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Research Article

Performance of phase changing material in an artificially created cold region to promote latent heat thermal energy storage

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ABSTRACT

In the present contribution, the authors investigate the peculiarity of Phase Changing Material for accumulating heat in the region equivalent to the hilly area by creating its atmosphere, having 20˚C DBT and 18˚C WBT. A water cooler is used in 5*7 feet bathroom to conceive the above-intimated temperature, measured by a sling psychrometer. In particular, in this study, trials are carried out in the LHTES tank where water is charged from ambient temperature to 55˚C with the aid of an Immersion water heater rod of 1000W,230V thereby liquifying PCM and then discharging to ambient temperature. Two Orientations namely, Circular and Cross are appropriated into the study, where Circular Orientation poses better results articulating the charging in an hour and discharging in 25 long hours, whereas Crossed Orientation represents charging in an hour and discharging in 23 hours. The volume of PCM and the net heat transfer surface have been kept constant in both cases, to compare them in the same operative conditions. The reason for the detour is manifested.

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INTRODUCTION

Renewable sources such as solar, wind, biogas, tidal may be harnessed to store energy to a greater extent since energy saving has become a primary priority for future generations. Since renewable sources are a source of intermittent supply, enriching existing technology of storing heat in the LHTES form has become a common concern of discussion due to its advantages of storing a large amount of heat even with small temperature changes and high storage density. More particularly, LHTES incorporated with PCM has been a popular approach for TES application but, PCMs are limited by their low thermal conductivity which is generally less than 0.5 W/mK. To enhance the heat transfer from the heat source to the PCM, many methods like using acetamide [1], tetradecane[2], heat exchanger pipes[3,4] commercial paraffin [5–8] as PCM have been developed. Many applications also use a single fin[9–13] or multiple aluminum fins

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attached to heat exchanger pipes, where storage material is separated from the heat exchanger to increase heat transfer rate. Advancing further, composites' applications have also shown a great advantage in buildings[14,15] and solar air conditioning applications[16]. Amongst all parameters to enhance the effectiveness of using LHTES, the orientation[17] in which the unit is placed marks criticalness as the location and geometry of PCM plays an important role in having required melting fronts[18,19].

In this regard, many authors have tested heat exchangers using PCM in various geometries, may it be concentric cylinders having internal heating[20], and a vertical cylinder having transient heat flow variation. Recently, one of the experimental studies concluded that the transient performance of a PCM-based heat sink under the different incline angles performance can be improved by simply changing the setup orientation[19]. However, there are some irregularities in the selected geometries/orientation. On the other side, there is no clear history of setting up a newly formed cost-effective orientation in hilly areas without harnessing fossil fuels. So, this gap between searching a better geometry in which PCM would be packed and using it in hilly(low solar radiation) areas to store latent heat in maximum duration possible is confirmed in this study.

Scientific and technical comparison with traditional method

According to one observation[16], the upper half of the spherical capsule to give stableness in melting n-octadecane while the lower half induced wavy abruptness giving lesser stable behavior. The spherical capsule taken for consideration was made of glass, thereby having no conformity in melting the PCM, resulting in chaotic fluctuations. To decrease this thermal stratification, dimples are produced on the copper sphere in the present study.

Novelty in research

Deriving from the observations, though PCM poses a greater advantage in examining different properties, research work is deprived of the study of the LHTES in the regions which get no/little solar radiation. The current work presents the experimental setup in an artificially created colder environment, thereby testing the usability of PCM, which has not been quantified in the study's past literature. Two orientations are taken under consideration, viz, Circular and Cross. These are spherical balls, made up of copper, to reduce the effect of low thermal conductivity posed by PCM and induce more contact area due to the addition of dimples on them.

EXPERIMENTAL METHOD

The Experimental setup of LHTES comprises of two tanks, 40 liters each. One of them is the LHTES tank and the other is a water heater tank that aims to heat the water till 55˚C(the average temperature one can achieve in the colder region is with the aid of a solar heater), after which the thermostats cuts off. The LHTES tank is composed of a

Figure 1(a). Cross orientation**.**

Figure 1(b). Circular orientation.

