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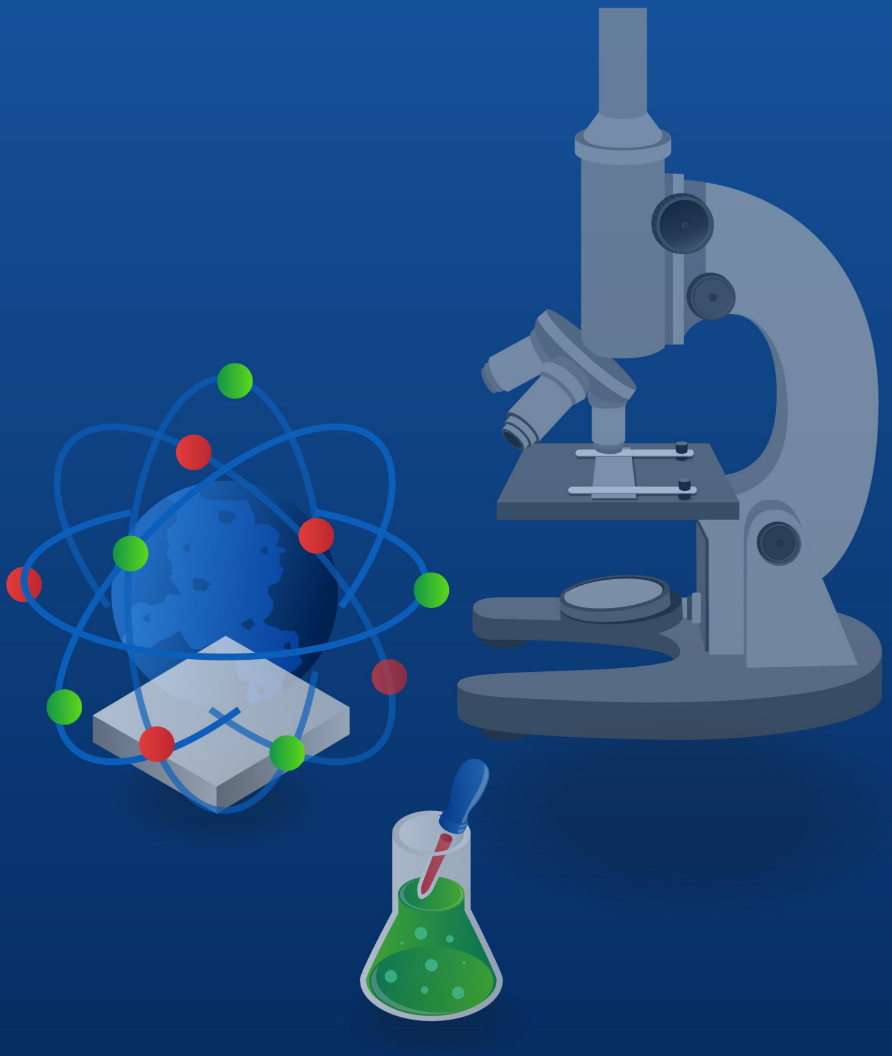

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Comparative CFD Analysis of Heat Transfer Enhancement in Phase Change Thermal Energy Storage with and without Fins for Solar Energy Storage

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ABSTRACT

Solar energy storage faces challenges due to its intermittent nature. Phase Change Thermal Energy Storage (PC-TES) offers a promising solution, utilizing materials that store energy by changing their phase. This study presents a comprehensive Comparative Computational Fluid Dynamics (CFD) Analysis aimed at evaluating the heat transfer enhancement in phase change thermal energy storage configurations with and without fins. The numerical simulations, conducted using ANSYS (fluent), investigate the dynamic interactions within the system during the charging phase. We developed detailed CFD models representing PC-TES systems with and without fins, investigating their thermal performance during melting under controlled conditions. The analysis focused on quantifying the impact of fins on key metrics like melting time and temperature distribution. Our results demonstrate the significant benefits of fin integration. Fins enhanced heat transfer area, leading to 33.33% faster melting compared to finless configurations. They created uniform temperature distribution by minimizing the thermal gradient within PCM. This thermal enhancement is due to combined effect of using Nanofluid as heat transfer fluid and use of fins. Overall, this study concludes that incorporating fins in PC-TES systems offers a potent strategy for significantly improved heat transfer and faster energy storage, highlighting their potential for efficient and cost-effective solar energy capture and utilization.

