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Enhancing Thermal Storage Performance Using Finned Tubes in PCM Units

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تحسين أداء التخزين الحراري باستخدام الأنابيب ذات الزعانف في وحدات المواد متغيرة الطور

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Abstract:
This research presents a comprehensive numerical investigation into the enhancement of latent heat thermal energy storage (LHTES) performance through the integration of finned tubes within phase change material (PCM) units. Given the inherent challenges in theoretically analyzing the non-linear moving solid-liquid interface during phase transitions, a robust finite volume model was developed to simulate the solidification process of PCM, specifically paraffin, around the outer surface of circular cylindrical finned tubes. The simulation utilizes an enthalpic formulation and a fully implicit scheme to accurately predict the fraction of solidified PCM and the transient evolution of the liquid-solid interface over time. Validation of the numerical model against established experimental and numerical data demonstrated excellent agreement, confirming the reliability of the proposed computational approach. A detailed parametric study was conducted to evaluate the influence of various geometric and operational factors on the energy charging rates and total discharge times. The results indicate that the thermal performance of the storage system is significantly improved by increasing the fin diameter, fin thickness, and the total number of fins, as these modifications facilitate superior heat conduction into the PCM. Furthermore, the study highlights that a higher temperature difference between the tube wall and the PCM, as well as the implementation of more compact tube arrays, leads to shorter discharge times and a greater amount of energy being recovered. The findings provide critical insights and practical design guidelines for optimizing PCM-based thermal energy storage systems, emphasizing the effectiveness of finned configurations in overcoming the low thermal conductivity of common phase change materials.

Keywords: Solidification; PCM Units; Finned Tube; Energy Storage; Finite Volume Method; Latent Heat.

الملخص
يقدم هذا البحث دراسة عددية شاملة حول تحسين أداء تخزين الطاقة الحرارية بأسلوب الحرارة الكامنة (LHTES)من خلال دمج الأنابيب ذات الزعانف داخل وحدات المواد متغيرة الطور .(PCM) ونظرًا للتحديات الكامنة في التحليل النظري للواجهة المتحركة غير الخطية بين الصلب والسائل أثناء تحول الطور،

تم تطوير نموذج حجم محدود قوي لمحاكاة عملية تصلب المادة (البارافين) حول السطح الخارجي للأنابيب ذات الزعانف الأسطوانية .تستخدم المحاكاة صيغة المحتوى الحراري (enthalpic formulation) ومخططًا ضمنيًا بالكامل للتنبؤ بدقة بكسر المادة المتصلبة والتطور العابر للواجهة بين السائل والصلب بمرور الوقت .أظهر التحقق من صحة النموذج العددي مقابل البيانات التجريبية والعددية المرجعية توافقًا ممتازًا، مما يؤكد موثوقية النهج الحسابي المقترح .تم إجراء دراسة بارامترية مفصلة لتقييم تأثير العوامل الهندسية والتشغيلية المختلفة على معدلات شحن الطاقة وأوقات التفريغ الكلية .وتشير النتائج إلى أن الأداء الحراري لنظام التخزين يتحسن بشكل كبير عن طريق زيادة قطر الزعانف، وسمكها، والعدد الإجمالي للزعانف، حيث تسهل هذه التعديلات انتقال الحرارة بشكل فائق داخل المادة .علاوة على ذلك، تسلط الدراسة الضوء على أن فرق درجة الحرارة المرتفع بين جدار الأنبوب والمادة، وكذلك استخدام مصفوفات أنابيب أكثر تضاماً، يؤدي إلى تقليل أوقات التفريغ واستعادة كمية أكبر من الطاقة .توفر هذه النتائج رؤى هامة وإرشادات تصميمية عملية لتحسين أنظمة تخزين الطاقة الحرارية القائمة على المواد متغيرة الطور، مع التأكيد على فعالية تكوينات الأنابيب ذات الزعانف في التغلب على انخفاض الموصلية الحرارية للمواد الشائعة.

الكلمات المفتاحية: التصلب؛ وحدات *PCM*؛ أنابيب ذات زعانف؛ تخزين الطاقة؛ طريقة الحجم المحدود؛ الحرارة الكامنة.

NOMENCLATURES.

Ks	thermal conductivity for solid phase
L	Latent heat of phase change material
R	Radial coordinate
Ra	fin radius
Rt	Domain radius
S	The interface location
T	Temperature
Tm	melting temperature of PCM
Z	Axial coordinate
Za	Fin thickness
Zt	The length of calculation domain
$\emptyset$	Dimension less temperature
$\emptyset_n$	Dimension less temperature for the north face control volume
$\emptyset_s$	Dimension less temperature the south face control volume
$\emptyset_w$	Dimension less temperature the west face control volume
$\emptyset_e$	Dimension less temperature the east face control volume
ξ	Dimension less temperature range for PCM
τ	Dimension less time
ρ	Density
ρ_s	solid phase density
ρ_l	liquid phase density
ΔT	mushy zone temperature range
η	unit step function
δ	Darcy function

Introduction

Melting and freezing process are encountered in a wide range of technologies, encompassing such diverse applications as casting of metals and glass crystal growth ground freezing, freeze drying preservation of food stuffs preservation of biological cells and thermal energy storage. prediction of the heat transfer process of melting and freezing are extremely important in the design of relevant equipment and for the quality control for the products involved.