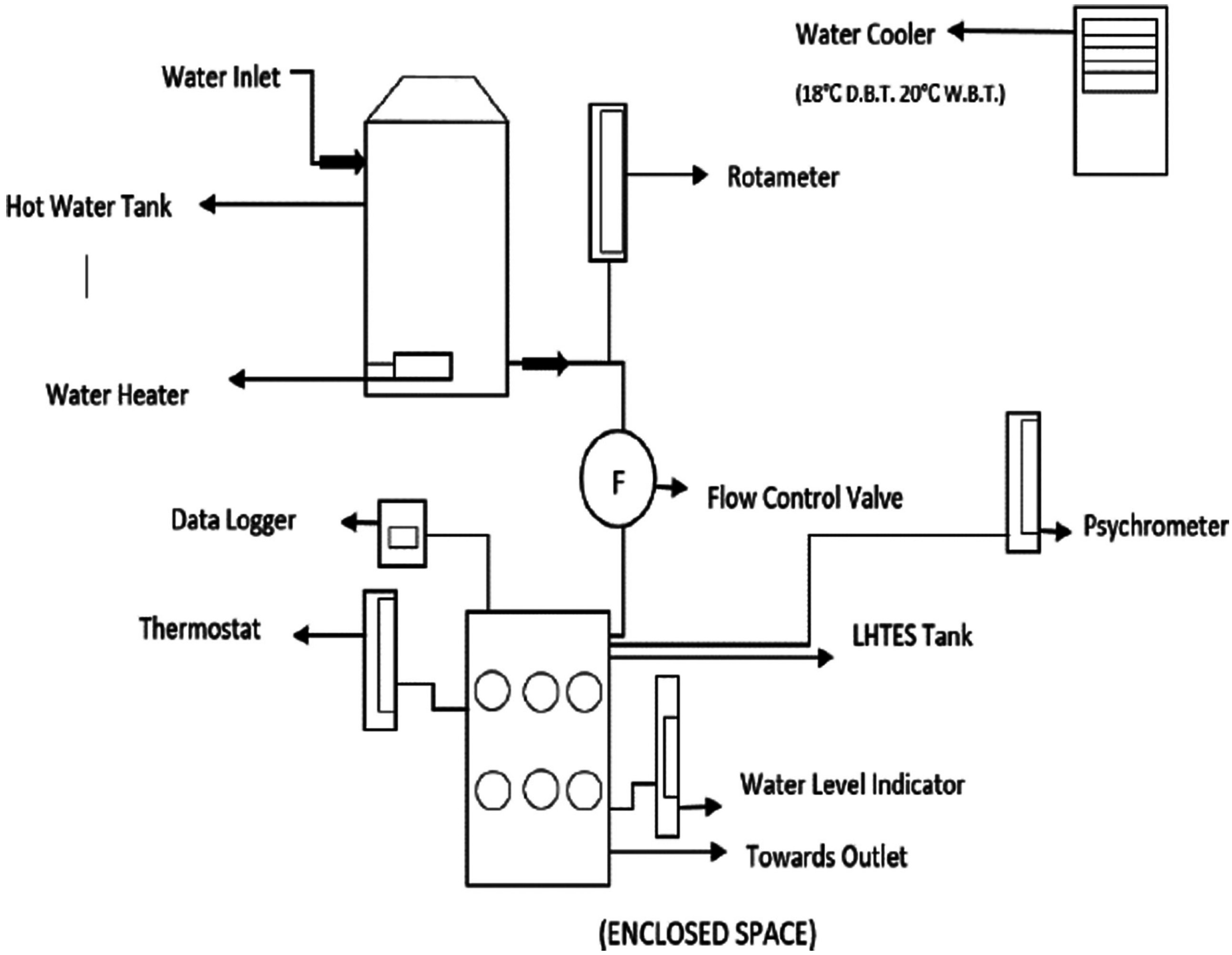

Figure 1(c). Schematic diagram of experimental setup.

cross and spherical oriented structures made up of spherical balls. A Flow control valve is attached between the tanks to regulate the flow of hot water inside the LHTES tank. The setup is installed in a bathroom of 5*7 feet, which tends to be the coldest room in any house. A colder zone is created by pasting wet cloth all over the walls and providing a water cooler in the room, thereby reaching 20˚C DBT and 18˚C WBT(checked with the help of Sling Psychrometer). The artificial conditions are created to understand the sustainability of PCM in this colder region. A Motor is attached to circulate water to the tank for heating if the water temperature is lowered by any of the peripheral changes. The PCM is of the quantity 2kg. It was distributed to 200gms in each of the spherical balls shown in Figure 1. Experiments were carried out to create some space inside spherical balls for vaporization. Less than 10% tolerance was making the PCM leak out from the balls due to the inability of the PCM to remain inside due to melting. In contrast, more than 20% tolerance would not justify the usability of PCM due to a very low amount of captured thermal energy. Hence, roughly 20% tolerance is kept inside the spherical balls to overcome the vaporization, if any. PCM selected is n-tetracosane having a melting point of 48–50˚C. Thermocouples are inserted vertically inside 10 spherical copper balls.

Water melts PCM at 55˚C (which is initially solid at room temperature) when it reaches the LHTES tank inside spherical balls. While PCM melts, it stores the heat energy given off by the heated water and this phase remains intact for a longer duration of time. The time required for the PCM to remain in the melting phase is plotted at regular intervals in this work.

CFD ANALYSIS

LHTES Model is validated with Ansys Design Modeler for de-featuring cad models &Ansys Fluent 16.0 to interpret time and temperature variations by performing CFD analysis.

Table 1. Properties of PCM

Property	Values
Material used	n-Tetracosane
Molecular formula	C24H50
Specific heat capacity	730.9 J/kmol
Boiling point	391.4˚Cat 760mmHg
Latent temperature	48˚C
Specific heat (liquid)	772.50 J/milk at 57.63˚C
Specific heat (gas)	1087.48 J/milk at 475.52˚C

The mathematical energy equation (Eq.1) which governs the physical phenomenon of phasechange problem is given below:

$$\partial/\partial t(\rho H) + \Delta.\rho vH = \Delta.\ (K\Delta T) + S \qquad (1)$$

Where,
∂ = partial derivative of ρH
ρH = conduction co-efficient
vH = convection co-efficient