INTRODUCTION

The use of solar energy for cooking, heating and cooling, refrigeration, and drying applications is the most promising source of energy. However, the use of solar energy is only limited for day time usage. Due to this problem many researchers has been working on this to fill this gap. They developed thermal energy storage materials mainly sensible and latent heat storage material. Thermal energy storage (TES) systems play a pivotal role in addressing the intermittency of renewable energy sources by storing excess energy during periods of abundance and releasing it when demand is high. Thermal energy storage can be classified as sensible heat storage (SHS), latent heat thermal energy storage (LHTES) and thermochemical storage. In sensible heat storage (SHS), the thermal energy is stored by rising the temperature of the storage material without undergoing phase transformation and therefore, the amount of energy stored is a function of the specific heat of the material, the temperature change, and the amount of storage material. On the other hand, LHTES involves phase transformation of the storage material from one state to another. The thermochemical storage, which involves a reversible physio-chemical phenomena to store the thermal energy chemically and recovers the energy upon supplying heat (Ibrahim, *et al.*, 2017). Among various TES technologies, phase change materials (PCMs) have gained considerable attention due to their high energy storage density during phase transitions. However, the efficiency of PCMbased TES systems, particularly during the charging process, remains a critical aspect influencing their widespread adoption. The use of PCM for latent heat storage application has a great potential to improve the solar system performance but there is one main limitation with the application of PCM to heat storage process. PCM's currently used as heat storage have low thermal conductivity. Therefore, heat transfer enhancement is one of the essential strategies that can overcome this obstacle (Youssaf,*et al.*,2018). The common shortcoming of many potential phase change heat storage materials is their low heat conductivity. This is between 0.15 and 0.3 W/(mK) for organic materials and between 0.4 and 0.7 W/(mK) for salt hydrates(Kenisarin and Mahkamov,2007).Uros Stritih has studied experimentally the heat transfer characteristics of a latent heat storage unit with a finned surface in terms of solidification and melting process by comparison with a heat storage unit with a plane surface(Stritih,2004). From the experimental studied it was concluded as heat storage (melting) is not a problem during thermal storage applications, and that the extraction of heat (solidification) can be effectively enhanced with fins. Heat transfer during solidification is greater if the fins are included. Youssef and Tassou have developed 3D modelling and validated with experimental result of a PCM heat exchanger with spiral wired tubes. The spiral-wired tube is firstly applied by this project into the heat transfer enhancement of the designed PCM HX. The special design of a spiral wired tube can improve the thermal conductivity of PCM and allow free movement of PCM during phase change processes which could further enhance the heat transfer.