The latent heat thermal energy storage (LHTES) systems have a large thermal heat capacity, high energy storage density, negligible temperature change throughout the charge /discharge cycles, wide phase transition temperature range, and low cost[1], [2]. These advantages enable them to have a wide range of applications in solar energy utilization[3], [4], energy-efficient buildings[5] and domestic hot water[6], load management[7], refrigeration and air conditioning [8], and industrial waste heat recovery [9],[10]. As a result, incorporating PCM-based TES in a variety of thermal applications is a hot topic of research. Narasimhan et al.[11] conducted a thermal examination of a storage unit with several PCM with high conductivity particles dispersed in this research ,the solution of two dimensional transient outward solidification of phase change material around the outer surface of a circular cylindrical finned tube is studied , often in a practical applications the heat conduction models describing the phenomena of interest are complex. as result the analytical methods presented so far in this specific area cannot be used to determine the temperature field and solid - liquid interface profile during the phase change process. in the present work the control volume based on finite deference methodology is used to investigation of a possible configuration of tubes with cylindrical fins for thermal energy storage systems, considering solidification controlled by heat conduction. using enthalpic formulation and a numerical solution is obtained by using fully implicit scheme. this method is recommended by Patankar[12],and the Gauss-seidel method is used to solve the discretized heat conduction equations . an iterative procedure due to the non-linearity of equation had been considered . in this investigation it was concluded that for shorter discharge times higher amount of energy can be achieved by increasing the radius of fins , the number of fins , the temperature difference between phase change material and tube wall , as well as by utilizing more compact tube array in the storage system .

Mathematical Formulation:

The physical system considered is an array of staggered finned tubes embedded in a phase change material fig.(1) . a fluid at temperature below the fusion temperature of PCM is pumped through the tubes and exchanges heat with the PCM long the flow length. During the energy storage period hot fluid flow through the tubes and the heat conveyed by the hot fluid is stored in PCM while during the energy extraction period cold fluid flow through the tube and extracts the thermal energy stored in the PCM and deliver it to the user due to symmetry only the region shown in fig.(2) can be considered.

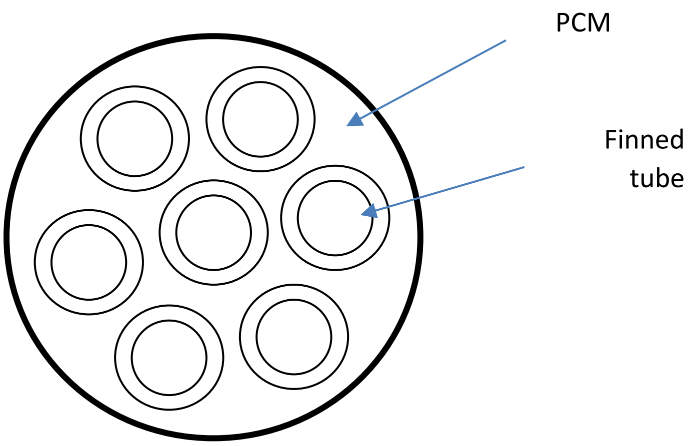

Fig. 1: Finned tubes embedded in a phase change material

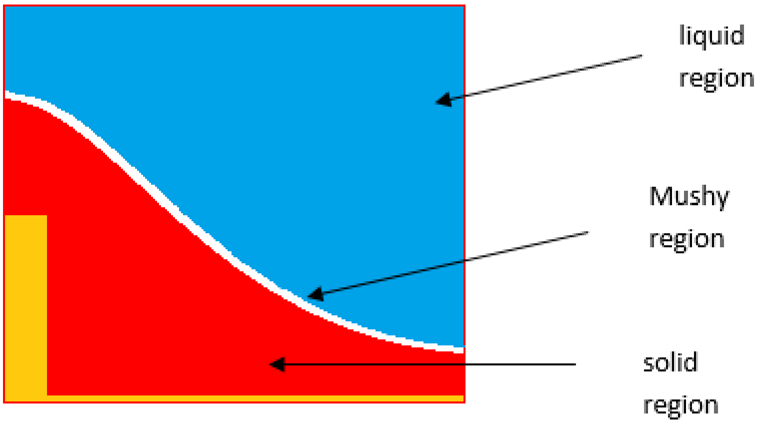

Fig. 2: The domain of calculation.

Mathematical model of solidification of PCM around finned tube is constructed taking into account the following simplifying assumptions.