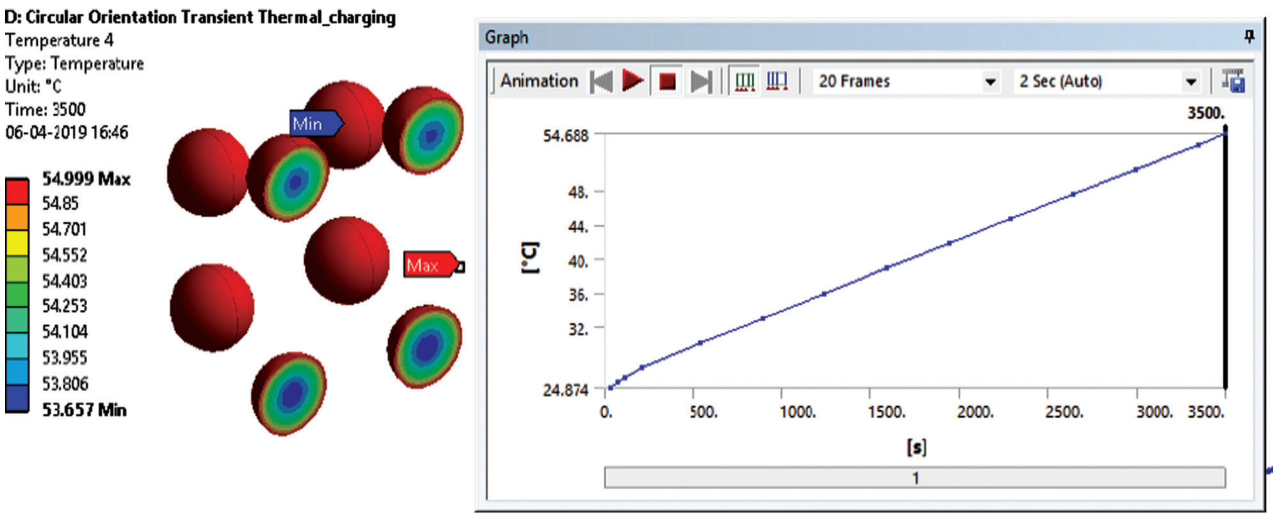

Figure 2. CFD results - charging for circular orientation (after 3500 seconds).

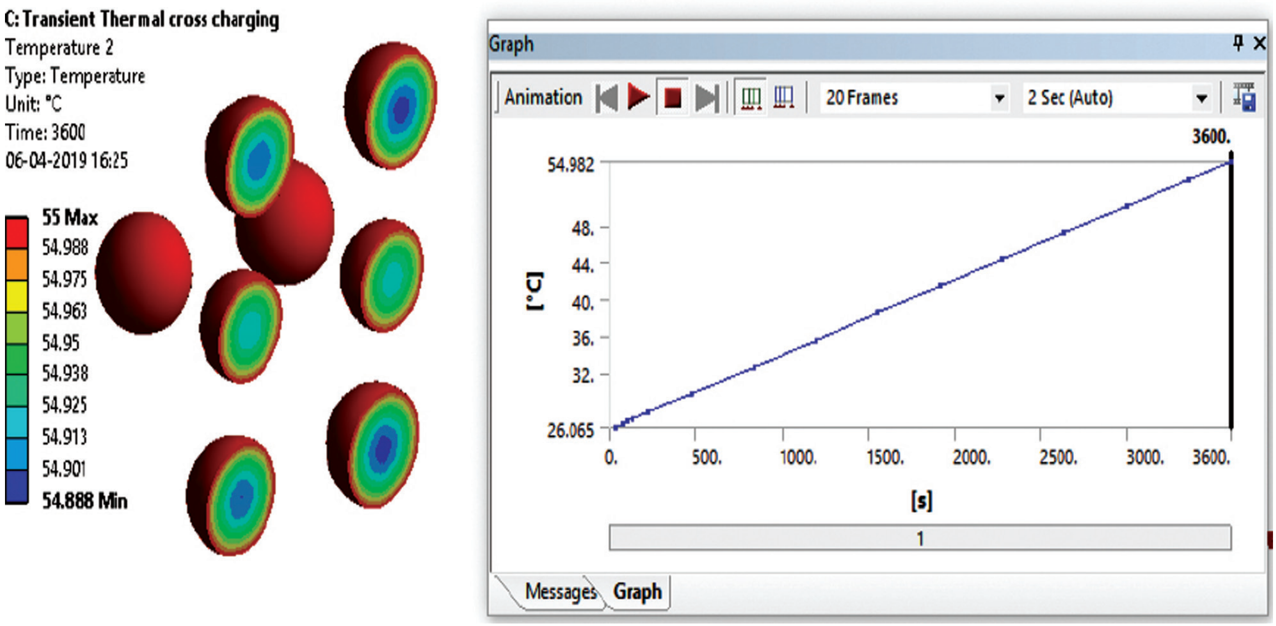

Figure 3. CFD results - charging for cross orientation (after 3600 seconds).

ΔT = change in temperature
S = Source term

Due to the absence of convection (vH) and source term(S), the governing equation is modified as in Eq. (2)

$$\partial/\partial t\ (\rho H) = \Delta.\ (K\Delta T) \tag{2}$$

As per one of the study[13], consideration of two resistances posed by ball surfaces - convective resistance and internal conductive resistance has to be conveyed in the LHTES System.