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Even so, further detailed evaluation and analysis are necessary. During melting, heat is transferred to the PCM first by conduction and later by natural convection. This is because, the solid region moves away from the heat transfer surface and the thickness of the liquid region increases near the heat transfer surface. Since thermal conductivity of liquid PCM is less than that of solid PCM, the heat transfer by conduction almost becomes negligible as the melting process continues (Youssaf, *et al.*, 2018). The further melting is mostly by natural convection due to the density gradient that exists within the liquid PCM (Jegadheesuwaran,et, *et al.*,2009).Lacroix and Benmadda have conducted a numerical simulation to study the process of natural convection-dominated melting and solidification from a finned vertical wall. In short, the research aims to model and understand how heat transfer and phase change occur in the presence of fins on a vertical surface. Numerical model was validated with experimental data. Their result indicates that the presence of long fins embedded in the PCM significantly accelerates the melting process. On other hand, the effect of short fins was much less significant (Lacroix and Benmadda,1997). Hang and Faghri, have discussed the enhancement of heat transfer in a latent heat thermal energy storage system by utilizing an internally finned tube. In this system, a phase change material fills the annular shell space around the tube, while a transfer fluid flows within the internally finned tube. The melting of the phase change material is modeled using a temperature-transforming model coupled to the heat transfer from the transfer fluid. The heat conduction within the internal fins is treated as an unsteady two-dimensional heat conduction problem, and it is solved using a finite difference method. The key finding of the study is that incorporating internal fins proves to be an effective method for enhancing heat transfer in thermal energy storage systems, especially when a fluid with low thermal conductivity is employed as the transfer fluid (Zhang and Faghri, 1996). The results suggest that the use of internal fins can significantly improve the overall efficiency of the thermal energy storage system by promoting better heat transfer between the phase change material and the transfer fluid. Lacroix, studied theoretical model for predicting the dynamic behavior of a shell-and-tube thermal storage unit featuring a phase change material (PCM) in the shell and a heat transfer fluid (HTF) circulating within the tubes. The tubes can either be bare or equipped with fins. The model employs an enthalpy-based approach to address the multidimensional phase change problem, coupled with convective heat transfer from the HTF. Experimental data are used to validate the numerical model. The study then conducts various numerical experiments to examine the impact of factors such as the shell radius, HTF mass flow rate and inlet temperature, and the presence of fins on the inner tubes. The results indicate that annular fins are most effective under conditions of moderate mass flow rates and low inlet temperatures (Lacroix, 1993). Liu numerically investigates the melting process of a PCM in an H-type finned concentric shell tube configuration. The authors found that the use of H-type fins can significantly increase the melting rate of the PCM (Liu,etal.,2010).Cao investigated the use of novel fins and nanoparticles to enhance the melting performance of PCMs in tubular energy storage systems. The authors found that the combination of novel fins and nanoparticles can achieve efficient melting performance in tubular thermal energy storage systems (Han,*et al.*,2022).These are just a few examples of the many studies that have been conducted on the use of fins with PCMs. The results of this research have shown that fins can be a valuable tool for improving the performance of PCM-based TES systems. Energy consuming devices needs energy to maintaining them in working condition. These paper concentrates on solar thermal cooking application especially for injera baking process. In solar thermal cooking application collector is used to collect solar radiation to heat fluid in the receiver. Solar energy is collected by heat transfer fluid is transferred to thermal energy storage material through pipes. Phase change material (PCM) is charged when solar energy is available and used at night time. A range of phase change materials (PCMs) have been explored for high-temperature cooking processes, with a focus on their thermal energy storage capabilities. Inorganic salt PCMs,such as graphite,meatl foams, and porous metal oxides, have been identified as potential options due to their ability to withstand repeated heating and cooling cycles(Fernandez,*et al.*,2018).These PCMs have also been applied in solar cookers, with coconut oil identified as a particularly effective option for improving efficiency and enabling cooking during off-sunshine hours (Kanimozhi,*et al.*,2015).The use of PCMs in solar cookers has been found to enhance performance ,reduce cooking time, and enable evening cooking (Omara,et,al.,2020).However, challenges remain in optimizing PCM quantity,types,and thermal control, as well as in addressing economic and environmental considerations(Omara,et,al.,2020 .These are materials whose phase change, from solid to liquid(melting), and liquid to solid (solidifying),are used to store and release heat. At a certain temperature Heat absorption melts the material. During melting, the material absorbs large amounts of heat from the environment. When the temperature drops, the material solidifies and releases heat .By storing the phase change material in insulated shields, the heat energy can be used at a later time. Francis were experimentally compered the heat transfer enhancement of thermal energy storage heat exchanger for the PCM without fins, with circular and longitudinal fins. From their experimental result longitudinal fins gave the best performance with increased thermal response during charging and reduced sub cooling in the melt during discharge (Agyenim,*et al.*,2009).

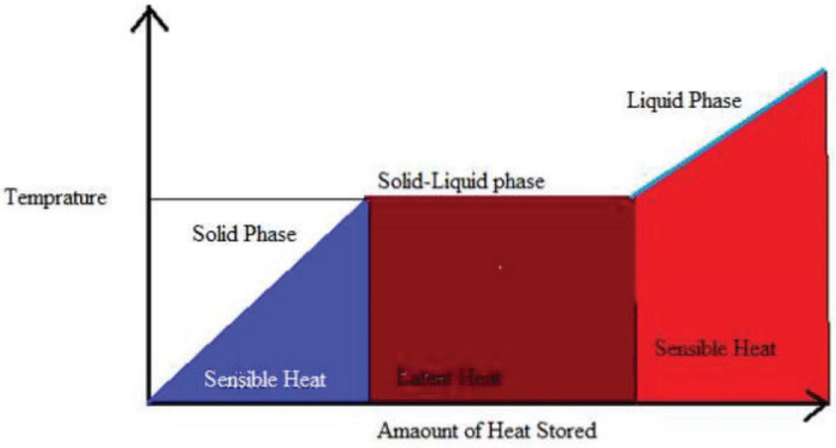

Figure 1: Schematic diagram of Phase Change material Phase transition of PCM [14]

Phase change materials (PCMs) have the potential to revolutionize the cooking process by providing a more efficient and uniform way to heat food. However, there are several key properties that PCMs must possess in order to be effective in cooking applications [14]

a. Thermo physical properties

- Melting temperature in the desired operating temperature range
- High latent heat of fusion per unit volume
- High specific heat to provide for additional significant sensible heat storage.
- High thermal conductivity of both solid and liquid phases
- Small volume changes on phase transformation and small vapour pressure at operating temperatures
- Congruent melting of the phase change material for a constant storage capacity of the material with each freezing/melting cycle

b. Chemical properties o Chemical stability. o Complete reversible freeze/melt cycle. o No degradation after a large number of freeze/melt cycle. o Non-corrosiveness to the construction materials and low cost. o Non-toxic, non-flammable and non-explosive materials for safety.