- The tube wall temperature assumed constant and equal to fluid temperature T_w.
- Thermal losses through the outer wall of the PCM are negligible.
- heat transfer in the PCM is controlled by convection.

based on the above assumption the governing heat conduction equation in cylindrical coordinate and associated boundary condition can be written as

$$\rho c(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \quad (1)$$

$$T(r_w, z, t) = T_w \quad (2)$$

Where :

$$\left|\frac{\partial T}{\partial r}\right|_{r=r_t} = 0 \quad (3)$$

$$\left|\frac{\partial T}{\partial z}\right|_{z=z_t} = 0 \quad (4)$$

$$\left|\frac{\partial T}{\partial z}\right|_{z=0} = 0 \quad (5)$$

The enthalpy method approach is adopted to complete the mathematical modeling of the solidification process .Following this approach the equation for enthalpy per unit volume considering phase change can be expressed as

$$H(T) = \int_T C(T)dT + \lambda\eta(T - T_m) \quad (6)$$

The $\lambda = \rho L$

Where λ is the latent heat per unit volume of phase change material and $\eta(T - T_m)$ is the unit step function. From this definition of the enthalpy, an equation that describes the calorific heat capacity per unit volume as was suggested by Bonacina and Alii [13].

$$\check{C}(T) = \frac{dH(T)}{dt} = C(T) + \lambda\delta(T - T_m) \quad (7)$$

Where:

$$\check{C}(T) = \begin{Bmatrix} C(T) & ,T < T_m - \Delta T \\ C_l(T) & ,T > T_m + \Delta T \end{Bmatrix} \quad (8)$$

Integrating equation (8) over the solid liquid and mushy regions, yields

$$\int_{T_m-\Delta T}^{T_m+\Delta T} \check{C}(T)dT = \lambda + \int_{T_m-\Delta T}^{T_m} C_s(T).dT + \int_{T_m}^{T_m+\Delta T} C_l(T).dT \quad (9)$$

In a similar manner to the formulation of the specific heat, the thermal conductivity at the solid liquid and mushy regions can be expressed as:

$$\breve{K}(T) = \begin{Bmatrix} k_s(T) & ,T < T_m - \Delta T \\ k_l(T) & ,T > T_m + \Delta T \end{Bmatrix} \quad (10)$$

$$C(T) = \begin{Bmatrix} C_s(T) & ,T < T_m - \Delta T \\ C_l(T) & ,T \geq T_m + \Delta T \\ \frac{\lambda}{2\Delta T} + \frac{C_s + C_l}{2}, & T_m - \Delta T < T < T_m - \Delta T \end{Bmatrix} \quad (11)$$

$$k(T) = \begin{Bmatrix} k_s(T) & ,T < T_m - \Delta T \\ k_l(T) & ,T \geq T_m + \Delta T \\ k_s + \frac{k_l - k_s}{2\Delta T}[T - (T_m - \Delta T)] & ,T_m - \Delta T < T < T_m - \Delta T \end{Bmatrix} \quad (12)$$

The governing equation and boundary conditions are converted to dimensionless form by using the dimensionless variables □□**, R ,** □□**, Z** and□□**ξ** □ in addition the non-dimension form of the boundary condition can be expressed as:

$$\emptyset(R_w, Z, \tau) = \emptyset_w \ , \quad \left(\frac{\partial \emptyset}{\partial R}\right)_{R=R_t} = 0 \ , \quad \left(\frac{\partial \emptyset}{\partial Z}\right)_{Z=Z_t} = 0 \ , \left(\frac{\partial \emptyset}{\partial Z}\right)_{Z=0} = 0$$

Where:

$$C(\emptyset) = \begin{Bmatrix} 1 & , \ \emptyset > \xi \\ \frac{C_l}{C_s} & ,\emptyset \leq -\xi \\ \frac{\lambda}{2C_s\Delta T} + \frac{C_s + C_l}{2C_s}, & -\xi > \emptyset > \xi \end{Bmatrix} \quad (13)$$

$C(\emptyset) = \frac{C_a}{C_s}$ For the fin.

$$k(\emptyset) = \begin{Bmatrix} 1 & , \quad \emptyset > \xi \\ \frac{k_l}{k_s} & , \quad \emptyset \leq -\xi \\ 1 + \frac{k_l - k_s}{2k_s}\left(1 - \frac{\emptyset}{\xi}\right) & , \ -\xi > \emptyset > \xi \end{Bmatrix} \quad (14)$$

Numerical model:

To handle moving interface numerically in solving melting and solidification problem the methodology of control volume based finite deference method is used to construct the numerical model Patankar[12] the main step of this method is to divide the calculation domain into a number of non-overlapping control volume fig. (3) where each control volume surrounds the main grid point at which the variable are calculated. the discretization procedure is to integrate the governing equation over each control volume where piecewise linear profile scheme is adopted to account for the variation between the main grid points the result of diecretization process transforms the partial differential equation , and the associated boundary condition into a set of linear algebraic equations. in the present work the fully implicit scheme is used to discretize the governing equation , and the Gauss-sidle method is used to solve the resulting set of algebraic equations.

