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Qualitative & Quantitative estimation of the effects of longitudinal fin parameter with different configurations on thermal performance of PCM-LHTES unit.

Mohammad Khan[1], Zulkar Nain[2], Lubon Putul[1], Jawad[1]

[1]*Department of Nuclear Engineering, University of Dhaka, Bangladesh*

[2]*Doren Power Ltd, Bangladesh*

[*]**Corresponding author:** Mohammad Khan, Department of Nuclear Engineering, University of Dhaka, Bangladesh.

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Synopsis
The current study is a continuation of a series of experiment & computational studies in the field of heat transfer augmentation process in thermal energy storage device. In this study, we have demonstrated prospects of our proposed PCM-LHTES system, embedded with different configurations of longitudinal fins for obtaining better heating performance for latent heat storage by numerical heat transfer modelling. As a part of the study, the onset of phase change to the offset, driven by the mechanism of natural convection in the working domain is numerically investigated applying state-of-the-art commercial code: ANSYS FLUENT, a reliable & powerful CFD software for analyzing natural circulation of fluid & associated heat transfer process during melting of PCM. The particular target is to focus on contact surface area extension between PCM and capsule shape enclosed cylinder by the addition of longitudinal fins to accelerate heat transport process. Two commercial PCM: Rubitherm-50 & Climsel-58 are filled into a cylindrical pipe with their properties for modelling input. To qualify our modelling approach, the selected model is validated against experimental result: change of total enthalpy. Finally, the effect of fin parameters including longitudinal fin length, fin thickness and fin number on thermal performance of PCM-LHTES system is investigated.

Keywords: Modelling approach, Governing equations, Longitudinal fins, Phase Change Materials (PCM), Sensible Heat Storage (SHS), Latent Heat Thermal Energy Storage (LHTES).

Introduction

Heat energy storage system using phase change materials is an efficient and economical energy storage method where excess energy is stored after meeting the demand for electricity [1]. The most common heat energy storage techniques using phase change materials are Latent heat storage (LHS) & Sensible heat storage (SHS). Under LHS principle, huge amount of thermal energy can be stored with small temperature range, while SHS is based on temperature rise of storage material for storing heat energy without phase change and release it with decreasing temperature while required [2]. For both cases, it is beneficial to use PCM for storing heat energy. PCM is used for many engineering applications like thermal energy storing unit design and optimization, analyzing transient behavior of phase change materials, accelerating heat transfer process in LHTES system.

For the purpose of storing heat energy, LHTES with PCM becomes one of the most promising technique because of its high energy density with little temperature variation [3]. However, it is needed to make sure that phase change temperature of materials should be kept between charging and releasing temperatures. One of these associated phenomena during melting is natural convection.Therefore, there must be a clear understanding about this phenomena.

Several research works have been performed so far, focusing heat transfer enhancement techniques in LHTES components with associated phenomena (natural convection). During the period of 1970s, Kulacki & his associates carried out various tests employing inner heat generation to examine the dynamics of natural heat transport phenomena applying different boundary cooling conditions [4-6].

With the aim to evaluate thermal performance of three (3) horizontal concentric heat exchangers identified as ‘Circular fin’, ‘Without fins’ (control PCM) and ‘Longitudinal fins’, a study was conducted by Agyenim et al. [7]. The study revealed that the highest thermal performance is found by longitudinal fins during PCM charging and discharging process.

A numerical investigation was done on unsteady performance of shell-and-tube heat exchanger utilizing PCM by Lacroix with the target of identifying the influence of flippers on heat exchanger performance [8]. Under this investigation, the impact of natural circulation was considered. It is detected that increasing fin number can improve heat dispersion of heat sink.

Mahmoud Jourabian et al. examined the melting phenomena in a heat exchanger applying fins [8]. The study revealed that melting rate rises with increasing fin length and relative heat conductivity. It was also detected that movement of fins (located bottom of the cavity) to the center indicated no influence on melting phenomena but moving fin to the top of the cavity causes delayed melting.

A computational study was done by Bergman et al. on relatively higher temperature LHTES system [10]. During CFD study, both energy charging & discharging process were analyzed. It is revealed that the charging and discharging rate is strongly affected by the presence of HP in the PCM domain.

Energy analysis has been done by Doma fiski & Fellah to assess the thermal performance of a LHTES, using two different PECM with two PCMs [11]. To achieve the highest second-law efficiency, they advised that the downstream unit's melting temperature need to be very close to ambient temperature.

Optimization of energy storage in latent heat transfer energy unit was done by Yang et al. and it is revealed that shorter fin pitches result quicker melting/solidification time [12]. The impact of nanoparticles in PCM was examined by Mahmoud Jourabian et al. and found that the melting process is accelerated by the nanoparticles, mixed with PCM [13].