The properties of selected PCM (specified by the producer) are as stated below:

RESULTS AND DISCUSSION

To ensure correct practice (i.e to check whether the experimental readings coincide with the ANSYS software) on LHTES experimental setup, a validation study has been conducted. The CFD results obtained from ANSYS depict PCM's performance for the time required in charging and discharging vs. temperature of PCM, which will first shoot up and then gradually lower.

Charging for circular orientation

The charging cycle is the process in which the solid PCM (which is at room temperature) proceeds to initiate the melting process, turning solid PCM to liquid PCM. The time required to complete this charging cycle is 60 mins, during which all the PCM inside the spherical balls melt and achieve 54.99˚C (approx 55˚C) as shown in figure 2. A temperature of around 55˚C is the required temperature to be attained in a colder environment.

Charging for cross orientation

While charging, the following plots are reported for Cross Orientation as in figure 3. After the Charging Cycle of 60 minutes, the maximum temperature inside the LHTES attained by PCM is 55˚C while the minimum temperature is 54.88˚C. Both the orientations require the same time to increment the temperature.

Discharging of circular orientation

The discharging cycle is the process in which the liquified PCM (from 55˚C) proceeds to initiate the solidifying process, hence liquid PCM turns back to solid PCM. The time required to complete this cycle is 25 hours i.e 90,000secs in circular orientation, where all the PCM inside the spherical balls solidifies and retains its original room temperature as shown in figures 4 and 5. Precisely, after 900secs, as shown in figure 4, PCM reaches 49˚C and after 9000secs, as shown in figure 5, PCM reaches room temperature. The more the PCM remains in its liquid form, the more it stores thermal energy. In this study, a complete day is required for the PCM to come back to its solidified state.

Discharging of cross orientation

Discharging (as explained in above section) of PCM starts from 55˚C approximately and continues up to the ambient temperature (from the point where the cycle started). This depicts that water comes down to ambient temperature in 23 hours i.e 82,800 secs., quicker than in circular Orientation. This deduces the fact that cross-orientation takes 2 hours lesser time than in circular orientation, which may happen due to the location of one spherical ball at the center in cross-orientation, thus reducing the number of balls circumferentially.

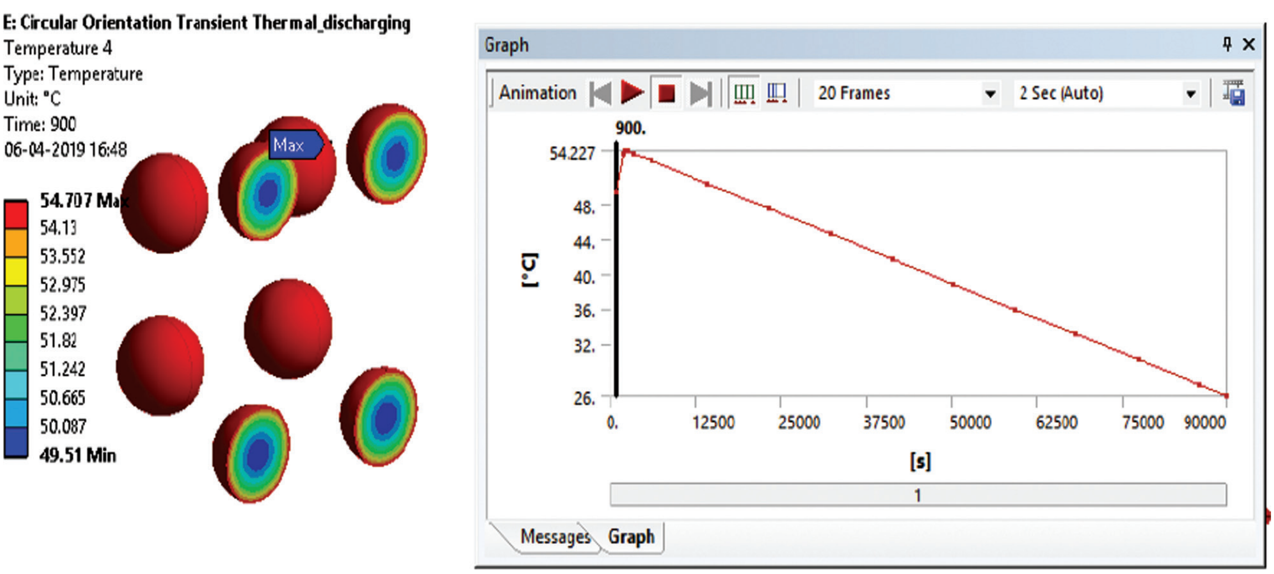

Figure 4. CFD results - discharging for circular orientation (after 900 seconds).