Injera baking process require temperature in the range of $(165^0C - 220^0C)$.So the phase change material required for this process should be melting point greater than the above temperature ranges.

Table 1: Physical properties of pure nitrates and nitrite salts

PCM	**Melting Temperature (C)**	**Melting enthalpy(J/g)**	**Thermal Conductivity(w/m.K)**		**Specific heat capacity (J/g.k)**		**Density (g/cm^3)**
			Solid	**Liquid**	**Solid**	**Liquid**	
$NaNO_2$	270	200	0.96	0.54	1.8	1.6	2.17
$NaNO_3$	306	175	0.59	0.57	1.78	1.8	1.9
KNO_3	337	100	-	0.4	1.43	1.46	1.85
60% $NaNO_3$ -40% KNO_3	222	100	-	0.5	1.42	1.53	1.95

The PCM material selected for this application is a mixture of $(60\%NaNO_3 - KNO_3)$.

Theoretical Models Used to Calculate Thermo Physical Properties of Nanofliud

Nanofluid are colloidal suspensions of Nanosized solid particles in a liquid. Recently conducted experiments have indicated that Nanofluid tend to have substantially higher thermal conductivity than the base fluids (Bianco, *et al.*,2015).

Theoretical models used to calculate the property are given below on the table

Table 2: Theoretical model for specific heat,density and thermal conductivity of nanofluid[20]

No	**Property nanofliud**	**Model**
1	Specific heat (KJ/kg.k))	$C_{nf} = (1-\emptyset)\varrho_f C_f+\emptyset\varrho_p C_p/(\varrho_{nf})$
2	Density (kg/m3)	$\varrho_{nf} = (1-\emptyset)\varrho_f+\emptyset\varrho_p$
3	Thermal Conductivity	$Knf = Kbf [(Kp+2Kbf-2\emptyset(Kbf-Kp))/(Kp+2Kbf+\emptyset(kbf-Kp))]$

Table 3: Theoretical model for Prandtl number, dynamic viscosity and thermal diffusivity [20]

No	Property nanofliud	Model
1	Prandtl number	$Pr = v_{nf}/\alpha_{nf}$
2	Dynamic viscosity	$\mu nf = \mu_{bf}/((1-\emptyset)^{2.5})$
3	Thermal diffusivity	$\alpha nf = k_{nf}/((\rho cp)_{bf})$

Table 4: Properties of Copper

Density (kg/m3)	Thermal Conductivity (w/m.k)	Specific heat (J/kg.k)	Thermal expansion(1/k)
8907.665	392.504	398.15	0.000051

The thermo physical properties of nanofliud is mainly depends on the properties of nanoparticles. Copper nanoparticle with thermal conductivity of 400 $Wm-1k-1$ was used for this research.

The base fluid used was shell Thermia oil and its thermophysical property was given below

By using above theoretical model the property of nanofluid was calculated.

Table 5: Properties of Shell Thermia oil

T(^{0}C)	Density (ϱ,kg/m3)	Thermal conductivity (K,w/m.k)	Kinematic viscosity (v,m2/s) 10^{-6}	Prandtl number pr	Specific heat (Cp,J/kg.k)	Thermal expansion 1/k	Dynamic viscosity Kg/m.s 10^{-3}
134.5	788.4	0.126	3.49	43.36	2298	0.0008	2.75

Table 6: Thermophysical properties of nanofluid

T(^{0}C)	Density (ϱ,kg/m3)	Thermal conductivity (K,w/m.k)	Prandtl number pr	Specific heat (Cp,J/kg.k)	Thermal expansion 1/k	Dynamic viscosity Kg/m.s 10^{-3}
134.5	950.78	0.14w	38.7	1874	0.00066	2.89

System Description

Heat energy collected from the solar radiation is transferred to the PCM material storage, and it charges PCM. During the cooking process, energy stored in the PCM is transferred to the baking pan by circulating fluid in the system with the help of a pump. The main objective of this research is to enhance the heat transfer process during the charging process by adding fins in different arrangements to the PCM material. The energy storage tank is filled with PCM. A copper tube is used to circulate the heat-transfer fluid through the system.