Kh. Hosseinzadeh et al. studied on Effect of two different fins (longitudinal-tree like) and hybrid nano-particles (MoS2-TiO2) on solidification process in triplex latent heat thermal energy storage system. The results unveiled that, while the combined usage of nanoparticles and tree-like fins gives the best result by lowering the solidification time by 78% compared to bare tube, tree-like fins claim the best performance taking 1700 s followed by rectangular fins with 3500 s if nanoparticles are out of reach. M.A.ErfaniMoghaddam et al. conducted a research work focusing on Metal foam and fin implementation into a triple concentric tube heat exchanger over melting evolution. It is found that the results provided by multiple cases underlined the significance of natural convection in the bare system, although finned and copper-metal-foam cases outshine buoyancy forces by roughly 45% and 97%, respectively.

Study on Solidification enhancement in triplex thermal energy storage system via triplets fins configuration and hybrid nanoparticles was done by Kh.Hosseinzadeh et al.Under this investigation, influences of applying various nanoparticle volume fractions, radiation parameter, and shape factor on the assessment of the liquid-solid interfaces, phase change rate, and solidification process time over the whole solidification procedure was calculated and reported.

Effect of internal fins along with Hybrid Nano-Particles on solid process in star shape triplex Latent Heat Thermal Energy Storage System by numerical simulation was carried out by Kh.Hosseinzadeh et al. The effect of internal fins on the solidification rate is investigated, which is been increased by 14% when applying HNPs and fins.

The major limitation of using phase change materials comes from the fact that because of its low thermal conductivity, charging and discharging process in LHTES system becomes slow [14]. That's why, employing an improved thermal energy transport enhancement technique for the LHTES becomes necessary to overcome this limitation. There are two ways to improve heat transportation, identified as upgradation of PCM thermo-physical properties and the second option is optimizing heat exchanger, by extending surface contact area. The surface area can be extended by fin with different configuration. Because of combined effect of conduction & convection, it is very hard to evaluate heat transfer precisely from complex geometry to PCM. Therefore, it is crucial to calculate & optimize the designed thermal storage system for which proper understanding of transient heat transfer phenomena in PCM body is a must.

Even though a series of experiments have been conducted so far with the aim of improving thermal performance of LHTES, but to some extent direct experimental studies with lot of parameters are not possible because of the complexity & drawback of measurement capabilities in experiments. That is why, the role of computer codes & models are important to address these gaps.
In this study, close-contact melting process of PCM inside capsule shape enclosed cylinder through distribution of heat energy by the extended contact surface area of fins of different configuration is numerically investigated. Under this investigation, onset of phase change to the offset, driven by comprehensive understanding of natural convection heat transfer in PCM molten body has been done applying state-of-the-art commercial code: ANSYS FLUENT, a reliable and powerful CFD software for analyzing natural circulation of fluid & associated heat transfer process during melting of PCM. Two commercial PCM: Rubitherm-50 & Climsel-58 are filled into a horizontal cylindrical pipe with their properties for modelling input. To qualify our modelling approach in upcoming calculation (parametric analysis), the selected model is validated against experimental result: change of total enthalpy. Finally, as a part of management of heating load, the effect of fin parameters is evaluated on thermal performance of PCM-LHTES system.

Computation model

Cylindrical pipes are used as a very common engineering application, especially in the application of commercial heat exchanger. The proposed heat exchanger (used here) has a horizontal cylindrical tube as its preliminary design (Figure 1). The outer domain is made up of phase change material & boiling water (HTF) with constant temperature flows through the inner tube.

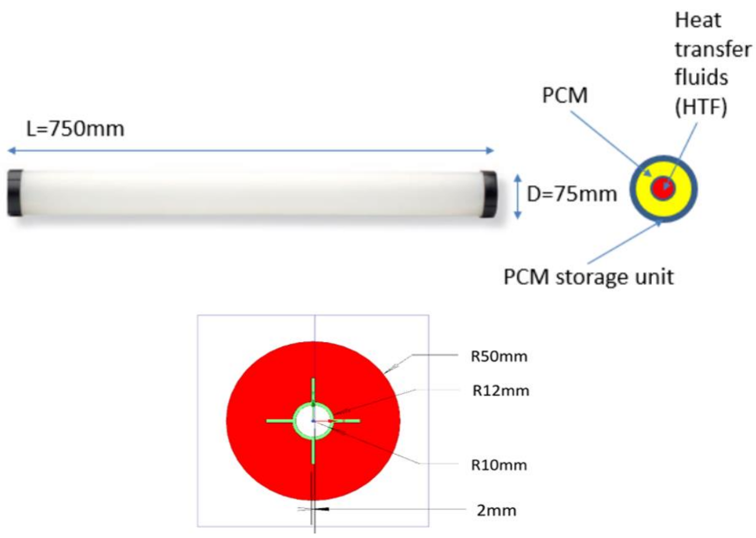

Figure 1: Sectional view of the heat exchanger with dimensions

A parametric test matrix is considered here in Table 1. Before implementing test matrix, we first run a case so called 'reference case' with 4 fins (measuring 15mm in length and 5mm in thickness), utilizing paraffin PCM.