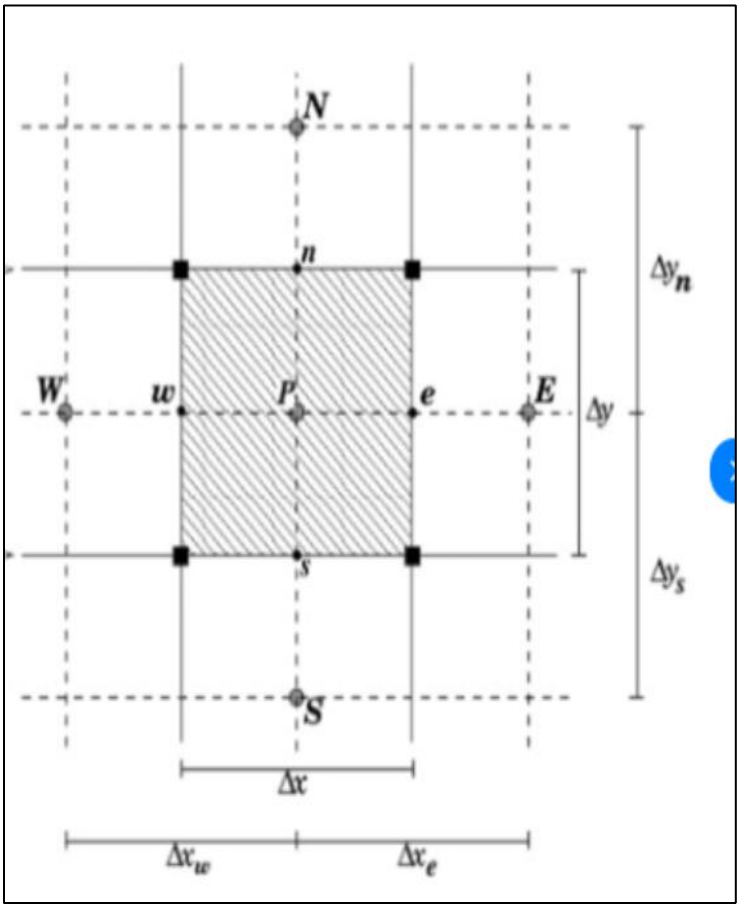

Fig. 3: The domain divided into a number of control volume.

Discretization Of the Boundary Condition:

Integrating of the governing equation over the control volume with respect to □**, Z** and **R** over intervals $(\boldsymbol{\tau} \rightarrow \boldsymbol{\tau} + \Delta\boldsymbol{\tau}), (\boldsymbol{w} \rightarrow \boldsymbol{e}), (\boldsymbol{s} \rightarrow \boldsymbol{n})$ Respectively Patankar [12].

$$\int_{\tau}\int_{Z}\int_{R} R\left(c(\emptyset)\frac{\partial\emptyset}{\partial\tau}\right).dR.dZ.d\tau = \int_{\tau}\int_{Z}\int_{R}\frac{\partial}{\partial R}\left(R\,K(\emptyset)\frac{\partial\emptyset}{\partial R}\right).dR.dZ.d\tau$$

$$+\int_{\tau}\int_{Z}\int_{R} R\frac{\partial}{\partial Z}\left(K(\emptyset)\frac{\partial\emptyset}{\partial Z}\right).dR.dZ.d\tau \qquad (15)$$

Yields to

$$a_p\,\emptyset_P^1 - f a_e\,\emptyset_E^1 - g a_s\,\emptyset_S^1 - f a_w\,\emptyset_W^1 - g a_n\,\emptyset_N^1 = (1-f)a_e\,\emptyset_E^0 - (1-g)a_s\,\emptyset_S^0 - (1-f)a_w\,\emptyset_W^0 - (1-g)a_n\,\emptyset_N^0 + \left[a_p^0 - (1-g)a_s - (1-g)a_n - (1-f)a_w - (1-f)a_e\right]\emptyset_p^0 \qquad (16)$$

Where:$\boldsymbol{a_p}, \boldsymbol{a_p^0}, \boldsymbol{a_e}, \boldsymbol{a_w}, \boldsymbol{a_s}, \boldsymbol{a_n}$ are the diffusion coefficient . The implementation of fully implicit scheme by utilization **of** $\boldsymbol{f} = \boldsymbol{g} = \mathbf{1}$ and the harmonic mean of thermal conductivity $\boldsymbol{k_e}$ has been used to represent the value of **k** pertaining to the control volume face. Similarly$\boldsymbol{k_s}$**,** $\boldsymbol{k_n}, \boldsymbol{k_w}$ refers to the interface **s, v, w,** respectively.

Results And Discussion

In order to investigate the effect of various parameters on energy charging rates in each freezing process, the process is simulated using the numerical model as mentioned earlier. The mesh dependency study has been done and the model is first validate against published work [14] by comparing in dimensionless form the liquid fraction vs. Time with both the experimental and numerical results of Richard H. HENZE [14] and there was good agreement with the result of the above mentioned reference . Numerical simulation of the solidification process of the energy storage unit were carried out to investigate the effect of various parameters on energy charging rates in each freezing processes . Initially the tube wall assumed to be at a uniform temperature of 5 C^0, at the start of the freezing process the PCM (paraffine)is surrounded by liquid phase at temperature T_{int} which is above the fusion temperature of the PCM after some time solidification tackes place and three distinct regions surround the pipe : a solid region , a mixed region (mushy region), and a liquid region the interface location at different solidification time is shown in figure (4)

