Case Studies in Thermal Engineering 39 (2022) 102399

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Performance of latent heat storage (LHS) systems using pure paraffin wax as working substance

Dawit Gudeta Gunjo [a], Vinod Kumar Yadav [b,*], Devendra Kumar Sinha [c], H.A. Refaey [e,g], Gulam Mohammed Sayeed Ahmed [f], Mostafa A.H. Abelmohimen [d,g]

[a] *Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia*
[b] *Department of Mechanical Engineering, G. L. Bajaj Institute of Technology and Management, Greater Noida, India*
[c] *Department of Mechanical Design and Manufacturing Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Ethiopia*
[d] *Mechanical Engineering Department, College of Engineering, King Khalid University, Abha, 61421, Saudi Arabia*
[e] *Department of Mechanical Engineering, College of Engineering at Yanbu, Taibah University, Yanbu Al-Bahr, 41911, Saudi Arabia*
[f] *Center of Excellence (COE) for Advanced Manufacturing Engineering, Program of Mechanical Design and Manufacturing Engineering, School of Mechanical, Chemical and Materials Engineering, ASTU, Adama, Ethiopia*
[g] *Shoubra Faculty of Engineering, Benha University, Cairo, 11629, Egypt*

ARTICLE INFO

Keywords:
Charge time
Discharge time
Melt fraction
Paraffin
Phase change

ABSTRACT

No single energy source, either conventional, or renewable, is self-sufficient to meet the energy demand of any country. The intermittency in the supply of energy, as in the case of solar radiation, creates a mismatch between the demand and the supply of the energy. This necessitates the development of an efficient energy storage system that can be used as stand-by in case of unavailability of the primary energy source. A properly designed thermal storage system may overcome inherent intermittency of energy supply. In the present work, the charge-discharge characteristics of the 5 MJ capacity storage system, based on latent heat storage, with paraffin wax as a phase change substance, is numerically investigated. The performance of shell and tube type device is evaluated using COMSOL®4.3a software. The results revealed that the paraffin wax, as a Phase Change Material (PCM), charges more quickly (25% faster) as compared to discharge. The PCM with a latent heat of 168 kJ/kg, was found suitable for effective heat storage and does not undergo sub-cooling. This work suggests that the selection of the heat exchangers, based on charging time, may be done by suitably designing the number of tubes. In this work, the tubes in the heat exchanger were varied from 9 to 25 and through computational analysis, 17 tubes were found to be the most economical selection with better effectiveness.

* Corresponding author.
E-mail address: vinod.yadav@glbitm.ac.in (V.K. Yadav).

https://doi.org/10.1016/j.csite.2022.102399
Received 10 June 2022; Received in revised form 17 August 2022; Accepted 29 August 2022
Available online 3 September 2022
2214-157X/

Abbreviations

LHS	Latent Heat Storage
PCM	Phase Change Material
TESS	Thermal Energy Storage System
LHST	Latent Heat Storage Technology
SNT	Shell and Tube
LHSD	Latent Heat Storage Device
FE	Finite Element
EHC	Equivalent Heat Capacity
BDF	Backward Differentiation Formula

1. Introduction

Intermittent supply of solar radiations limits its utilization in power plants that are dependent on solar energy. One of the sustainable solutions to ensure continuous supply of solar energy for solar power plants is to integrate the solar collectors with Thermal Energy Storage System (TESS), that works on the principle of latent heat storage technology (LHST). This technology ensures availability of energy for future. The Phase Change Materials (PCMs) are used in LHST as medium of energy storage that stores energy while melting. The stored energy is retrieved during the process of solidification. Phase Change Materials (PCMs), exhibited by high heat of fusion and vaporization, allows them to melt and solidify at fixed temperatures. In addition, PCMs can store and release a significant amount of heat at any specified temperature. Compared to sensible heating technology, the PCM storage technology ensures the storage of considerable amount of energy within a confined volume and at an economical storage cost [1]. During daylight, when there is availability of sun, the heat harnessed from the solar collector may be stored in PCMs during its phase conversion (solid to liquid). The phenomenon of phase change is termed as charging. Conversely, when there is intermittency in sun's availability, due to any reason (e.g., cloudy weather), the energy that was stored during charging can be retrieved by changing the phase of PCM from liquid to solid. This process is termed as discharge. Medrano et al. [2] conducted experiments on five different heat exchanger configurations using PCM filled latent heat storage systems and reported that a double-pipe heat exchanger, implanted with graphite matrix, exhibit superior performance compared to other heat exchanger configurations studied by them. Herrmann et al. [3] performed comparative analysis of solar based power plants without and with thermal storage technology and reported a reduction in electricity charges by 10% by employing thermal storage technology. Jesumathy et al. [4,5] investigated the characteristics of shell and tube heat storage device filled with paraffin wax under vertical as well as horizontal orientations. They found that the inlet temperature of the paraffin wax affects melting rate more predominantly compared to the flow rate. In a study, Rathod and Banerjee [6] analyzed the thermal characteristics of paraffin wax (60 °C melting point). They reported that the inlet (entry) temperature of the HTF significantly affects the melting of PCM as compared to its mass flow rate. Sari and Kaygusuz [7] studied the solidification and melting of a PCM, using latent heat storage (LHS) with double-pipe configuration, and reported that the coefficient of heat transfer, when averaged, significantly affects the melting process, as a consequence of natural convection compared to the flow rate of the HTF. Trp [8] experimented the thermal performance with paraffin (RT-30) in shell and tube (SNT) type heat-exchanger maintaining a fixed flow rate of HTF and noticed a constant temperature phase transformation in melting region. He et al. [9] used RT-5 paraffin in cold storage applications and proved them to be effective and stable during melting. Akgun et al. [10] experimented the solidifying and melting nature of PCM with SNT type heat exchanger in vertical orientation and observed that the time of melting get reduced considerably with an increase in the temperature of the HTF. Castell et al. [11] experimented the heat transfer pattern of the PCM during heating and reported that fitting fins over the PCM improves the heat transfer rates with the surrounding environment (i.e. water). Huang [12] derived analytical results for one-dimensional equation of momentum considering buoyancy effects encountered during melting. Lamberg [13] established one-dimensional model to examine solidification process using LHS tubes with fins. Lacroix [14] studied 2D SNT-LHST and observed that by choosing appropriate parameters, the performance of the system improves. Ng et al. [15] established a two-dimensional model for studying the melting rate of PCM placed inside a cylinder that was kept in horizontal orientation. They observed enhanced melting rate due to natural convection phenomena. Tiari et al. [16] prepared a LHS model (two-dimensional, transient) of heat pipe, fitted with fins, to evaluate the rate of discharge and reported that by increasing the number of heat transfer tubes, the rate of discharge increases. Seddegh et al. [17] reported that horizontal orientations of the tubes perform better compared to the vertical orientation. Aly and Sharkawy [18] numerically evaluated the impact of storage bed material on the thermal performance of the LHS and reported that the storage capacity may be enhanced by using denser medium. Wang et al. [19] computationally evaluated the performance of the shell and tube LHS device by changing the flow rates and inlet temperature of the HTFs and found that the inlet temperature of the heat transfer fluid has a predominant effect on the melting rate and the thermal storage compared to the mass flow rates. Niyaset al. [20] found that by blending sodium, potassium nitrates and sodium nitrite in PCM, the thermal performance gets improved compared to base materials. Kibria et al. [21] performed numerical as well as experimental investigation of the SNT-LHST with paraffin wax as PCM and reported that the inlet temperature predominantly affects the performance compared to the mass flow rate of HTF. LHS systems were also used by many researchers in applications like solar heating [22], space cooling/heating [23,24], building materials and automobile [25–27] with reduced emissions at the beginning of the processes [28].

