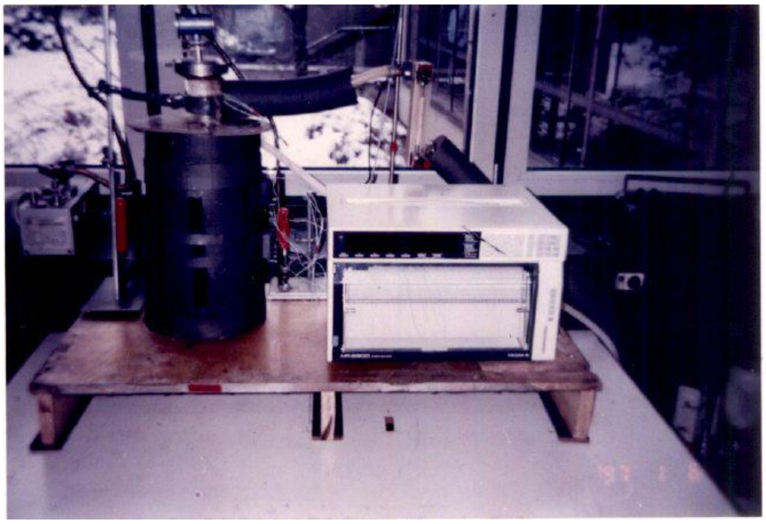


Figure 3: A Picture of The Arrangement Used for The Experiment

At its base, the vessel receives water, and at its apex, it empties. For precise regulation of the cooling water's mass flow rate, a controllable flow metre is supplied. The thermostat, which can adjust the heating coil capacity from 500 to 2000 W, controls the water bath's temperature. At the base of the trough, there is a magnetic stirrer that ensures the temperature remains consistent along the axial axis of the cylindrical tank. A tiny section at the top of the tube unit is elevated above the water level to facilitate thermocouple connections and external handling of the tube. Inside the tube, a set of four rectangular, vertical aluminium finseach measuring 50 cm in length, 2.7 cm in height, and 0.15 cm thickform a cross-shaped cross-section. The fins are welded at the top and bottom of the tube, and solder is used to thermally bond the intermediate length of the fin to the tube.

Figure 1 shows that six NiCr-Ni thermocouples (Type K) are positioned in two separate horizontal planes, 20 cm and 35 cm from the tube bottom, respectively. Figure 2(b) shows the thermocouples arranged in a single plane. Figure 2(a) shows the placements of three thermocouples positioned in two planes at the same heights from the bottom of the tube as in the case with fins, when the tests are conducted without fins. To keep the axial temperature change to a minimal, three thermocouples are placed at varying heights in the water bath. In order to minimise the end effects, which include heat flow from the bottom of the tube and potential heat flow in the axial direction within the paraffin, the thermocouples are positioned appropriately.

An instantaneous digital and analogue output is possible thanks to the thermocouples' connection to a recorder. A storage disc is an appropriate place to keep this data. When using a K type thermocouple, the recorder can accurately measure temperatures to within ±0.05% of the reading plus or minus 0.5°C, with a resolution of 0.1°C. The tube is filled with melted paraffin, being careful not to let any air bubbles escape. Paraffin RT 58 is utilised in research using the plain tube, while paraffin RT 60 is utilised in experiments including heat transfer enhancement methods. With the exception of the phase transition temperature, the thermophysical characteristics of the two paraffin groups are identical.

3.2 A 50-LITER PARAFFIN STORAGE CAPACITY EXPERIMENT

The PCM container diameter to lessing ring diameter ratio determines the k_e increase for the lessing ring method. A 50-liter experimental setup is built to get the k_e enhancement for large diameter ratio and to see if this heat transfer enhancement method can be used for huge storage capacity.An existing oil-pebble bed thermal storage test setup for a solar cooker is modified to build an experimental set-up. The test module's paraffin lessing ring container is a repurposed cooking vessel with a 50-liter capacity.

- While the oil tank is being charged, the path is as follows: flow pump - heater - oil tank.
- The paraffin must be melted before the experiment begins by following this path: paraffin container - pump - heater.
- In order to maintain a constant temperature for the solidification studies, the HTF (oil) is circulated around the paraffin container via a pump and back into the oil tank.
- A natural convection discharge pathway consisting of an oil tank, a paraffin container, and another oil tank.

Examining THE Numerical Model FOR Validity

The specified locations' expected temperature-time variation is derived from a numerical model that accounts for the experimentally-correlated factors. Curves from theory and experiment are very similar; however, the rate of temperature drop in theory is slower during phase change and faster after phase change is finished at all TC locations, whereas curves from experiment show that the rate of temperature drop remains relatively constant even after the phase change temperature range's lower limit is reached. There may be some latent heat in the solidified paraffin even after it reaches the lowest point in the phase change temperature range, which could explain this. Since this is the case, it's possible that the manufacturer's specified range for the phase transition temperature is off. Not only that, but Abhat (1983) found the same thing for the majority of paraffin groups.But that temperature range is where the big phase transition happens. In addition to being beneficial from an application standpoint for greater Biot numbers, this short-range drift of a small amount of latent heat below the lower limit of the phase transition temperature range is intriguing. Even while the paraffin in the middle of the area is solidifying, it is still feasible to harvest energy at a relatively constant temperature since this decreases the sub-cooling of the solidified layer. In addition, while the theoretical scenario sees a fixed beginning temperature of 60.5°C across the entire domain. The trials, the temperature could only be kept at 60.5 ± 0.3°C.

The Impact of Convection on The Liquid Zone

Natural convection's impact on outward cylindrical melting was investigated by Sparrow et al. (1977). Based on the vertically-obtained melt area shape, they deduced that the effect is of first-order importance and must be considered in phase transition situations. As for outward cylindrical freezing, Sparrow et al. (1979) found that spontaneous convection in a superheated liquid PCM can slow down and stop the freezing rate.

4. CONCLUSION

This paper presents the specifics of a vertical finned storage tube design, including the formulation, numerical scheme/results, and parametric studies. Two more approaches to improve heat transmission in LHTS units are detailed, and the numerical model's predictions of temperature fluctuation across space and time are contrasted with experimental findings. This paper provides a concise overview of the study's main findings and conclusions.

- The current internal fin design uniformly reduces the PCM's thermal resistance, allowing the PCM furthest from the heat transfer surface to communicate with the fluid as much as possible through the fin.
- As solidification advances in an inward cylindrical solidification process, the interface's surface area shrinks. Therefore, the impact of natural convection diminishes with time and eventually becomes insignificant when the fin arrangement is used.
- There isn't enough surface area at the tip of the internal fin to directly transfer all the heat from the fin to the coolant around it. This means that there is a significant amount of circumferential heat flow through the boundary wall when there is a lot of heat flow through the fin at the start of the process. So, when modelling these kinds of storage units with fins, it's important to include the effect of heat flowing around the outside of the wall, especially for higher Biot

numbers, so that the predicted heat transfer properties are right.

- Enhancing heat transfer with fin configuration for storage tubes and using lessing rings in storage tanks is impressive, and these two methods are perfect for making solidification better. Addition of high conductivity-lowering bands to a tube raises the enhancement factor, but not as much as it would be with fins for the same amount of material. Using bubble motion in storage may work well in situations where a lot of thermal energy needs to be taken out of exit hot streams in a short amount of time.
- For heating home water, a method that stores both sensible and latent heat is suggested. LHTS system can be used as a single big module for heating air, and the unit's performance can be improved by adding high conductivity material to the PCM to make it more effective at transferring heat.

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