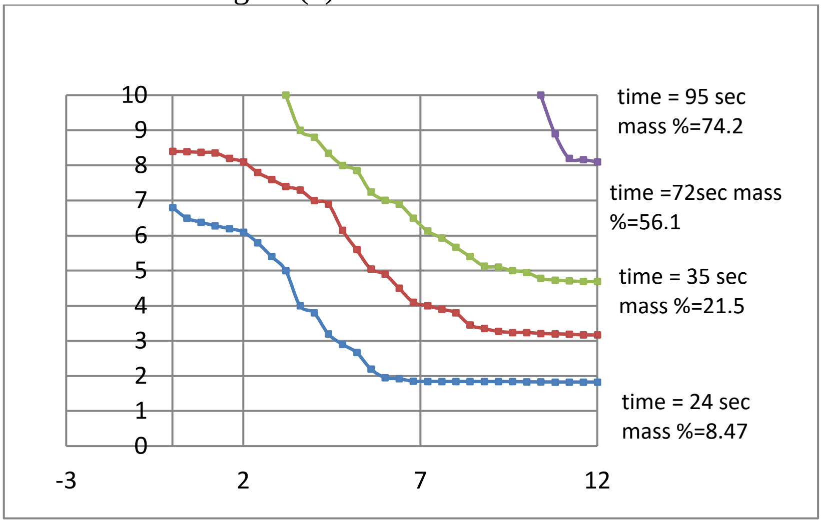

Fig. 4: Interface location at different solidification times

Parametric Study

1- Effect of Tube Wall Temperature

four cases were computed to investigate the effect of tube wall temperature on the performance of the solidification process , from figures (5) and (6) it is seen that the enhancement of cumulative energy charged decreases with an increase of tube wall temperature .However the numerical results show that the total solidification times for the tube wall temperature (T=5 C^0 ,10 C^0 ,15 C^0)are as lower as (66% ,60 %, 54 %)than that for 25 C^0 respectively.

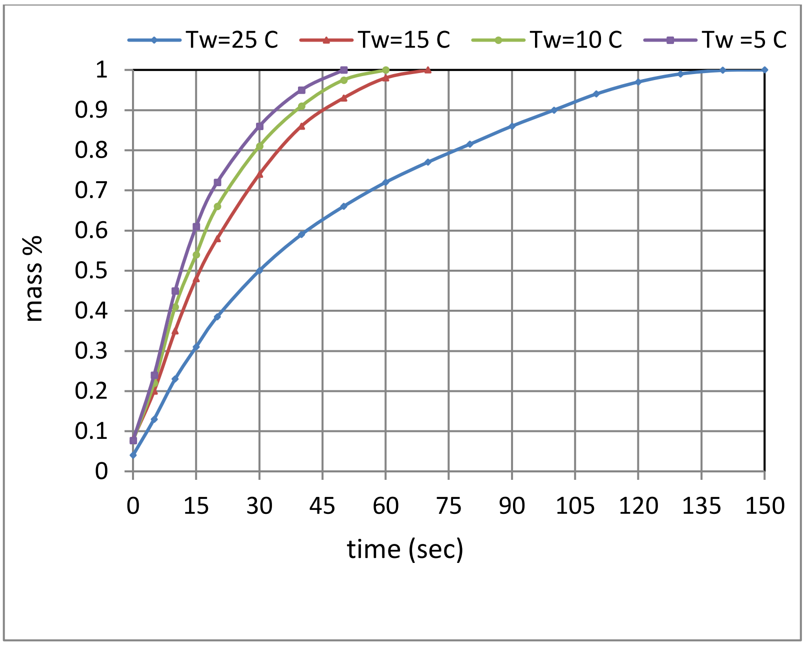

Fig. 5 Solidified mass ratio vs, time for different.

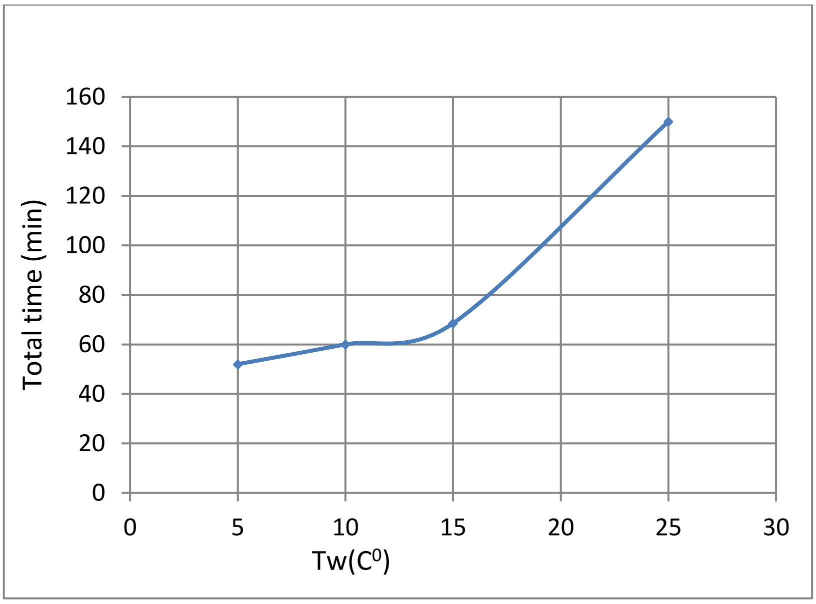

Fig. 6: Total Solidification time vs, Tube wall Temperature**.**

2- Effects of Number of Fins

Three cases were used to investigate the effect of number of fins on the solidification phenomena and energy charging/ discharging rates. Figures (7)and (8) show that the enhancement of the cumulative energy charged increase with an increase of the number of fins , However the numerical show that the total solidification time for number of fins (N= 4,6) are as lower as (7.8 % , 13.32 %) than that in case of two fins respectively.