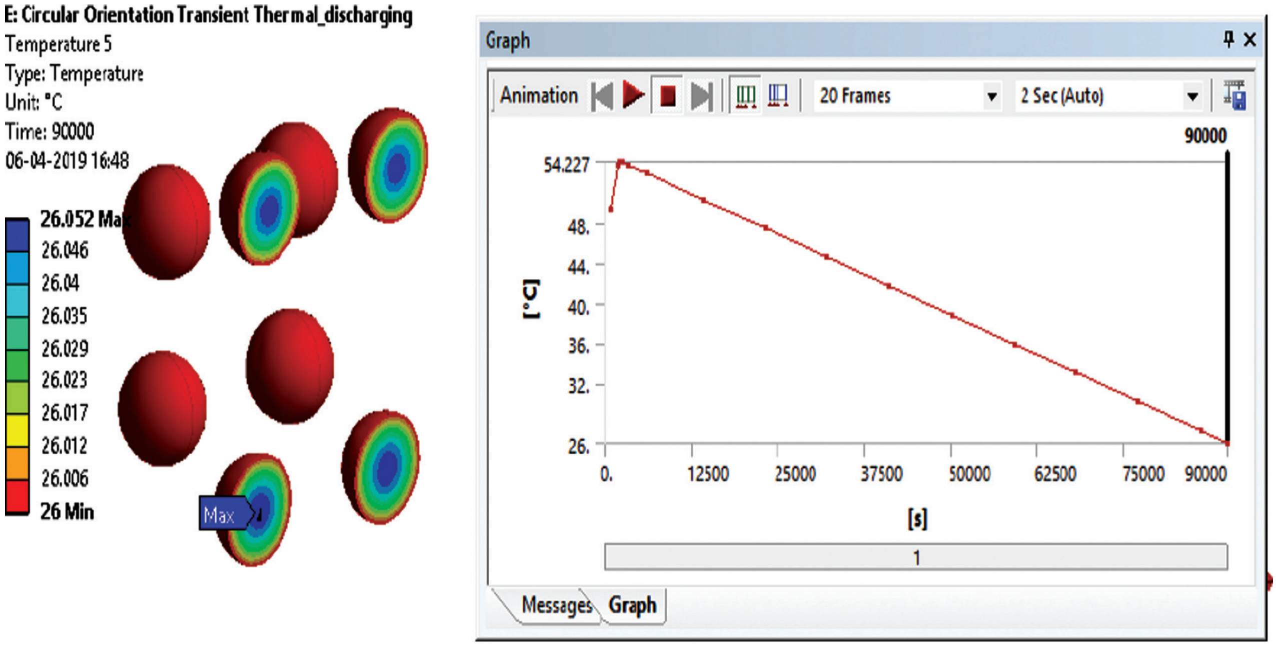

Figure 5. CFD results - discharging for circular orientation (after 90000 seconds).

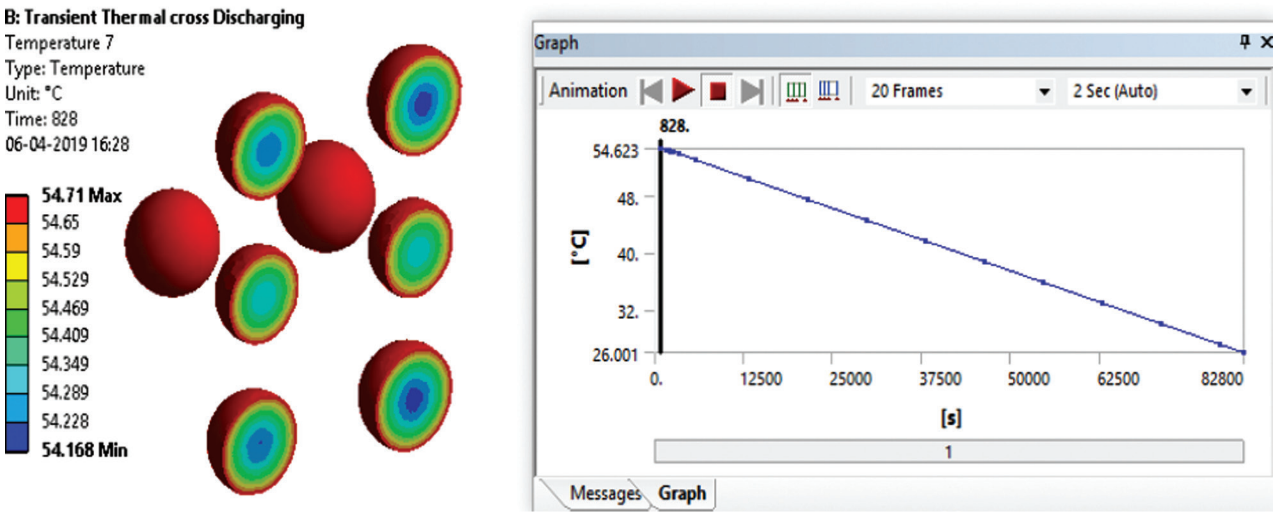

Figure 6. CFD results - discharging for cross orientation (after 828 seconds).

Validation of CFD with experimental results

Experimental results manifest validation of CFD by taking several trials. The trial is taken by creating the cold atmosphere as stated before thereby taking readings in the hilly-like environment. The charging and discharging of PCM results are stated briefly as under:

Charging results-circular orientation

According to experimental results, the upper ring and lower rings take around 105 minutes to get charged (by the heater) from 20°C DBT up to 50°C DBT. This value is more than expected CFD results. This difference occurred due to the lesser urge of immersion heater to remain consistent in increasing the heating element's temperature because of the colder environment.