Table 1: Different fin configurations based test matrix

Materials	Fin length	Fin number	Fin thickness
RT-50	5mm/15mm/25mm	4/6/8	5mm
Climsel C-58	5mm/15mm/25mm	4/6/8	5mm/10mm/15 mm

Computational Domain

Because of the three-dimensional model and mesh, the CFD approach is very expensive in terms of computation. Therefore, it is not affordable for sensitivity analysis of important parameters in many circumstances. For this reason, to simulate close contact melting process in a LHTES unit, a simplified 2D model is employed. The model is generated using a commercial CFD code: ANSYS DESIGN MODELLER. The associated mesh is generated using the O-grid method by ICEM CFD, which ensured an unstructured mesh with hexahedral cells (Figure 2).

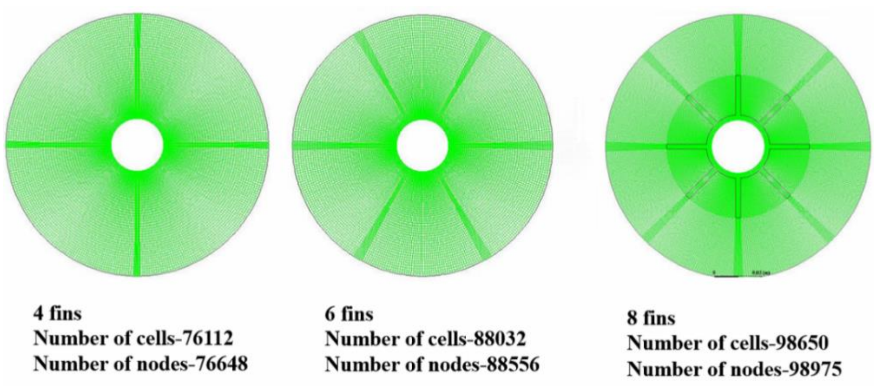

Figure 2: Sectional view of the discretized fin body with different configuration.

Physical properties of PCM materials

Two commercially available PCM materials (Climsel and Parafin), are encapsulated in the cylinder (used in our current study:Table 2), which is filled up by simulant compositions with their properties for modelling input. The PCMs, used here possess different thermo-physical properties but are similar in melting point. That means, which means that they can be implemented in the similar working temperature during span of a heat energy charging process.

Table 2: Thermo-physical properties of PCM [15]

Thermo-physical Properties	Climsel (C 58)	Parafin (RT 50)
Melting temperature range (º C)	55-60	45-51
Solidification temperature range (º C)	56-53	51-46
Latent Heat of Fusion (J/Kg)	212,000	160,000
Liquid density (Kg/m3)	1280	760
Solid Density (Kg/m3)	1460	880
Average Specific Heat (KJ/Kg*K)	3.6	2
Conductivity in Solid (W/m*K)	0.57	0.2
Conductivity in Liquid (W/m*K)	0.47	0.2

Boundary conditions applied

The computation is executed under the following thermal boundary conditions, excludng mechanical load, (Table 3) for study the influence of a boundary temperature mode.

Table 3: Boundary conditions applied

Inner surface temperature of pipe (isothermal), K	373
Outer surface temperature of pipe	Adiabatic
Initial temperature of the domain, K	315

Meshing grid independence study

To justify the reliability of the numerical models, a grid independence study needs to be conducted. In reality, mesh quality is directly linked to the precision of the simulation results. That is why, we have studied different mesh densities in the following table.

Case	Node number
1	22936
2	42293
3	50008
4	100384

The transient case of density and liquid fraction is presented in figures 6 and 7

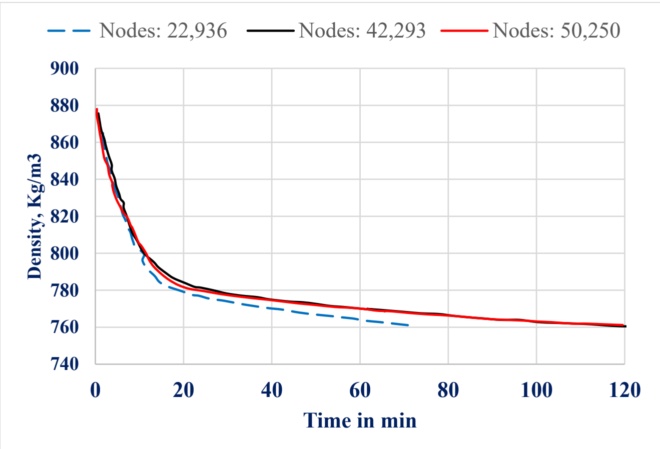

Figure 6: Surface-averaged density.