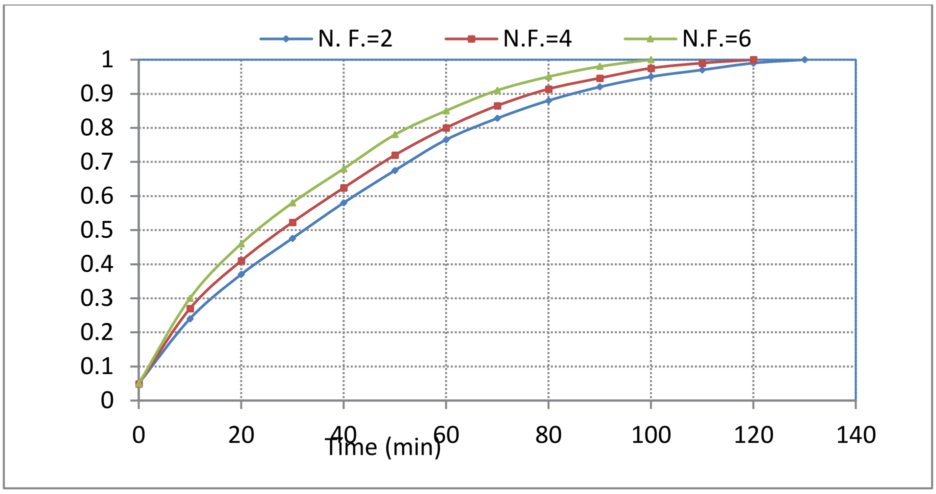

Fig. 7: Solidified Mass ratio vs, time for different number of fins.

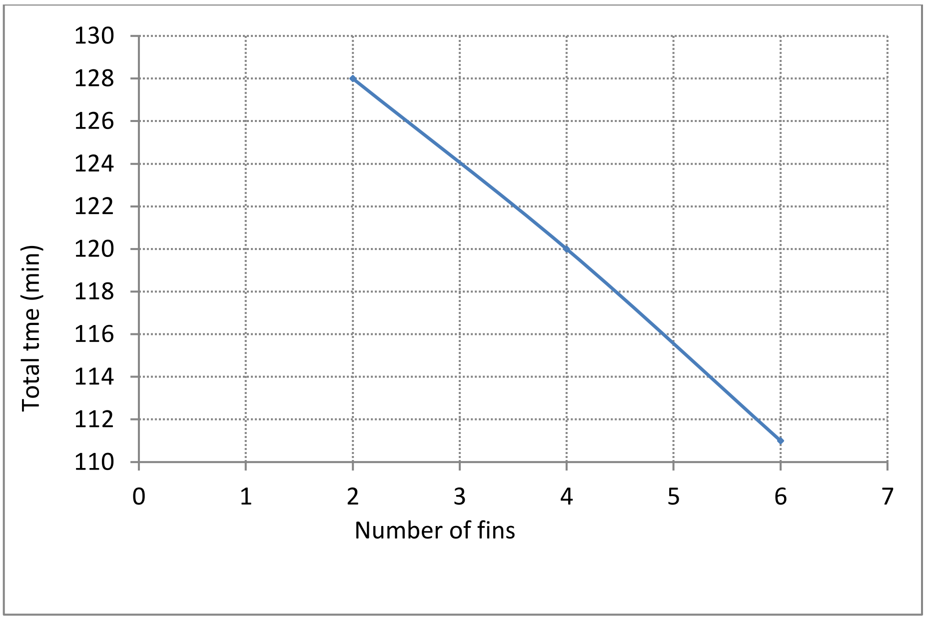

Fig. 8: Total Solidification time vs, number of fins.

3- Effect of Fin Thickness

Four cases of different fin thicknesses are used to investigate the effect of this parameter on the solidification phenomena and energy charging / discharging rates . Figures (9)and (10) give comparison of runs for different fin thicknesses . It is seen that the enhancement of cumulative energy charge increase with an increase of the fin thickness t = (0.01, 0.05,0.07)are as lower as (6% ,11.3%,16.9%)than that in case of t=0.005m respectively . However the effect of fin thickness in the simulated range seems not to affect much the solidification process specifically in the early solidification times . This conclusion on the effect of fin thickness is demonstrated in figure(10).