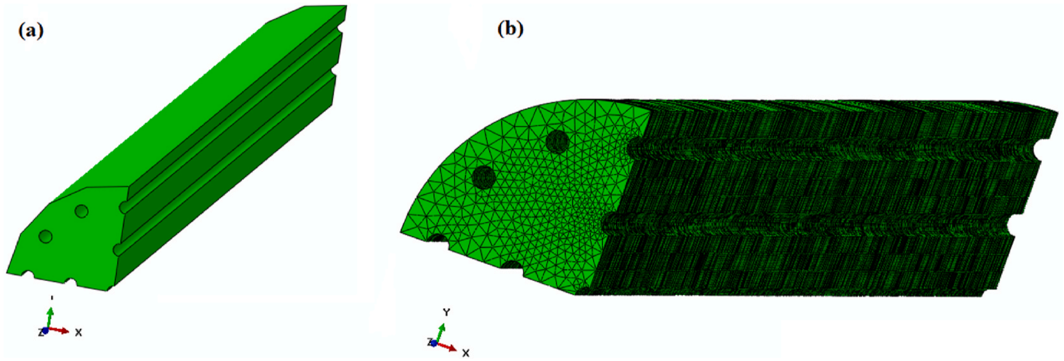

Fig. 1. (a) LHSD - Computational domain (b) Mesh details.

Table 1
Properties of the PCM used in this study [29].

Properties (unit)	Value
Latent heat (LH) of fusion (kJ/kg)	168.00
Viscosity (Pa s)	0.0039
Specific heat (Cp) (J/kg K)	2000.0
Density (kg/m^3)	780.00
Melting temperature range (K)	321.00
Thermal conductivity (W/m K)	0.2000
Solidus temperature (K)	318.00
Coefficient of thermal expansion (K)	0.0006
Liquidus temperature (K)	324.00

From the surveyed literature, it was inferred that most of the studies available in the literature deals with effect of charge-discharge on the performance of LHS systems. The created models, for numerical simulations, have cylindrical, SNT and rectangular configurations. Furthermore, the researchers have dealt with one-dimensional or two-dimensional numerical models. Hence, there is a scope of creating and evaluating three-dimensional models to examine the actual effect of parameters on the performance of LHST. In this work, a three-dimensional computational model, to evaluate the performance of LHSD (5 MJ capacity), using paraffin wax as PCM, is dealt in detail.

2. Numerical modeling

The three-dimensional domain of SNT- Latent Heat Storage Device (LHSD) having paraffin wax in the shell and HTF in the tube (Fig. 1a) is used in the present work for numerical modeling. Fig. 1b shows the mesh created for numerical modelling. Due to the axis-symmetric nature of the chosen domain in x-axis, only one-quarter portion of the system was adopted for analysis. The LHSD shell diameter, HTF tube diameter, LHS shell length and HTF tube thickness are fixed as 200, 12, 1000, 1.5 mm respectively as studied by Gunjo et al. [33]. The LHSD model, used in this work, is a heat-exchanger of regenerative nature that releases or stores heat as and when the HTF is circulated inside the tubes. During charging, the warm fluid from the entry side of the tube transfers heat through convection. This heat is then transported to the PCM by conduction mode of heat transfer. During discharge, the colder HTF is circulated from the same side to extract the heat that was stored by the PCM. The external surface of the LHS is provided with adiabatic boundary condition ($Q = 0$) to exclude the heat loss to the environment (i.e., atmosphere). The properties of the HTF (i.e., paraffin wax), used as PCM in this study, are presented in Table 1.

2.1. Assumptions made for the analysis

To investigate the thermal storage characteristics of LHSD, flow rate of HTF, convection, conduction and phase changing behaviour, the assumptions made during simulations are summarized as follows:

- The HTF is Newtonian, laminar, inviscid and incompressible fluid.
- The PCM is maintained at fixed initial temperature.
- The change of phase while solidification and melting occurs within a specified temperature range.
- Heat loss via PCM's external wall is insignificant and the PCM exhibit isotropic and homogenous behaviour.