Discharging results-circular orientation

The figure shows that the discharging time required is 23 hours for PCM to return it to the Solid Phase. The Discharging takes place from 50˚C to 24˚C (ambient) for the artificial conditions created by 20˚C DBT & 18˚C WBT. More discharging time results in the slow rate of

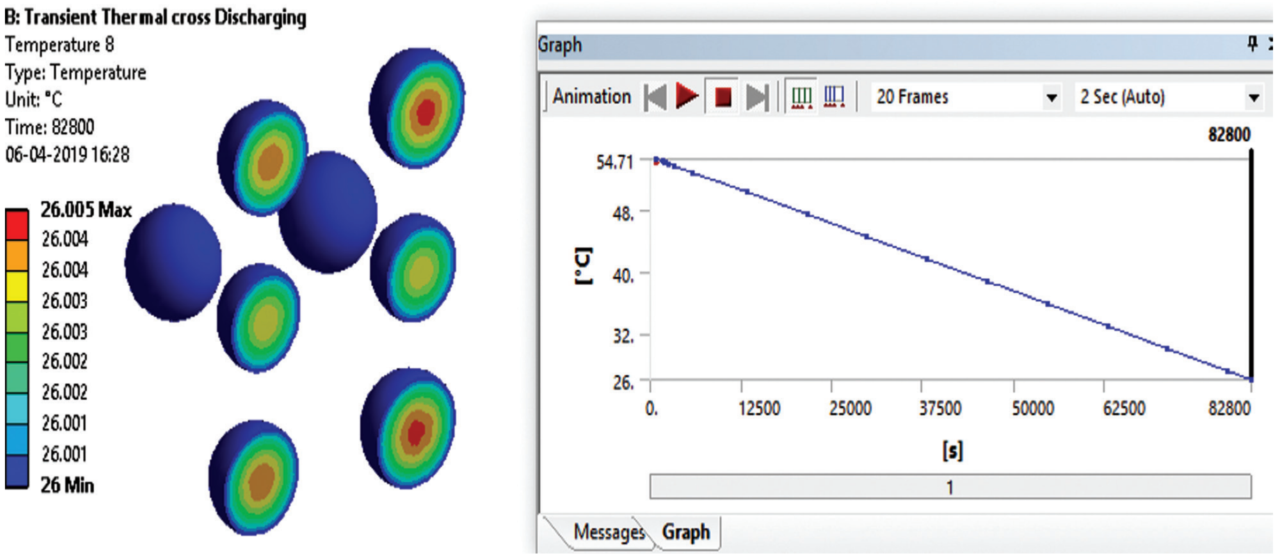

Figure 7. CFD results - discharging for cross orientation (after 82800 seconds).

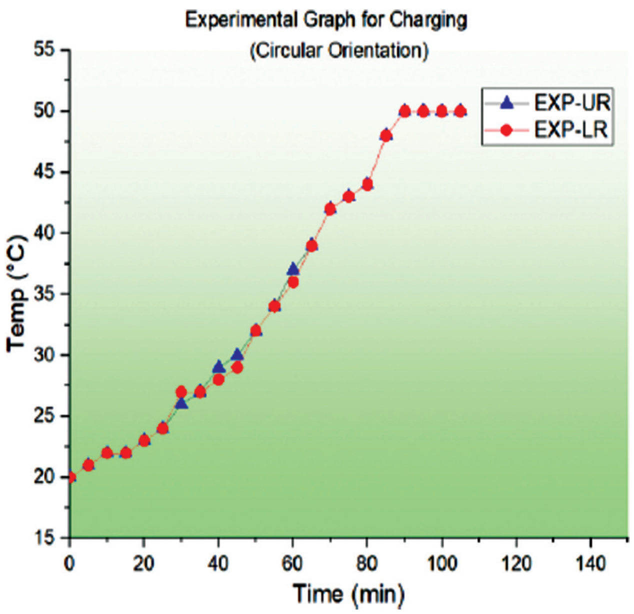

Figure 8. Experimental results - charging for circular orientation.

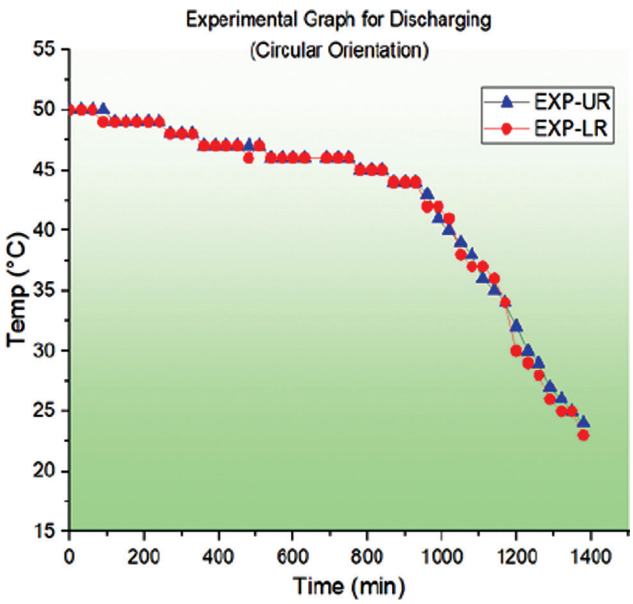

Figure 9. Experimental results discharging for circular orientation.