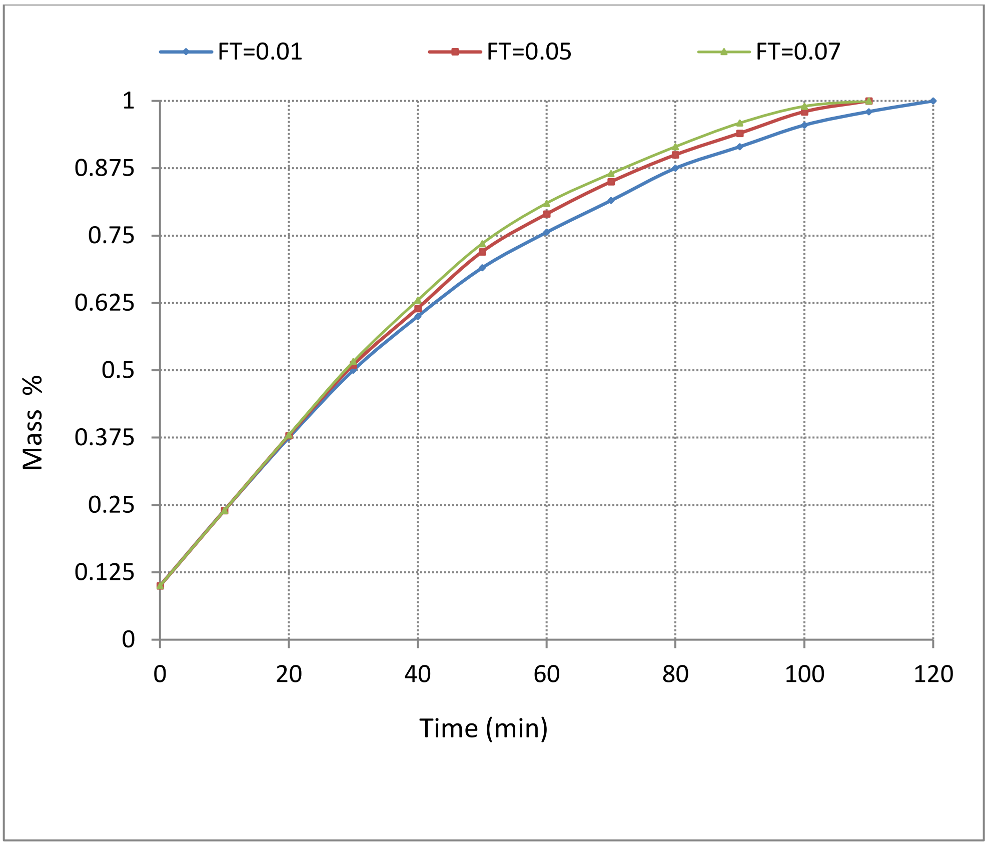

Fig.9: solidified mass ratio vs. time for different fins thickness

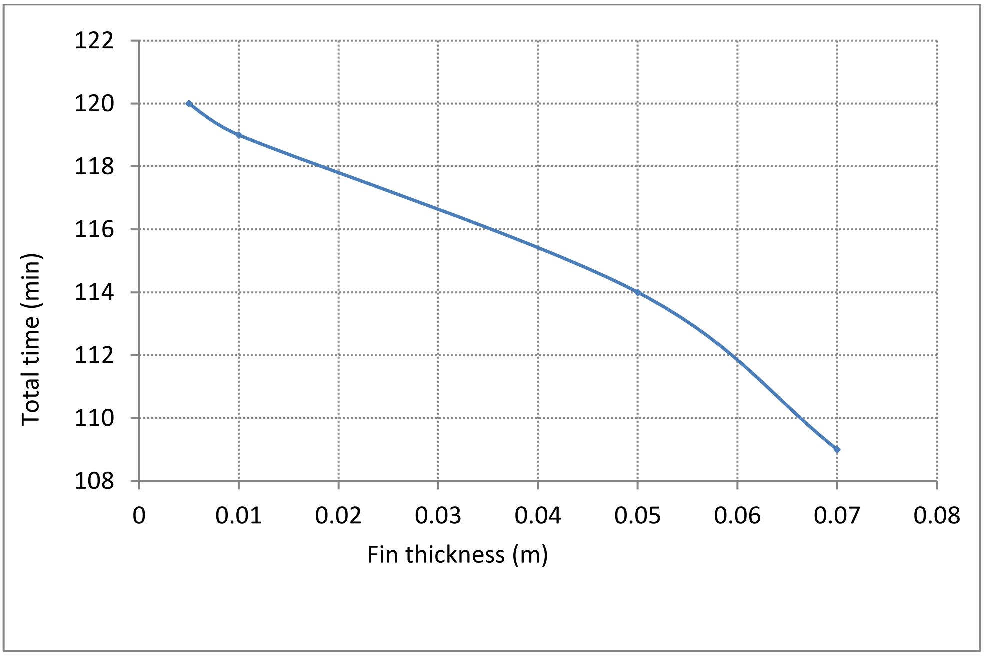

Fig. 10: Total solidification time vs. fins thickness

4- Effect of Domain Diameter

Four cases were computed to investigate the effect of the domain diameter on the solidification phenomena and energy charging /discharging rates from figures(11) and (12) it is seen that the enhancement of the cumulative energy charged decrease with an increase of the diameter of the domain , however the numerical results show that the total solidification time for domain diameters (D_t=0.04 ,0.06,0.1 m) are as much as (135% , 196% ,368%)than that in case of D_t=0.01 m respectively