3. Model governing equations

The developed model is analyzed based on the coupled-conjugate heat transfer approach that take cares the phase change of the PCM and flow pattern of the HTF. The difference between sensible heat and latent heat based model solutions is the combination of

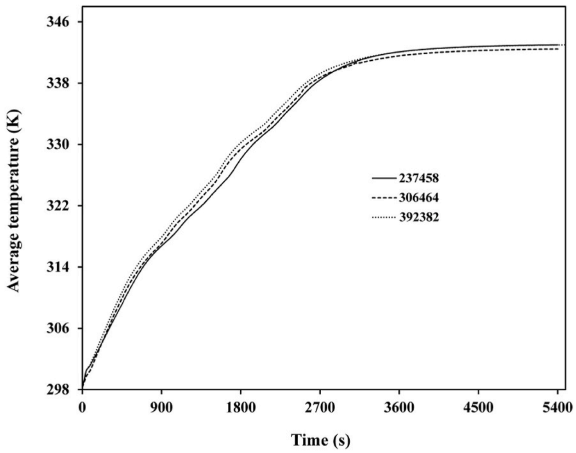

Fig. 2. Grid independency results.

latent heat term that take cares of melting as well as solidification of the PCM. These are solved using the Equivalent Heat Capacity (EHC) technique that encompasses both latent as well as specific heat of the PCM. The EHC of the PCM is calculated as per the expressions proposed by Ref. [29]. Bonacina et al. [30] adapted EHC technique to enumerate the case. The phase change occurs within a particular temperature range. Such problems are known as mushy zone problem due to the existence of a two-phase solid-liquid zone. Discontinuous modified heat capacity, with smooth function containing second derivative, was set in the software module. The momentum, continuity, and energy equations are referred from literature [29]. The buoyancy is considered in the Navier-stokes equation. In addition, Boussinesq approximation was supplemented to the momentum equation [20]. To evaluate the velocity in the solid zone, the source term of Darcy law's [20] is assimilated with the momentum equation. Mushy zone constant, that acts as an alteration of velocity in the mushy zone, lie within 103 to107 in most of the computational studies. In this work, it is set as 104 as per the recommendations of [20]. Larger values of mushy constant may result into steep damping curve and velocity drops to zero rapidly when PCM solidifies. This may result in fluctuation of the solution as the element solidify and melt with minute perturbation within liquid-volume segment. While charging, the source terms of the Darcy laws dominates in the momentum equation and causes the velocity to reach near to zero value before the PCM melts. After the formation of melting layer in the PCM, the melt segment raises which in turn decreases the source term. As the PCM melts, the melt fraction (% of liquid present in liquid-solid (mushy) zone) becomes unity which causes the source term to diminish. Hence, the momentum equation works like actual velocity of the fluid. At discharge, with unity melt fraction, the source term becomes zero. In addition, the momentum equation attains the actual fluid velocity. After the initiation of solidification, the value of source term rises. This dominates the remaining terms of the momentum equation and cause the estimated velocities to reach zero at the discharge end.

3.1. Domain's boundary conditions

Initially (when $t = 0$), no flow (zero velocity) was set for the computations. The HTF, PCM and the tubes are provided with constant high and low temperature during charge and discharge respectively. At any time ($t > 0$), the inlet velocity was kept constant and high and low temperature is specified throughout charge and discharge phenomena. The external surfaces are provided with adiabatic condition ($Q = 0$) to disregard heat losses towards the surrounding. No slip condition was chosen to account for the zero velocity gradients at the walls. The outflow boundary was implemented to integrate the temperature gradient along the normal of the HTF boundary layer, which may be negligible.

3.2. Mesh creation

As per geometry, triangular and tetrahedral mesh (with 306464 elements) was used (Fig. 1b). The small sections, like thickness, were densely meshed. In addition, the boundary layers, corners, and other crucial zones were also meshed using (COMSOL Multiphysics) meshing features.

3.3. Numerical modeling

Equations of continuity, momentum and energy were solved using COMSOL Multiphysics 4.2a software that is based on FE technique. In COMSOL Multiphysics, the Galerkin method, based on finite element (FE) discretization, was used. By using EHC, system equation becomes irregular and hence an irregular time dependent solver called PARADISO was used. For the charge/discharge cycle, time-steps, based on backward differentiation formula (BDF), is used. The time step was fixed to 0.01 s. Due to the non-linearity, the convergence was set more than $>10^{-3}$ while the temperature and velocity convergence were set to 10^{-3}.

3.4. Grid independency test

The results of any computational model rely on the mesh type and size. As a result, grid independency test is done to warrant the repeatability and accuracy of the simulated results. The average temperature and charging time curve is plotted in Fig. 2 to ensure grid-

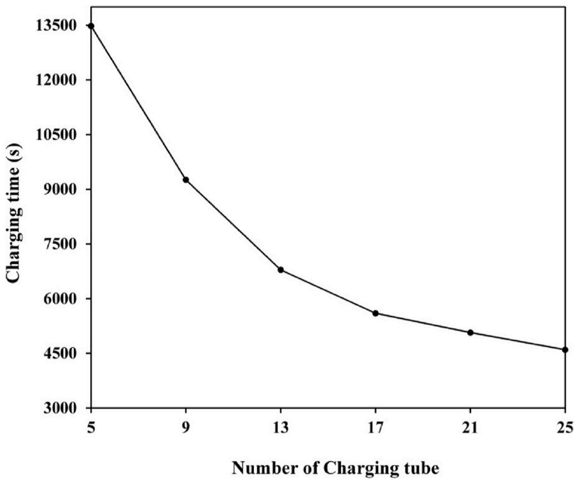

Fig. 3. Effect of number of tubes on charging time.