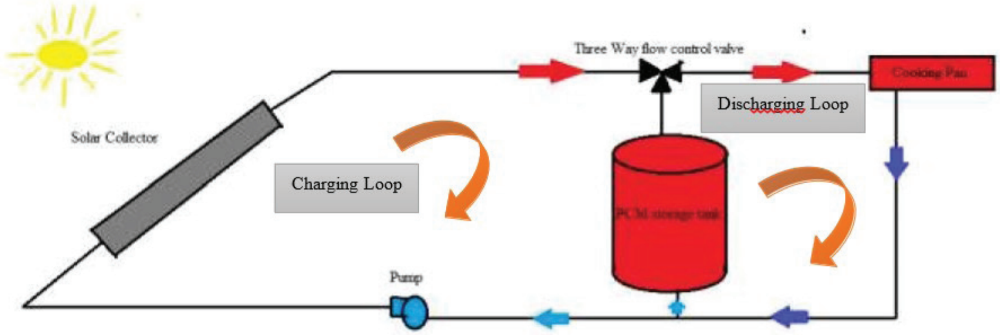

Figure 2: Concept Model for the system

METHODOLOGY

The study aims to investigate and compare the heat transfer enhancement characteristics in two different configurations of phase change thermal energy storage systems (with and without fins). Computational Fluid Dynamics (CFD) is the chosen methodology for the analysis. This involves using numerical simulations to model and analyze fluid flow, heat transfer, and other related phenomena within the given thermal energy storage systems. ANSYS workbench (fluent) is used for the simulation.

Sizing of Thermal Storage

The amount of heat stored on the PCM equal to the amount of energy required for baking injera (Yohannis,2022)

Table 7: Storage Tank Specification

Mass of PCM	Volume of Tank considering expansion	Height of storage tank	Diameter of storage tank
20kg	0.01225$m3$	0.4m	0.2m

Qu = 17,417.16KJ (1)

So the storage system will be designed to this amount of energy to meet the energy demand of the baking pan.

Mathematical Modelling and CFD Analysis

Mathematical Modelling

To calculate the phase change process numerically, the enthalpy–porosity approach was employed where, in each cell, the porosity and the liquid fraction were considered equal. The Newtonian free convection flow of melted PCM was generated because of the buoyancy forces, which were transient and placed in the laminar flow regime because of the range of fluid velocity in the domain. The Boussinesq approximation was also employed in the momentum equation because of the small temperature gradient. Thus, the governing equations were derived based on these assumptions and are as follows neglecting viscous dissipation (Sun,*et al.*,2021).

$$\partial \varrho/\partial t + \nabla.\varrho\overline{V} = 0 \quad (2)$$

$$\varrho\, \partial V/\partial t + \varrho(\vec{V}.\nabla)\vec{V} = \nabla\varrho + \mu(\nabla^2) - Am(1-\lambda)^2/(\lambda^3 + 0.001)\vec{V} - \varrho ref\ \beta(T - Tref)g \quad (3)$$

$$\varrho Cp\partial T/\partial t + \nabla(\varrho Cp\vec{V}T) = -[\partial\varrho\lambda Lf/\partial t + \nabla(\partial\varrho\lambda Lf)] + \nabla(K\nabla T) \quad (4)$$

Where $\vec{V}$= Velocity vector, T= Temperature,= Liquid volume fraction, t= Time

Tr, are the reference temperature and density

The third term on the right-hand side of equation (2) represents the momentum sink for the phase change in the mushy zone [16].

L_f=*Latent heat of fusion*, ρ = *Density*, C_p=*Specific heat capacity*,

K = *Thermal conductivety*, μ = *Dynamic viscosity*,

A_m= *Mushy*, β = *Volume expansion coefficient*

Liquid fraction is expressed as;

$\lambda = \Delta H/L_f$, 0 if $T \leq T_S$ (5)

$T - T_S$ If $< T < T_L$

$L - T_S$

1 if $T \geq T_L$

Where the subscripts S and L denote the solidus and liquidus states of PCM, and DH is the enthalpy variation during the phase change [16].The solidification or discharge rate Q is introduced as

$$\dot{Q} = \frac{Q}{t_m} = \frac{m\left(\int_S C_p dT + L_f + \int_L C_p dT\right)}{t_m}, \quad (6)$$

Where t_m = Melting time and m = mass of PCM

$H = \Delta H + h$ (7)

$h = \int_{Tref}^{T} CpdT + href$ (8)

CFD Analysis

The simulation for PCM was performed by ANSYS 16.0 (fluent). Models used were Solidification and melting, energy and laminar flow. Steps used for simulation

Modelling of PCM with and without Fins

CFD analysis was done for PCM without fin and with longitudinal fin arrangement .So, CFD analysis only concentrates on charging process of PCM and compere the results.