PCM conversion from liquid to solid which means heat is stored for a longer duration of time. This means practically, 2 hours is the lagging time as compared to CFD results as shown from figure 2 to 7.

Charging results - cross orientation

The charging procedure is the same as stated above, except that the orientation has been changed from circular to cross.

For cross-orientation PCM is charged from ambient temperature (20˚C here) to 50˚C within 105 minutes which is quite close to CFD readings. Both the rings charged within the same amount of time.

Discharging results - cross orientation

For cross-orientation, the scenario is quite different. PCM discharges from 55˚C TO 24˚C within a time frame of 22 hours 30 minutes. Discharging results obtained for

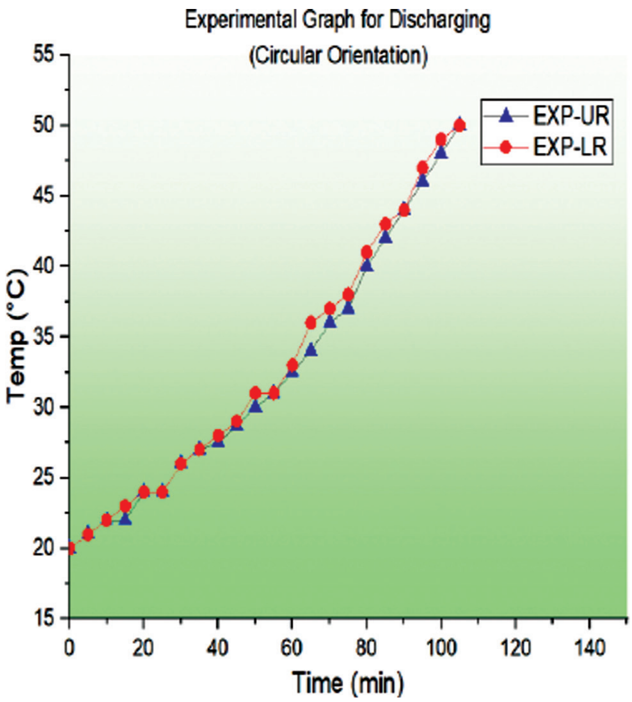

Figure 10. Experimental results charging for cross orientation.

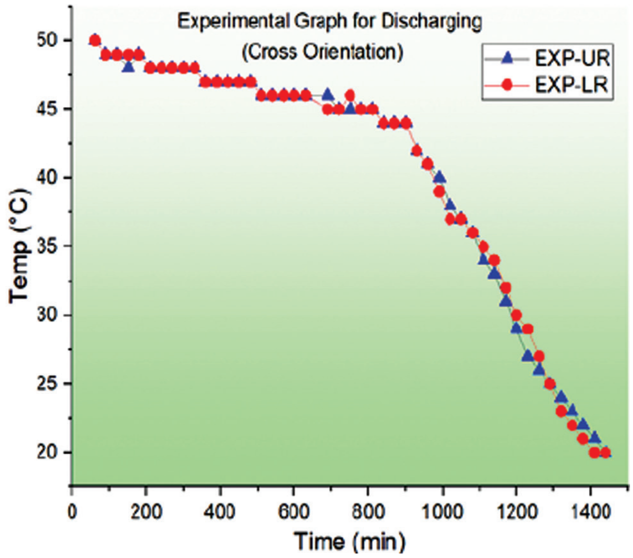

Figure 11. Experimental results discharging for cross orientation.

cross-orientation by PCM depicts that PCM cools 30 minutes earlier than circular orientation results, proving better pursuance of circular orientation.

CONCLUSIONS

In the present endeavor, an artificially established environment for examining PCM behavior in circular and cross-orientation has been drifted out.

- According to CFD results, the time required for the selected PCM-n tetracosane, to change its phase from solid to liquid is the same i.e 60mins in both, circular and cross-orientation. Hence, the charging cycle for both the orientations cross is collateral. While experimentation delineates that, it takes 105 minutes to charge the PCM in both orientations. The increased time reveals that there prevails an experimental error of around 40% which needs to be taken solemnly. This may indulge due to a lesser urge to heat the water in a colder environment which took 45mins more than what was expected. Hence better insulation needs to be provided in colder region areas.
- According to CFD, the discharging cycle for Circular orientation narrates that the PCM reaches 26˚C (from 55˚C) in 25 hours and for Cross Orientation PCM discharges in 23 hours, solidifying 2 hours earlier than in Circular Orientation, contending to store energy in water for a longer duration of time.
- According to experiments, the discharging cycle for Circular orientation shows that the PCM compasses 26˚C (from 55˚C) in 23 hours long and for Cross Orientation, PCM discharges in 22.30 hours, solidifying 30 minutes earlier than in Circular Orientation. Since, CFD and experimentation both confirm that the circular orientation stores thermal energy for a longer time as compared to cross-orientation, circular orientation rationalize to store superior.
- There exists an 8% variation in experimentation results from CFD results for discharging in circular orientation while cross-orientation produces only 3% variations, resulting in more closeness to the CFD values. Hence, Circular orientation conforms to a lesser difference in the experimental values from those of CFD.
- It could be signified that a colder environment doesn't affect the pursuance of selected PCM for the discharging cycle in cross-orientation since the time taken for both the CFD and experimental readings are almost the same.