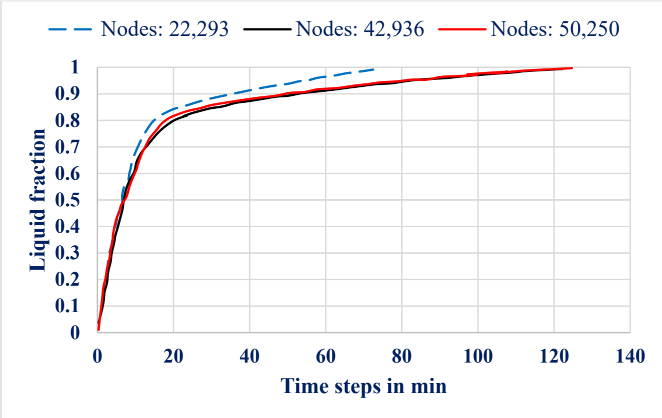

Figure 7: Liquid mass fraction.

As can be seen, no significant change is observed in case of average density and liquid fraction for the grids with the cell number higher than 42,936. Hence, the nodes number (42,936) are selected to investigate the heat transfer phenomena in these geometries.

Mesh independence study in terms of time-steps

For the purpose of obtaining picture of all flow field with high accuracy during transient simulation, smaller time step is needed to be applied. However, in that case it is required to make sure that local courant number fulfills the convergence criteria. The major limitation comes from the fact that using small time steps makes the simulation computationally more expensive. That is why, it becomes necessary to carry out time step independence study for obtaining optimal value of time step. Setting up of time step with different cases have been shown below.

Case	Node number	Time step
1	22936	0.01
2	229362	0.03
3	22936	0.05

The density vs time and liquid fraction vs time are presented in Fig. 8-9

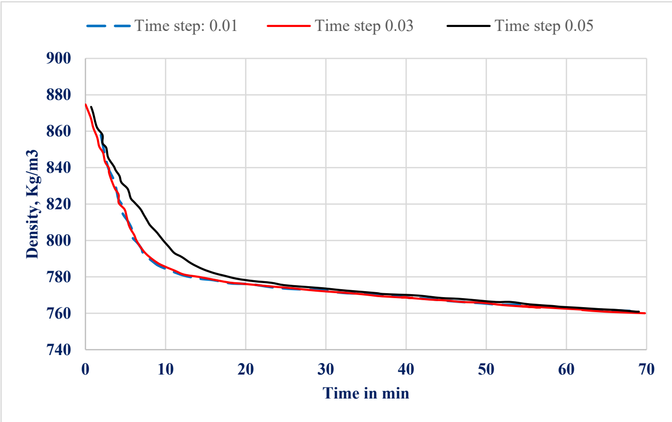

Figure 8: Surface-averaged density.

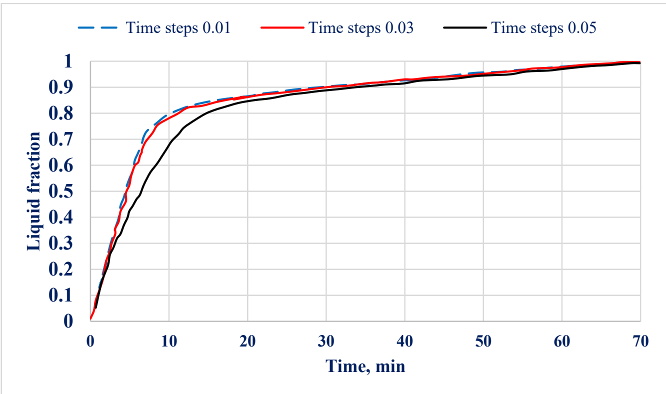

Figure 9: Liquid mass fraction

It is found that the deviation of surface average density and liquid mass fraction is very narrow with 0.01 and 0.03 time step size, which are acceptable to satisfy the calculation requirements.