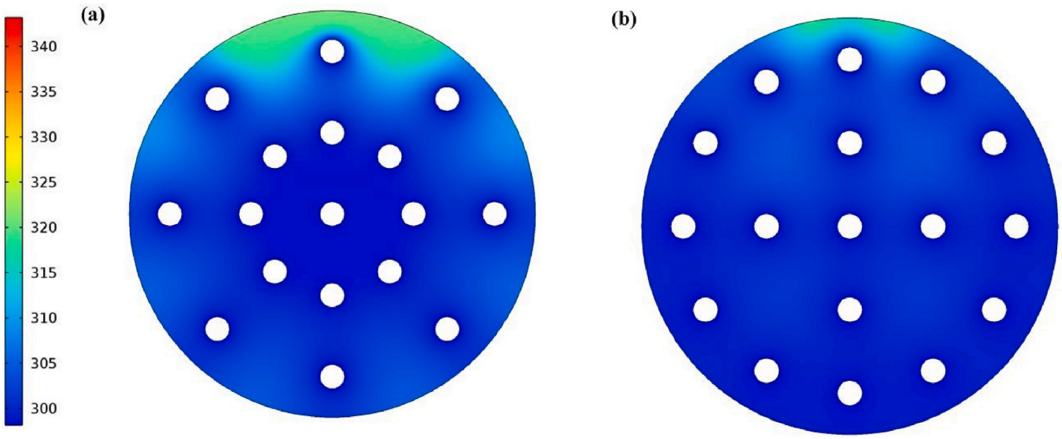

Fig. 4. Temperature distribution with (a) eight tubes at the inner side and eight tubes at the outer side (b) four tubes at the inner side and twelve tubes at the outer side during discharging process.

independent results. It was observed that with 306464 elements the results converged and exhibited same values. For t > 0, a flow rate of 30 L per hour with an inlet temperature of 343 K and 298 K was chosen during charge and discharge respectively.

3.5. *Number of tubes for charging and discharging*

Poor thermal conductivity is the main setback of PCMs which limits its use. To improve the rate of heat transfer, some technique must be adapted that may improve the charge-discharge of these devices. In this work, the charging tubes were increased to visualize the impact using a two-dimensional numerical model. Avci, M. and Yazici [31] optimized the number of tubes on the basis of discharge time. However, their technique took 4 times computational effort (time) compared to the optimized one. This was attributed to slower discharge due to lower conductivities of the PCM. Wang et al. [32] reported 40% reduction in heat storage time when copper foam/paraffin was used as PCM. In this work, the charging time is considered as the prime feature for optimizing the number of tubes of the HTF. Fig. 3 show that there is sharp decrease by about 22.5% in charging time of LHS when thirteen tubes were used as compared to nine tubes. In addition, on comparing seventeen tubes with thirteen tubes, about 17.5% decrease in charging time was noticed. But a marginal reduction of 8.7% in charging time of LHS is noticed when twenty one tubes were used as compared to seventeen tubes. There exists a difference of 400 s in charging time with twenty one tubes compared to twenty five tubes. By using twenty one and twenty five tubes, about 550 s were saved by employing four to eight tubes compared to seventeen tubes. Hence, LHSD, with seventeen tubes was found to be the best and economical arrangement for analysis in the present work.

3.6. *Effect of tubes*

The effect of number of tube on the performance of the LHSD model is analyzed in Fig. 4. After analyzing several tube arrangements, four tubes were fixed at the centre and twelve tubes at the outer side (Fig. 4b) and eight tubes at the centre with eight tubes at the outer side (Fig. 4a). Water at 298 K temperature is provided through the tubes and the shell was kept at 343 K. The results revealed

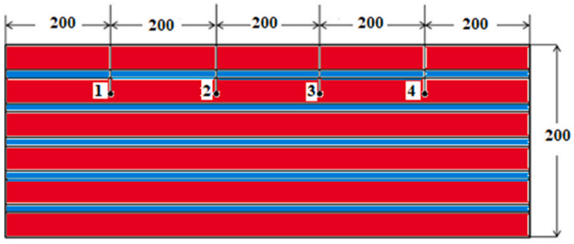

Fig. 5. Specifications of SNT heat exchanger.

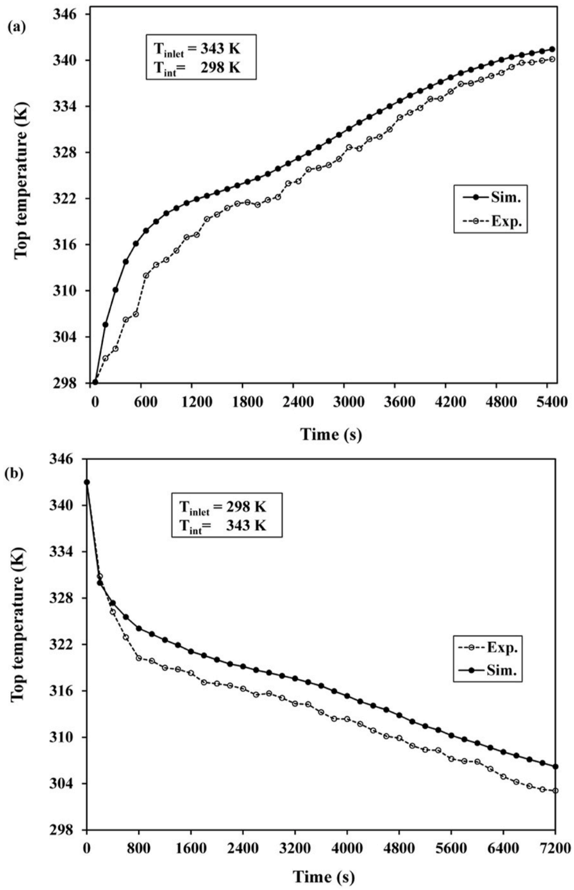

Fig. 6. Temperature versus time plot (a) charging (b) discharging.

that the discharge rate of four centered tubes and twelve outer tubes (Fig. 4b) was more as compared to arrangement shown in Fig. 4a. Hence, Fig. 4b, with four centered tubes and twelve outer tubes, were found suitable for rapid discharge.