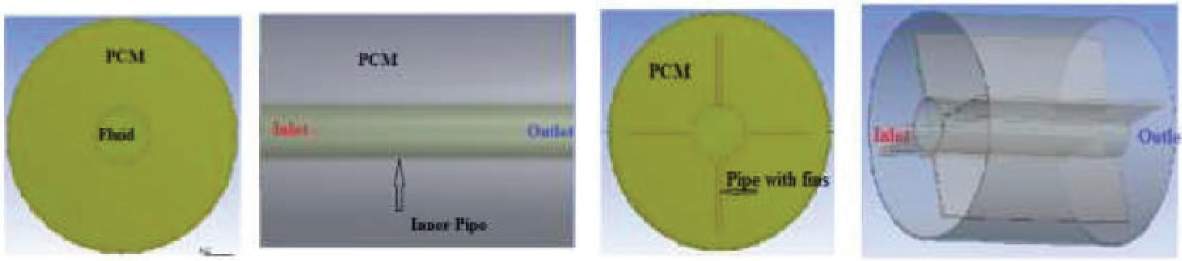

Figure 3: Schematic diagram a) PCM without fin b) PCM with longitudinal fin

Mesh Independency Test

A mesh independency test is a crucial part of any simulation-based analysis, especially in computational fluid dynamics (CFD) and finite element analysis (FEA). It assesses whether the results of the simulation are significantly affected by the chosen mesh resolution. In simpler terms, it checks if the results are consistent and converge towards a specific value as the mesh gets finer. Based on Fig.4 the average temperature of PCM on two storage tank is nearly constant for element division of 50.With the respect to the mesh number, the result do not changes much.

Therefore, number of division 50 is used for simulation.

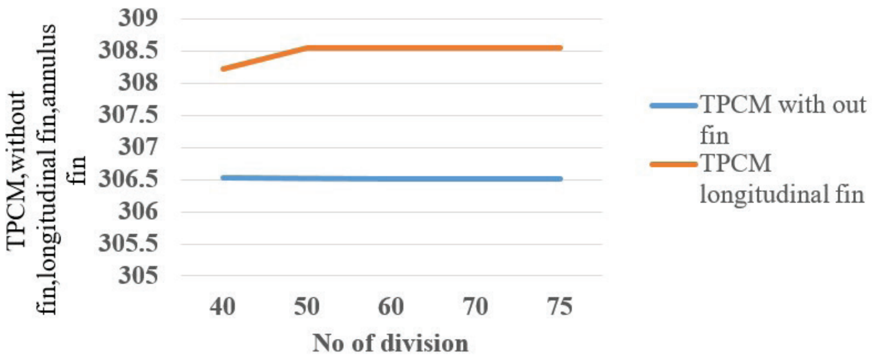

Figure 4: Mesh Independency Test

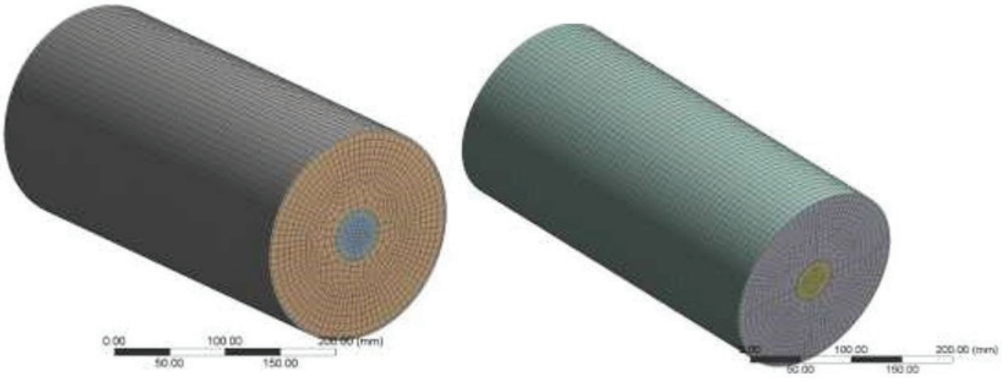

Figure 5: Mesh after grid independency test for a) PCM without fin b) PCM with longitudinal fin

Boundary Conditions Used for Simulation

Boundary conditions are the set of conditions specified for the behavior of the solution to a set of differential equations at the boundary of its domain. Boundary conditions are important in determining the mathematical solutions to many physical problems. Governing equation used were energy, momentum and continuity equations.