Numerical platform

Governing equations

The enthalpy-porosity approach is used to simulate close-contact melting process of PCM inside capsule shape enclosed cylinder through distribution of heat energy by the extended contact surface area of fins of different configuration [16-17]. In order to simulate melting process, the complete three-dimensional time dependent equations are involved as below:

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

Momentum :

$$\frac{\partial \overline{V}}{\partial t} + \overline{V}\nabla\overline{V} = \frac{1}{\rho}(-\nabla P + \mu\nabla^2\overline{V} + \rho\beta\overline{g}(T - T_{ref})) + \overline{S}$$

Thermal Energy

$$\frac{\partial h}{\partial t} + \frac{\partial H}{\partial t} + \nabla.(\overline{V}h) = \nabla.(\frac{k}{\rho c_p}\nabla h)$$

The enthalpy of the material is computed as the sum of the sensible enthalpy h, and the latent heat, ΔH:

H=h+ ΔH

Where,

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT$$

The latent heat content can be written in terms of the latent heat of the material L:

ΔH = λL, where ΔH may vary from zero (solid) to L (liquid). Therefore, the liquid fraction, λ, can be defined as:

$$\lambda = \frac{\Delta H}{L} = 1 \quad \text{if } T<T_{Solidus}$$

$$\lambda = \frac{\Delta H}{L} = 1 \quad \text{if } T<T_{Liquidus}$$

$$\lambda = \frac{\Delta H}{L} = \frac{T - T_{Solidus}}{T_{Liquidus} - T_{Solidus}} \quad \text{if } T_{Solidus}<T<T_{Liquidus}$$

To solve the governing equations in this study, the model uses the control volume approach.

Benchmark test for a reference case

With the aim of examining thermal performance of our proposed storage unit, a reference case was first studied numerically. The reference case is represented by a horizontal cylindrical tube, filled with RT 50 PCM, integrated with 4 fins. The fins are 15 mm in length and 5 mm inner thickness (Figure 3).

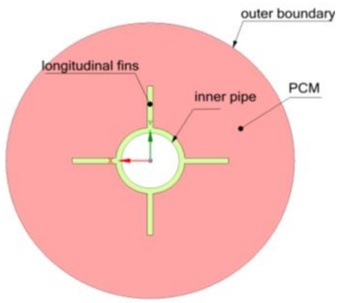

Figure 3: Sectional view of the heat storage unit, used in our case (Reference case)

While HTF (boiling water) flowing through the inner cylinder, PCM absorb heat and start melting while PCM temperature reaches to phase transition. During early phase of melting progression, conduction heat transport becomes dominant, because solid phase change materials and inner cylindrical capsule's exterior surface (connected with fins). Thereby, through the effect of conduction, a thin film of liquid forms (Figure 4) around the connecting zone between fins and cylindrical capsule. As a result, solid PCM absorbs and store heat energy from molten PCM through the influence of natural convection. Because of density difference of the liquid PCM, an upward motion of liquid PCM is generated, leading to turbulence flow inside the molten pool. As a result, a drastic rise of temperature is found at top part of the heat exchanger, compare to the bottom of the heat exchanger. In this situation, solid PCM moves to lower part of the capsule because of its higher density & gravity and liquid PCM remains in the top. With respect to time, cylinder oriented liquid layer thickness forms (Figure 4) and a visible thickness 'mushy zone' (mixture of solid and liquid) is formed at the region of phase transition.

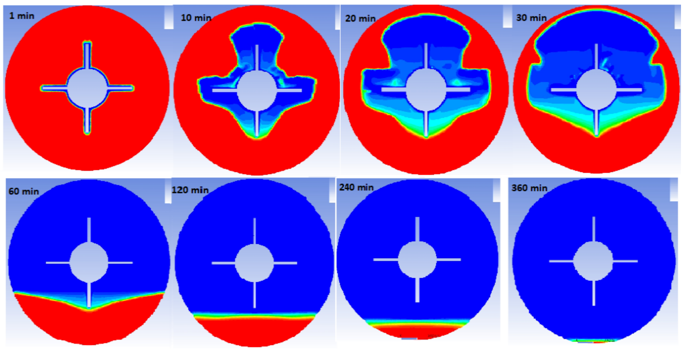

Figure 4: Transient case of density variation

The melting process is found no more symmetrical along x-axis with time steps as shown in Figure 4. As the density decreases with time steps, the molten part of PCM tends to rise in the upward direction accelerating melting phenomena. The series of images clearly indicates that during early phase, comparatively quick melting becomes visible whereas relatively slow melting rate is detected later on.

Because of the influence of natural convection & fluid flow surrounding the inner pipe, Nu 50 is obtained with small oscillation in the early phase of melting process. Afterwards, Nu sharply decreases and turns constant to approximately 1 when entire PCMs phase is about to the reach liquid state and the temperature is equal (Figure 5).