4. Facility for experimental work

An experimental facility with LHSD containing 17 copper tubes was developed. The tubes were located inside the stainless steel shell. The shell is fully filled with paraffin wax so as to retain (store) or release the heat during the passage of hot or cold fluid from the tubes. The shell was protected with thermo-foam to reduce the heat loss. During charge and discharge process, 343 K and 298 K temperature of hot and cold water was provided through HT tubes. Heat flow occurs between the working fluid and paraffin wax. Thermocouples of T-type were used to quantity the temperatures. Rotameter and pyranometers were used to measure the water flow rate. A multiplexer (Agilent-34972 A) with twenty-channel, embedded with data acquisition device, was used to measure the temperature at every 10 s interval. The experimental facility developed by the main author can be referred from his own work published in Gunjo et al. [33]. Fig. 5 shows the location of thermocouples fitted inside the shell and tube arrangement for measurement of the

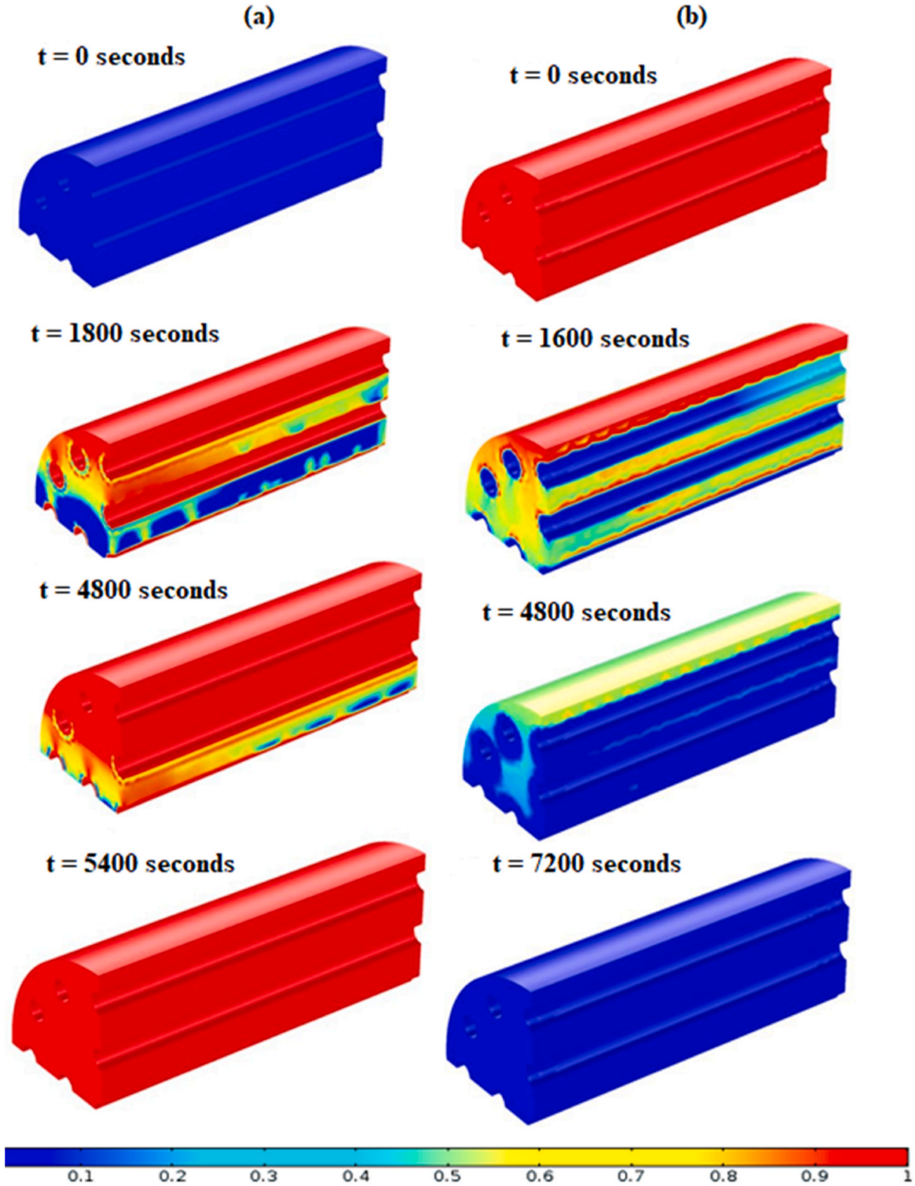

Fig. 7. Melting fraction (a) During charge (b) during discharge.

temperature.

5. Results and discussion

In this work, the temperature distribution along the length of the LHS, the melting fraction and average temperature during charge-discharge process is estimated.

5.1. Model validation

The numerical model was validated with experimental results by conducting comparative analysis of average temperature of LHS, filled with paraffin wax, at locations described elsewhere [1–4]. During charge and discharge, the paraffin wax was kept at 343 K and 298 K respectively. At time, $t > 0$, the heat transfer fluid (HTF), with 30 L per hour flow rate, and at 343 K temperature (while charging), and 298 K (while discharging), is maintained during the whole process. The computed average temperatures of the paraffin wax at some point of charging and discharging is extracted and plotted in Fig. 6a–b. A fairly good agreement can be observed between the measured and simulated results. The maximum difference in the computed and measured results was only 4 K during charging as well as discharging. Hence, it can be inferred that the model is predicting closer results as measured during experiments. It can also be observed that the numerically computed results resembles similar trend as that of the experimental results. The uncertainty in the