NOMENCLATURE

CFD	Computational Fluid Dynamics
HTF	Heat Transfer Fluid
PCM	Phase Change Material
TES	Thermal Energy Storage
LHTES	Latent Heat Thermal Energy Storage
UR	Upper Ring
LR-	Lower Ring

PW	Paraffin Wax
ECBC	Energy Conservation Building Code
DBT	Dry Bulb Temperature
WBT	Wet Bulb Temperature
H	Enthalpy, Joule
K	Thermal Conductivity, W M-1 K-1
S	Source Term
T	Time, Seconds
T	Temperature, ˚C
S	Source Term
P	Density, Kg /M3
B.P	Boiling Point

Subscripts:

Cp	Specific Heat Capacity, J Kg-1k-1

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Abu-Hamdeh NH, Alnefaie KA. Assessment of thermal performance of PCM in latent heat storage system for different applications. Sol Energy 2019;177:317–323. [CrossRef]

[2] Jeremy CC, Chua KJ, Islam MR. A study on latent heat energy storage performance of tetradecane. Energy Procedia 2017;142:3208–3213. [CrossRef]

[3] Yang T, Wang C, Sun Q, Wennersten R. Study on the application of latent heat cold storage in a refrigerated warehouse. Energy Procedia 2017;142:3546–3552. [CrossRef]

[4] Kurnia JC, Sasmito AP, Ping SI. Investigation of heat transfer on a rotating latent heat energy storage. Energy Procedia 2017;105:4173–4178. [CrossRef]

[5] Koukou MK, Vrachopoulos MG, Tachos NS, Dogkas G, Lymperis K, Stathopoulos V. Experimental and computational investigation of a latent heat energy storage system with a staggered heat exchanger for various phase change materials. Therm Sci Eng Prog 2018;7:87–98. [CrossRef]

[6] Tayssir M, Eldemerdash SM, Sakr RY, Elshamy AR, Abdellatif OE. Experimental investigation of melting behavior of PCM by using coil heat source inside cylindrical container. J Electr Syst Inf Technol 2017;4:18–33. [CrossRef]

[7] Fornarelli F, Valenzano M, Fortunato B, Camporeale SM, Torresi M, Oresta P. Heat transfer enhancement induced by the geometry of a LHTES device. Energy Procedia 2018;148:471–478. [CrossRef]

[8] Frazzica A, Palomba V, La Rosa D, Brancato V. Experimental comparison of two heat exchanger concepts for latent heat storage applications. Energy Procedia 2017;135:183–192. [CrossRef]

[9] Pointner H, Steinmann WD, Eck M, Bachelier C. Separation of power and capacity in latent heat energy storage. Energy Procedia 2015;69:997–1005. [CrossRef]

[10] Pointner H, Steinmann WD, Eck M. Introduction of the PCM flux concept for latent heat storage. Energy Procedia 2014;57:643–652. [CrossRef]

[11] Qin Z, Ji C, Low Z, Dubey S, Choo FH, Duan F. Effect of fin location on the latent heat storage: a numerical study. Energy Procedia. 2017;143:320–326. [CrossRef]

[12] Campli S, Acharya M, Channapattana SV, Pawar AA, Gawali SV, Hole J. The effect of nickel oxide nano-additives in Azadirachta indica biodiesel-diesel blend on engine performance and emission characteristics by varying compression ratio. Envir Prog Sust Energy 2021;40:e13514. [CrossRef]

[13] Nithyanandam K, Pitchumani R. Analysis and optimization of a latent thermal energy storage system with embedded heat pipes. Int J Heat Mass Transf 2011;54:4596–4610. [CrossRef]

[14] Fan L, Khodadadi JM. Thermal conductivity enhancement of phase change materials for thermal energy storage: a review. Renew Sust Energy Rev 2011;15:24–46. [CrossRef]

[15] Fan LW, Zhu ZQ, Xiao SL, Liu MJ, Lu H, Zeng Y, et al. An experimental and numerical investigation of constrained melting heat transfer of a phase change material in a circumferentially finned spherical capsule for thermal energy storage. Appl Therm Eng 2016;100:1063–75. [CrossRef]

[16] Tyagi VV, Pandey AK, Buddhi D, Tyagi SK. Exergy and energy analyses of two different types of PCM based thermal management systems for space air conditioning applications. Energy Convers Manag 2013;69:1–8. [CrossRef]

[17] Tan FL, Hosseinizadeh SF, Khodadadi JM, Fan L. Experimental and computational study of constrained melting of phase change materials (PCM) inside a spherical capsule. Int J Heat Mass Transf 2019;52:3464–3472. [CrossRef]

[18] Zohra MB, Amine Rİ, Alhamany A, Sennoune M, Mansouri M. Improvement of thermal energy storage by integrating PCM into solar system. J Therm Eng 2020;6:816–828. [CrossRef]

[19] Deokar V, Bindu R, Deokar T. Simulation modeling and experimental validation of solar photovoltaic PMBLDC motor water pumping system. J Therm Eng 2021;7:48–62. [CrossRef]

[20] Deokar V, Bindu R. Active cooling system for efficiency improvement of PV panel and utilization of waste-recovered heat for hygienic drying of onion flakes. J Mater Sci 2021;32:2088–2102. [CrossRef]