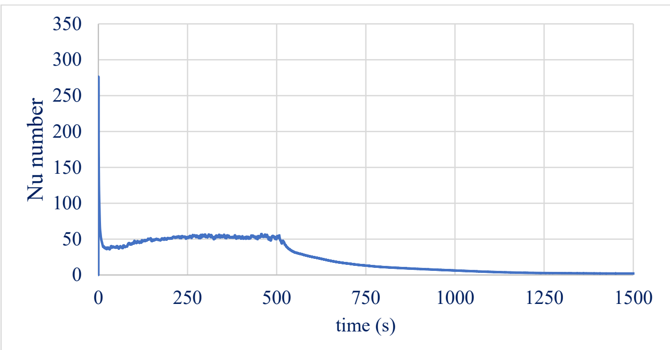

Figure 5: Nu number vs time (Sec) along inner pipe-PCM interface

To trust the model we are using, verification always needs to be done. To do this, computational result in terms of total enthalpy change is compared with experimental data, under transient state of natural circulation [18]. The experimental set up (Figure 10) was dedicated for performing heating load management. The facility consists of vertical cylindrical tank with PCM domain, which was modelled as the heat storage device. The used PCM was Climsel-C 58. Description of an experimental facility is presented in Figure 18, which has been designed & constructed for the purpose of improve understanding of the melting process in LHTES unit containing parallel arrangement of 50 PCM cylinders. The facility drives the laminar flow of HTF in the downward direction. The diffusers ensure even distribution of the flow of HTF before contacting PCM capsules. It is to be noted that heat transfer fluid was passed vertically from top to bottom throughout the whole unit. Under working condition mood, HTF is maintained with iso-thermal condition with temperature 338 K.

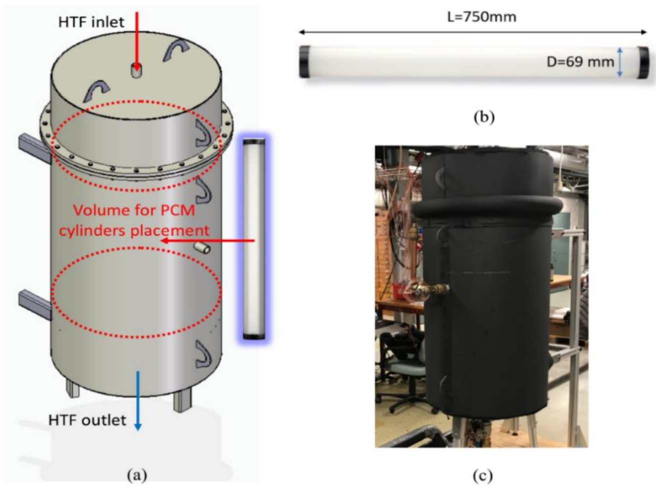

Figure 10: The description of the research facility (a) the schematic of the storage unit, loaded with PCM cylinder; (b) model of vertical cylinder filled with phase change material; (c) image of outer surface insulated heat storage device [18].

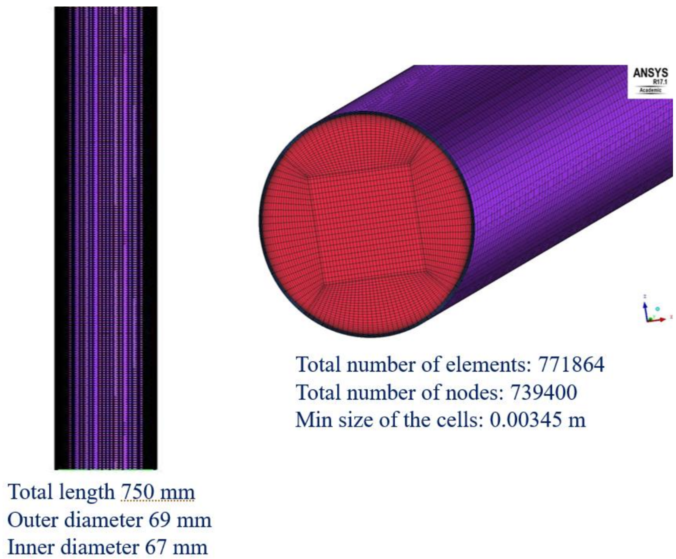

Figure 11: Front view of the mesh distribution of the domain.

Boundary condition applied:

The computation is executed under the following conditions shown in Table 4

Table 4: Boundary conditions applied at different locations in the model.