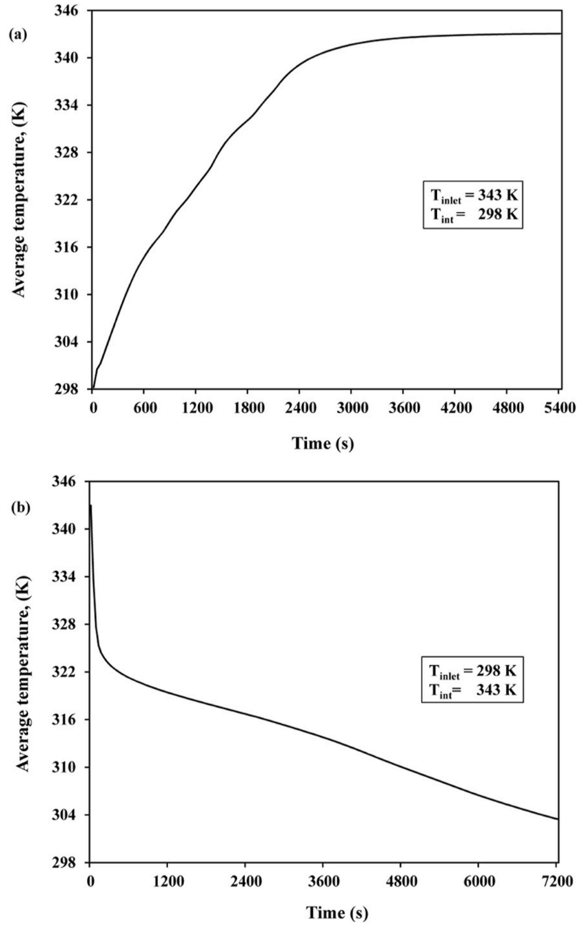

Fig. 8. (a) Average temperature during charge and (b) Average temperature during discharge.

temperature measurement was ±0.2 °C.

5.2. Melting fraction

The melting fraction (average) of the paraffin wax versus charge (Fig. 7a) and discharge time (Fig. 7b) is presented in Fig. 7.

It can be inferred from Fig. 7 that the temperature, using paraffin wax as PCM, was 298 K and 343 K at the beginning of the charging and discharging process (i.e., t = 0). Furthermore, the paraffin wax was fully charged (melted) in 5400 s while discharged (solidified) in 7200 s. The rapid charging is due to heat flow by natural convection as reported by Gunjo et al. [33]. On the other hand, the discharge process was slowed down due to the predominance of the conduction mode of heat transfer.

5.3. Paraffin wax temperature

When the heat transferring fluid passes through the heat transfer tube, at 343 K or 298 K, the heat exchange takes place between HTF and the PCM. The pattern of the temperature distribution, using paraffin wax, for charging and discharging is plotted in Fig. 8a and 8b respectively. The temperature variation curve predicts a sharp growth or fall of temperature when the PCM undergoes charge-discharge.

5.4. Average melting fraction

The performance of the latent heat storage systems get significantly affected by melt fraction that varies from 0 to 1 during melting or solidification. While passing through charge cycle, the HTF in LHS gets melted (i.e., melt fraction = 1). Conversely, during discharge cycle, PCM gets solidified (i.e., melt fraction = 0). It was observed that the rise or fall of the average molten fraction of the LHS throughout the charge-discharge cycle is rapid at the beginning of the process due to superior heat transfer behaviour. Thereafter, it ends up slowly because of the low heat transfer rate between the HTF and the PCM. In addition, the time taken by the PCM to become fully charge and discharge was 5400 s and 7200 s respectively. This indicates that the paraffin wax, which was selected as a PCM, gets charged quickly (25% faster) compared to the discharge owing dominant convective heat phenomena identical to the trends observed with paraffin wax.