Table 8: Boundary Conditions

Zones	Conditions
Inlet	Mass flow rate (0.0123kg/s) and inlet fluid temperature (255^{0}C)
Outlet	Outflow
Outer walls	Adiabatic
PCM	Interior

Boundary Conditions Used

o No slip conditions, (At fluid wall interface, there must be no slip) o Inlet temperature of the fluid (260°C)

o Inlet mass flow rate

o Outlet was set to outflow (for unknown flow condition) condition

o Interface between the pipe and PCM face was coupled

o Outer wall of the container is insulated so zero heat flux.

For the PCM heat transfer was by conduction at its solid state and convection at its liquid phase.

Assumptions used

- Melting process is transient
- Two dimensional analysis
- Thermo physical properties of the HTF and the PCM are constant
- Initial temperature of the system is uniform and the PCM is in the solid phase for melting.
- Inlet temperature and mass flow rate of HTF is constant

Table 9: Properties of selected PCM material

PCM	Melting temperature (C)	Melting enthalpy (J/g)	Thermal conductivity (w/m.k)		Specific heat capacity (J/g.k)		Density (g/cm^3)
			Solid	Liquid	Solid	Liquid	
60%$NaNO_3$ -40%KNO_3	222	100	0.5	0.5	1.42	1.53	1.95

RESULTS AND DISCUSSION

This section presents the key findings of our CFD analysis investigating the impact of fins on heat transfer enhancement in a phase change thermal energy storage (PC-TES) system for solar energy storage applications. The numerical simulation in PCM.The simulations were conducted using ANSYS (Fluent) software, with careful consideration of melting temperature flow time and mass fraction of PCM.

CFD analysis revealed significant differences in the thermal performance of the PC-TES system with and without fins. Below the temperature and mass faction contour for the pcm with and without fins is given.

From the above Figure (7) it was observed that the introduction of fins resulted in a more uniform temperature distribution within the PCM, indicating reduced thermal resistance and enhanced heat transfer. The presence of fins led to a marked increase in heat