Location/Position of the domain	Type of BC	Applied value
Top of the PCM cylinder	Thermal condition: Adiabatic	q=0
Side of the PCM cylinder	Thermal condition: Adiabatic	q=0
Cylinder outer surface	Isothermal boundary condition	t=338 K

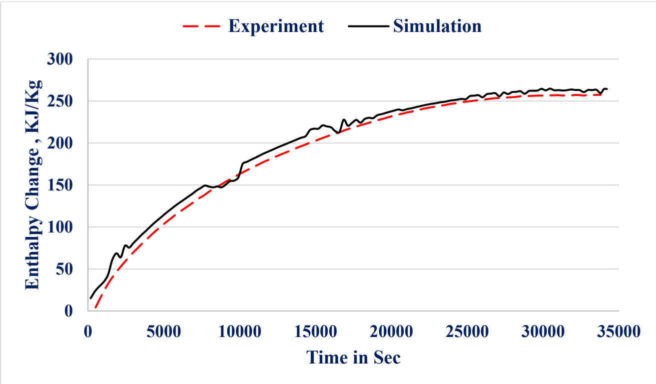

Figure 12: Experiment Vs CFD in terms of enthalpy change

The numerical computational results are in line with the experiment with some minor deviation. Therefore, it can be said that the numerical approach is valid. However, the principal reason behind the deviation might be because of applying constant properties of the PCM materials. The deviation could be minimized by applying temperature dependent material properties.

Discussion & parametric analysis

Once validation is done, the impact of extended surface with different fin configuration (in terms of fin number, fin length and fin thickness) has been examined. In addition, comparison is done among different fin configurations with respect to melt timing, fraction of melt and the time required to complete energy storage cycle.

It is revealed that heat energy distribution is accelerated by increasing fin number & fin length, consuming less time to experience full melting of PCM and charging the capsule with same amount of energy as shown in Figure 13-15. It can be seen that paraffin PCM with 8 fins consumes around fifty percent less time than that of Climsel PCM to be fully melt with full charge. The similar scenario can be seen in case of increasing fin length. Therefore, it undoubtedly indicates that the number of fins and fin length significantly accelerates the melting process by augmenting natural convection inside PCM pool.

On the other hand, even after having low thermal conductivity comparing with Climsel PCM, paraffin PCM melts faster than Climsel to reach melt fraction 1. This is due to higher impact of latent heat of paraffin PCM. Apart from this, because of having gelled property, Climsel PCM shows higher viscosity & protects phase separation after phase is changed. As a result, strong motion is observed in Climsel fluid domain driven by buoyancy effects, leading to faster melting rate in C 58 PCM.

**Calculation of total thermal energy charged in the storage device

-Initial supplied thermal energy to RT 50 body=33 KJ/Kg
Heat energy stored finally in RT 50 body=253 KJ/Kg (with 6 fins) & 260 KJ/Kg (with 8 fins)
Actual heat energy stored in RT 50 body=220 KJ/Kg (with 6 fins) and 227 KJ/Kg (with 8 fins)

-Initial supplied thermal energy to C58 body=61 KJ/Kg
Final heat energy stored finally in C58 body=410 KJ/Kg (with 6 fins) & 425 KJ/Kg (with 8 fins)
Actual energy stored in C58 body= 349 KJ/Kg (with 6 fins) & 364 KJ/Kg (with 8 fins).

The calculation clearly indicates, charging in the PCM capsule is highly influenced by the fin number.