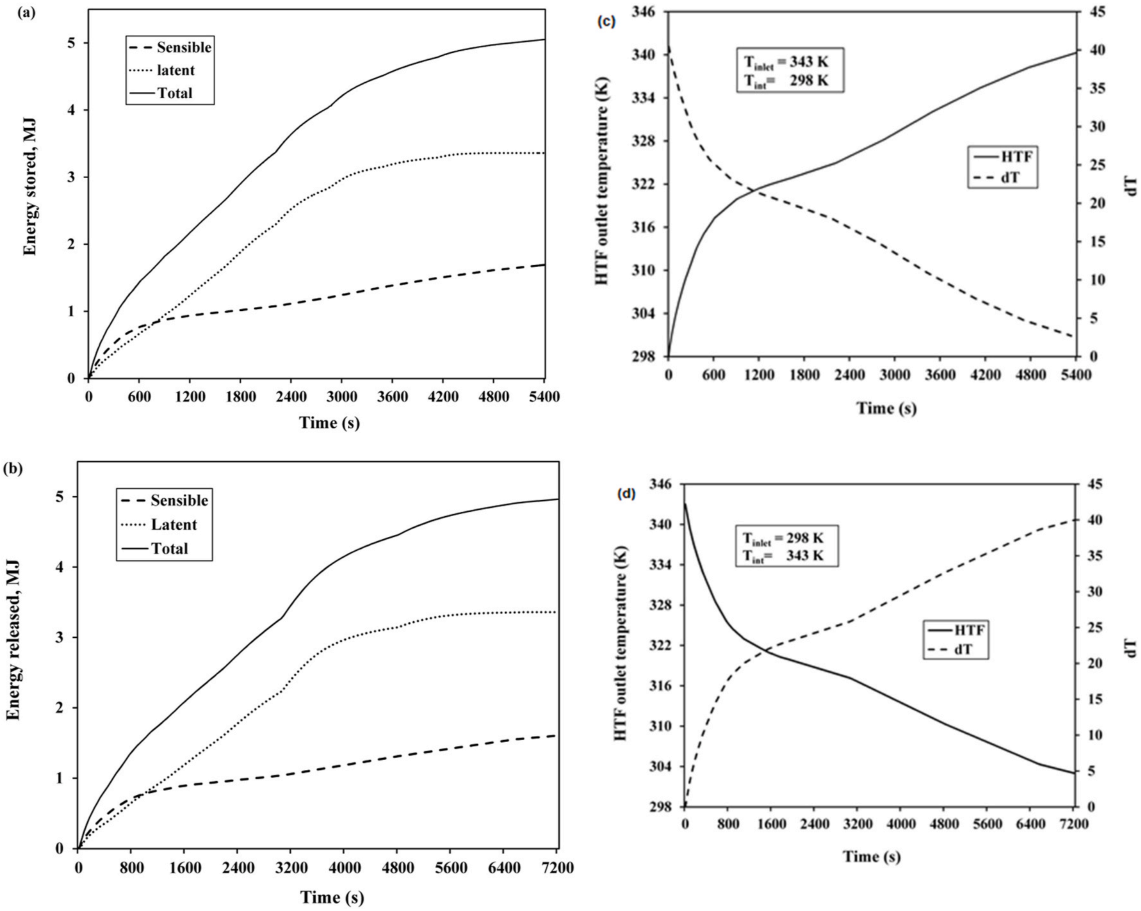

Fig. 9. (a) Rate of energy storage and release during charge (b) rate of energy storage and release during discharge (c) outlet temperature during charge (d) outlet temperature during discharge.

5.5. Energy store and release

The computed results of latent, sensible, and total heat release rate while charging-discharging is plotted in Fig. 9a–b. While charging and discharging, the HTF passes within the tube at a temperature of 343 K and 298 K respectively. In addition, during charge/discharge, the sensible form of heat is received inside. On the other hand, when the PCM attains the phase change temperature of 321 K, the heat is received in the form of latent heat. The heat that is stored or released after the occurrence of phase change of the PCM is again in the form of sensible heat. As the PCM attains the average temperature of 343 K (within 5400 s), the quantity of latent, sensible and the total heat stored is 3.4, 1.7 and 5.1 MJ respectively. As the PCM temperature becomes 303 K (within 7200 s), during discharge process, the quantity of latent, sensible and the total heat released from HTF are 3.2, 1.3, and 4.45 MJ respectively. The PCM releases sensible heat within a temperature range of 40 K.

5.6. The outlet (exit) temperature

The variation of the outlet (exit) temperature of the HTF, when it undergoes charge-discharge, is shown in Fig. 9c–d. It is evident that the outlet temperature of the HTF relies upon its thermo-physical properties and the heat exchange between HTF and the PCM. It can also be inferred from Fig. 9c–d that the outlet temperature of the HTF rises and falls sharply during charge-discharge respectively. This is because of higher rate of heat flow during the beginning of the process. Thereafter, the slope gets dampens due to reduced heat transfer ability between HTF and the PCM. About 2 K temperature difference (between PCM and the HTF) at 5400 s was noticed. Similarly, at discharge, the temperature difference reaches to 5 K at 7200 s. The PCM with a latent heat of 168 kJ/kg was found suitable for effective heat storage systems. Also, the selected PCM does not undergo sub-cooling. This indicates that the selection of the best configuration of the heat exchangers, based on charging time, may be done by suitably varying the number of tubes. In this work, the tubes in the heat exchanger were varied from 9 to 25 and through computational analysis, 17 tubes were found to be the best configuration with enhanced effectiveness.

6. Conclusions of the present work

In the present work, a three-dimensional model of SNT-LHS, for investigating the storage characteristics of the PCM (containing paraffin wax), during charge-discharge process, was prepared and analyzed. For validation, the numerical results were compared with experimentally measured results. The numerical and experimental results showed fair agreement with each other. The performance parameters like charge time, discharge time, storage rate, discharge rate, melting rate etc. were estimated. The outcomes of the present work are summarized as:

1. The charge and discharge time of LHS were 5400 s and 7200 s respectively. Charge and discharge processes are governed by convection and conduction processes respectively. The paraffin wax, which was selected as a Phase Change Material (PCM), gets charged quickly (25% faster) compared to discharge due to superior convective heat transfer behaviour.
2. The paraffin wax, as PCM, with a latent heat of 168 kJ/kg, was found suitable for effective heat storage systems. No sub-cooling is observed with paraffin wax.
3. The selection of the best configuration for the heat exchanger, based on charging time, may be done by suitably choosing the number of tubes. In the present work, the tubes in the heat exchanger were varied from 9 to 25, and through numerical analysis, 17 tubes were found to be a good selection for better effectiveness.
4. The total stored energy during charging and discharging was 5.1 MJ and 4.5 MJ respectively. This indicates that the paraffin wax is more suitable for charging compared to discharging processes.

Funding

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups (RGP.2/94/43). The numerical simulations were conducted at IIT Guwahati.

Author contribution

All authors have equal contribution in the development of this paper.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Dawit Gudeta Gunjo reports financial support was provided by Scientific Research at King Khalid University. Dawit Gudeta Gunjo reports a relationship with Indian Institute of Technology Kharagpur that includes: non-financial support.

Data availability

Data will be made available on request.

Acknowledgement

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups (RGP.2/94/43). The numerical simulations were conducted at IIT Guwahati.