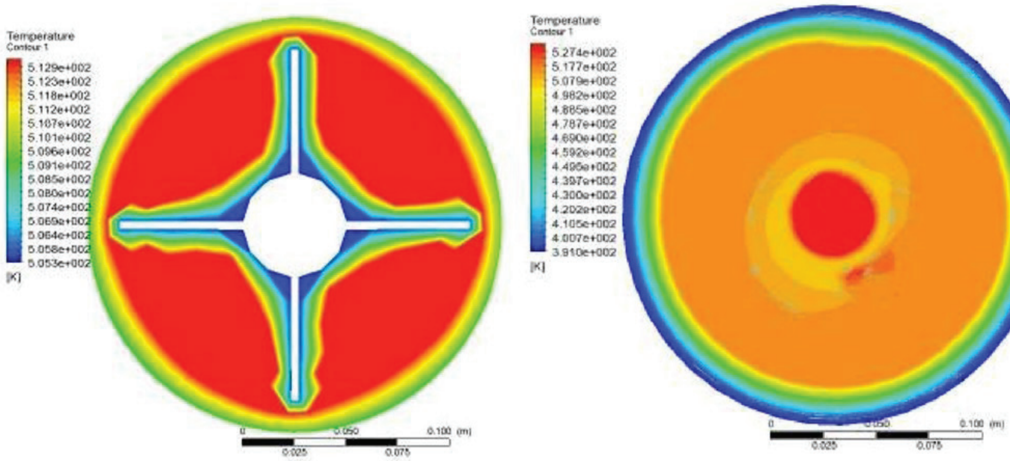

Figure 6: Temperature contour a) PCM with longitudinal fins b) PCM without fins

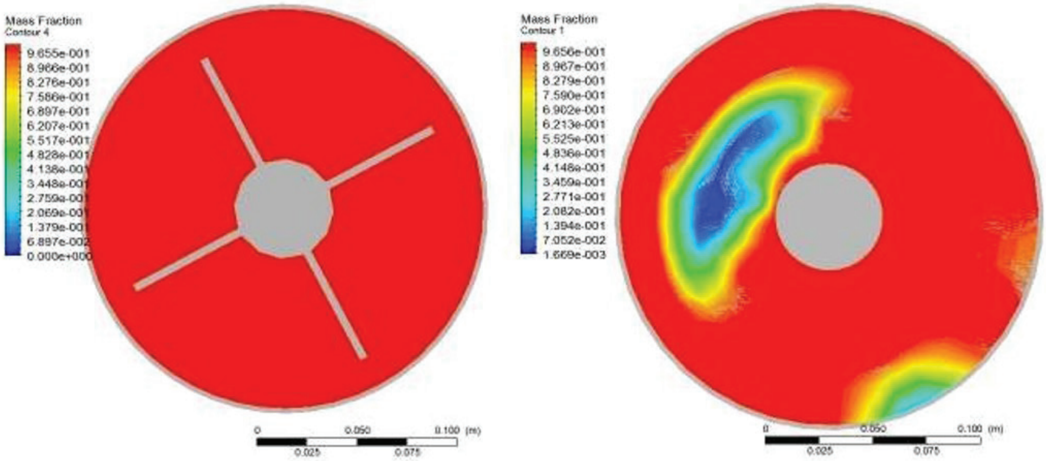

Figure 7: Mass fraction contour a) PCM with longitudinal fins b) PCM without fins

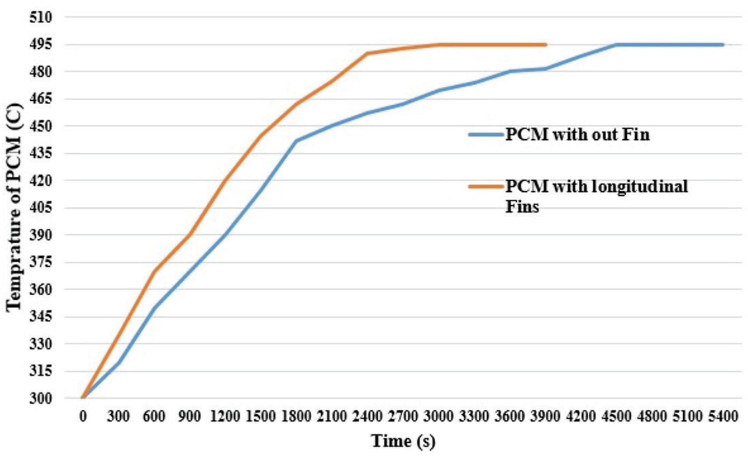

Figure 8: Temperature versus time graph

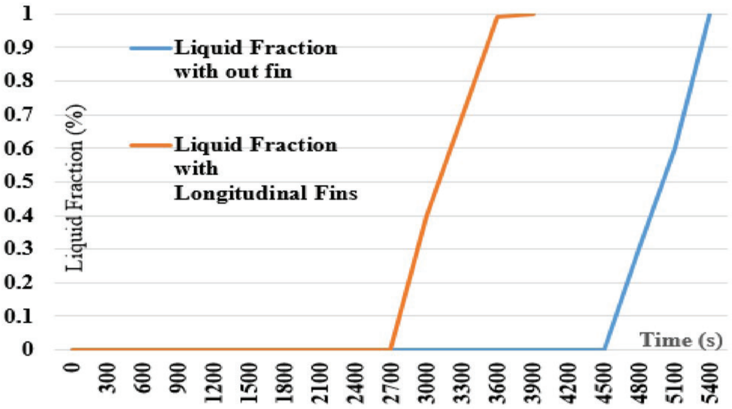

Figure 9: Mass fraction versus time graph

transfer rates between the heat transfer fluid and the PCM. This is evident in significantly shorter melting times observed in the finned case compared to the no-fin case. From the figure (8&9) given below it was observed that Melting of PCM with longitudinal fins is started at 3000s and that of PCM without fin started at 4500s.So presence of fin enhanced the performance of melting process.

CONCLUSION

In this study, we have conducted a comprehensive comparative CFD analysis of phase change thermal energy storage systems with and without fins. The simulations have provided valuable insights into the system's thermal performance under solar energy storage conditions. The use of longitudinal fins significantly enhanced the heat transfer rate between the storage material and the heat transfer fluid (HTF) due to increased surface area and reduced thermal resistance within the storage unit, leading to faster charging times. The use of fins created uniform temperature distribution within the storage material, minimizing thermal stresses and enhancing system stability. From the simulation it was observed that the use of fins reduced melting time by 33.33%.This is primarily due to the increased heat transfer area provided by the fins, leading to faster heat absorption by the PCM. Fins act as thermal pathways, efficiently conducting heat from the HTF to the PCM core. This enhanced heat transfer translates to faster melting of the PCM, reducing the overall charging time of the storage unit. The comparative CFD analysis provides valuable insights into the role of fins in enhancing heat transfer for phase change thermal energy storage in solar applications. Further research should focus on developing advanced fin design, experimental validation and cost-effectiveness analysis

Abbreviations

CFD Computational fluid dynamics
HTF Heat transfer fluid
LHTES Latent heat transfer energy storage
PC-TES Phase change thermal energy storage
PCM Phase change material
PCMHX Phase change material heat exchanger

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