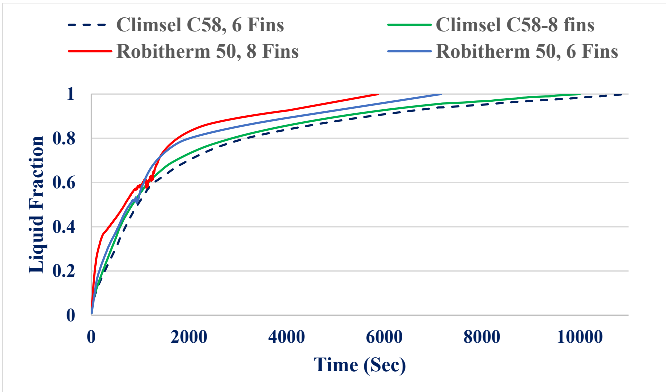

Figure 13: Transient case of liquid fraction

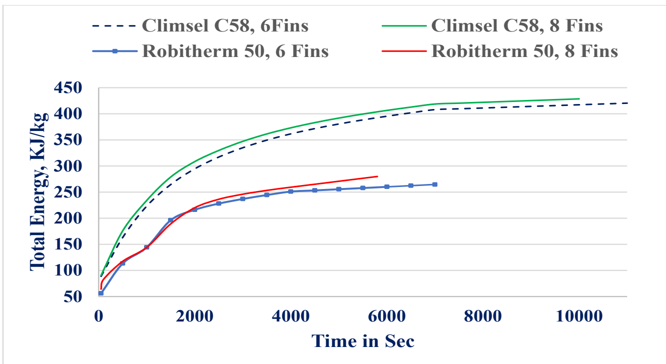

Figure 14: Total energy variation with time

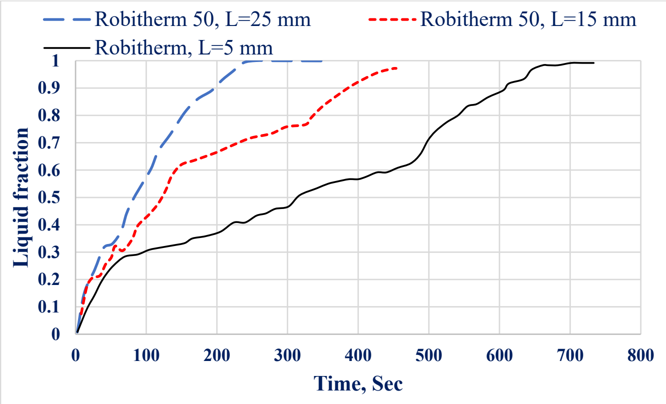

Figure 15: Liquid Fraction Vs time [s]

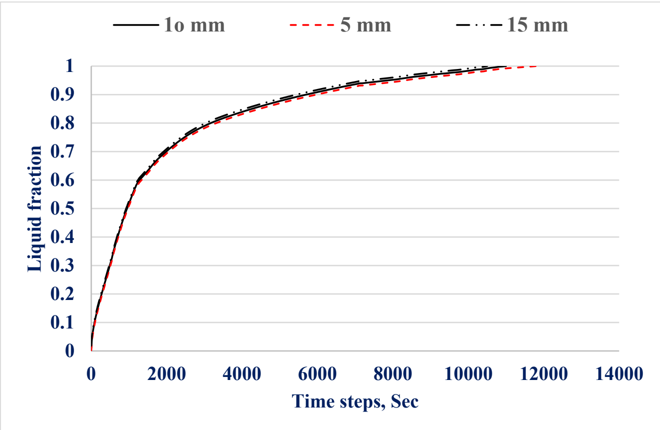

Figure 16: Liquid fraction Vs time [s]

On the other hand, it is found that the melting process is not significantly influenced by the fin thickness, compare to fin length and fin number, which is confirmed by Figure 16.

Conclusions & future recommendations

With the target of improving understanding of thermal performance of heat storage unit, a comprehensive study has been performed using a numerical heat transfer model, that includes encapsulated cylinder, embedded with longitudinal fins with different configurations. Under this study, the onset of phase change to the offset, driven by the mechanism of natural convection in the working domain is numerically investigated applying state-of-the-art commercial code: ANSYS FLUENT. This code is a powerful tool to gain this type of knowledge and improve existing understandings of the LHTES unit. The particular target of this study is to focus on improving thermal performance of PCM-LHTES system by extended contact surface area using longitudinal fins to accelerate heat transport process. Finally, the effect of fin parameters including longitudinal fin length, fin thickness and fin number on thermal performance of PCM-LHTES system is investigated.

In the light of numerical investigation, the following summary can be drawn:

a. Convective flow is found along the spherical boundaries of the pool from top to the bottom, replenishing the fluid in the stationary and highly turbulent region of the pool.
b. In case of Climsel PCM, we can experience slow melting process with respect to paraffin PCM. This is because of its gelled criteria and due to this criterion, it inhibits phase separation after phase transformation. That means, higher viscosity is found during Climsel PCM melting progression than that of paraffin, resulting less fluid motion causes slower melting rate.
c. RT 50 Paraffin with 8 fins consumes around fifty percent less time than Climsel-58 (with same number of fins) to be fully melt & complete the charging cycle. On the other hand, same scenario is found in case of increasing fin length. That clearly indicates that during the progression of PCM melting process, the number of fins and fin length significantly accelerates the melting process by augmenting natural convection inside PCM pool.
d. Overall thermal performance of heat storage device can be developed by increasing number of fins and fin length because of faster heat energy release from fin body to phase change material body whereas, increasing fin thickness provides comparatively lower effect.
e. It is also found from the analysis that the charging process in the PCM cylinder is highly influenced the number of fins, embedded with the encapsulated cylinder.
f. Due to buoyancy effects, the drastic temperature increase is found at the upper part of the heat storage unit.

Numerical analysis can be further conducted by the application of a set of simulation tools: CFX, CFD++ & OPENFOAM and compare with the results, obtained from FLUENT CFD to justify their applicability and reliability in this research domain.

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Conflicts of interest

The authors of the Article hold no conflict of interest.

Nomenclature

Cp Heat capacity [Jkg-1K-1]
H Height of the melt pool
Pr Prandtl number (υ/α)
Ra Rayleigh number (g βH5Q/k α υ)

Greek symbols

β Thermal expansion coefficient [K-1]
ρ Density [kg.m-3]
α Thermal diffusivity [m2S-1]
υ Kinetic viscosity [m2S-1]
g Acceleration due to gravity force [ms-2]
k Heat conductivity [Wm-1K-1]

Subscripts

Fig Figure
Ref Reference

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