References

[1] A. Shukla, D. Buddhi, R.L. Sawhney, Solar water heaters with phase change material thermal energy storage medium: a review, Renew. Sustain. Energy Rev. 13 (8) (2009) 2119–2125.
[2] M. Medrano, M.O. Yilmaz, M. Nogués, I. Martorell, J. Roca, L.F. Cabeza, Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems, Appl. Energy 86 (10) (2009) 2047–2055.
[3] U. Herrmann, B. Kelly, H. Price, Two-tank molten salt storage for parabolic trough solar power plants, Energy 29 (5) (2004) 883–893.
[4] S.P. Jesumathy, M. Udayakumar, S. Suresh, Heat transfer characteristics in latent heat storage system using paraffin wax, J. Mech. Sci. Technol. 26 (3) (2012) 959–965.
[5] S.P. Jesumathy, M. Udayakumar, S. Suresh, S. Jegadheeswaran, An experimental study on heat transfer characteristics of paraffin wax in horizontal double pipe heat latent heat storage unit, J. Taiwan Inst. Chem. Eng. 45 (4) (2014) 1298–1306.
[6] M.K. Rathod, J. Banerjee, Thermal performance enhancement of shell and tube Latent Heat Storage Unit using longitudinal fins, Appl. Therm. Eng. 75 (2015) 1084–1092.
[7] A. Sari, K. Kaygusuz, Thermal energy storage system using stearic acid as a phase change material, Sol. Energy 71 (6) (2001) 365–376.
[8] A. Trp, An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit, Sol. Energy 79 (6) (2005) 648–660.
[9] B. He, F. Setterwall, Technical grade paraffin waxes as phase change materials for cool thermal storage and cool storage systems capital cost estimation, Energy Convers. Manag. 43 (13) (2002) 1709–1723.
[10] M. Akgün, O. Aydın, K. Kaygusuz, Experimental study on melting/solidification characteristics of a paraffin as PCM, Energy Convers. Manag. 48 (2) (2007) 669–678.
[11] A. Castell, C. Solé, M. Medrano, J. Roca, L.F. Cabeza, D. Garcia, Natural convection heat transfer coefficients in phase change material (PCM) modules with external vertical fins, Appl. Therm. Eng. 28 (13) (2008) 1676–1686.
[12] S.C. Huang, Analytical solution for the buoyancy flow during the melting of a vertical semi- infinite region, Int. J. Heat Mass Tran. 28 (6) (1985) 1231–1233.
[13] P. Lamberg, Approximate analytical model for two-phase solidification problem in a finned phase-change material storage, Appl. Energy 77 (2) (2004) 131–152.
[14] M. Lacroix, Numerical simulation of a shell-and-tube latent heat thermal energy storage unit, Sol. Energy 50 (4) (1993) 357–367.
[15] K.W. Ng, Z.X. Gong, A.S. Mujumdar, Heat transfer in free convection-dominated melting of a phase change material in a horizontal annulus, Int. Commun. Heat Mass Tran. 25 (5) (1998) 631–640.

[16] S. Tiari, S. Qiu, M. Mahdavi, Discharging process of a finned heat pipe–assisted thermal energy storage system with high temperature phase change material, Energy Convers. Manag. 118 (2016) 426–437.
[17] S. Seddegh, X. Wang, A.D. Henderson, A comparative study of thermal behaviour of a horizontal and vertical shell-and-tube energy storage using phase change materials, Appl. Therm. Eng. 93 (2016) 348–358.
[18] S.L. Aly, A.I. El-Sharkawy, Effect of storage medium on thermal properties of packed beds, Heat Recovery Syst. CHP 10 (5–6) (1990) 509–517.
[19] W.W. Wang, K. Zhang, L.B. Wang, Y.L. He, Numerical study of the heat charging and discharging characteristics of a shell-and-tube phase change heat storage unit, Appl. Therm. Eng. 58 (1) (2013) 542–553.
[20] H. Niyas, S. Prasad, P. Muthukumar, Performance investigation of a lab–scale latent heat storage prototype–Numerical results, Energy Convers. Manag. 135 (2017) 188–199.
[21] M.A. Kibria, M.R. Anisur, M.H. Mahfuz, R. Saidur, I.H.S.C. Metselaar, Numerical and experimental investigation of heat transfer in a shell and tube thermal energy storage system, Int. Commun. Heat Mass Tran. 53 (2014) 71–78.
[22] M. Mazman, L.F. Cabeza, H. Mehling, M. Nogues, H. Evliya, H.Ö. Paksoy, Utilization of phase change materials in solar domestic hot water systems, Renew. Energy 34 (6) (2009) 1639–1643.
[23] E. Halawa, W. Saman, Thermal performance analysis of a phase change thermal storage unit for space heating, Renew. Energy 36 (1) (2011) 259–264.
[24] G. Fang, S. Wu, X. Liu, Experimental study on cool storage air-conditioning system with spherical capsules packed bed, Energy Build. 42 (7) (2010) 1056–1062.
[25] N. Soares, J.J. Costa, A.R. Gaspar, P. Santos, Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency, Energy Build. 59 (2013) 82–103.
[26] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, Energy Build. 42 (9) (2010) 1361–1368.
[27] H. Liu, H.B. Awbi, Performance of phase change material boards under natural convection, Build. Environ. 44 (9) (2009) 1788–1793.
[28] M. Gumus, Reducing cold-start emission from internal combustion engines by means of thermal energy storage system, Appl. Therm. Eng. 29 (4) (2009) 652–660.
[29] C. Bonacina, G. Comini, A. Fasano, M.1. Primicerio, Numerical solution of phase-change problems, Int. J. Heat Mass Tran. 16 (10) (1973) 1825–1832.
[30] H. Niyas, P. Muthukumar, Performance analysis of latent heat storage systems, Int. J. Sci. Eng. Res. 4 (2013) 2229–5518.
[31] M. Avci, M.Y. Yazici, Experimental study of thermal energy storage characteristics of a paraffin in a horizontal tube-in-shell storage unit, Energy Convers. Manag. 73 (2013) 271–277.
[32] C. Wang, T. Lin, N. Li, H. Zheng, Heat transfer enhancement of phase change composite material: copper foam/paraffin, Renew. Energy 96 (2016) 960–965.
[33] D.G. Gunjo, S.R. Jena, P. Mahanta, P.S. Robi, Melting enhancement of a latent heat storage with dispersed Cu, CuO and Al_2O_3 nanoparticles for solar thermal application, Renew. Energy 121 (2018) 652–665.