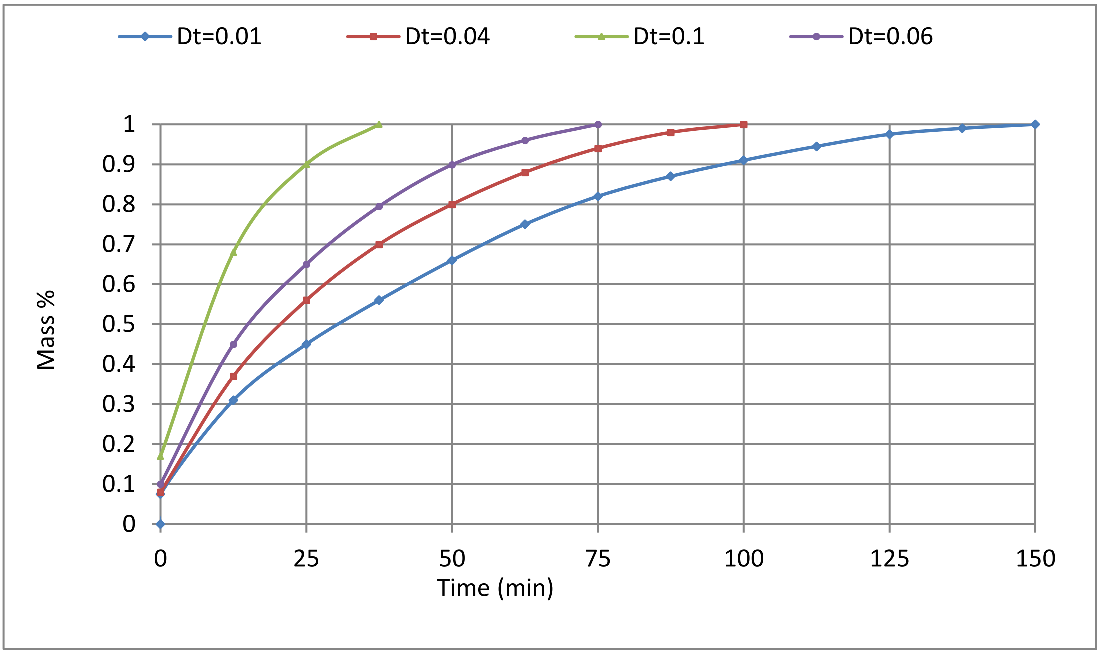

Fig. 11: solidification mass ratio vs. time for different domain diameter.

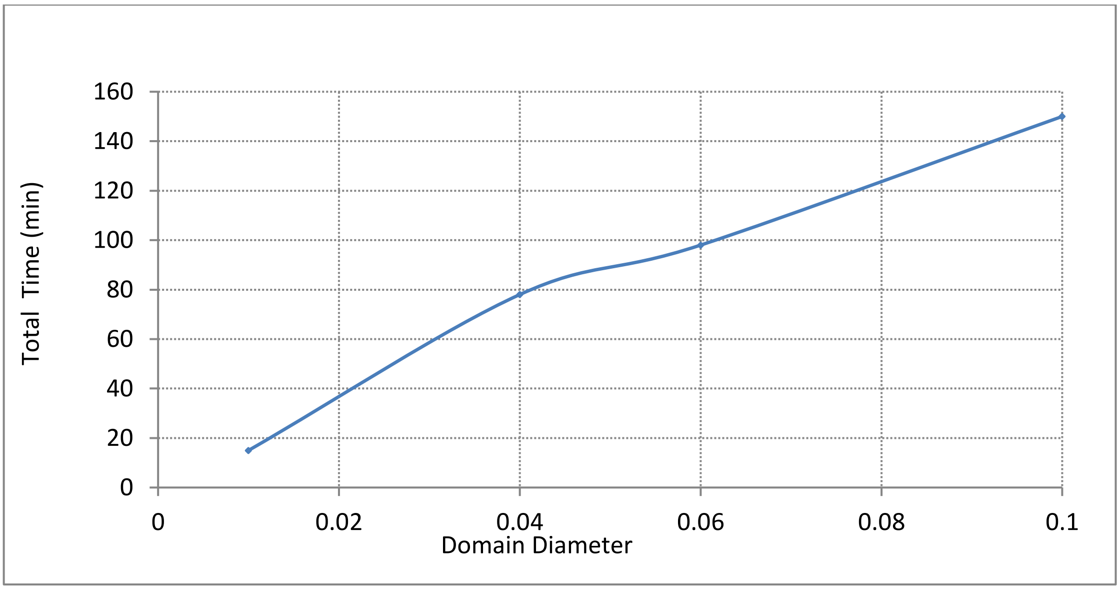

Fig. 12: Total solidification time vs. domain diameter

5- Effect Of Phase Change Temperature Range

Two cases were computed to investigate the phase change temperature range ΔT on the solidification phenomena and energy charging / discharging rates from figures (13)and (14) it is seen that the enhancement of the cumulative energy charge increase with an increase of ΔT mushy . However the numerical results show that the total solidification time for ΔT mushy =2C^0 are as lower as (13.5%) than that in the case of ΔT =1 C^0 .

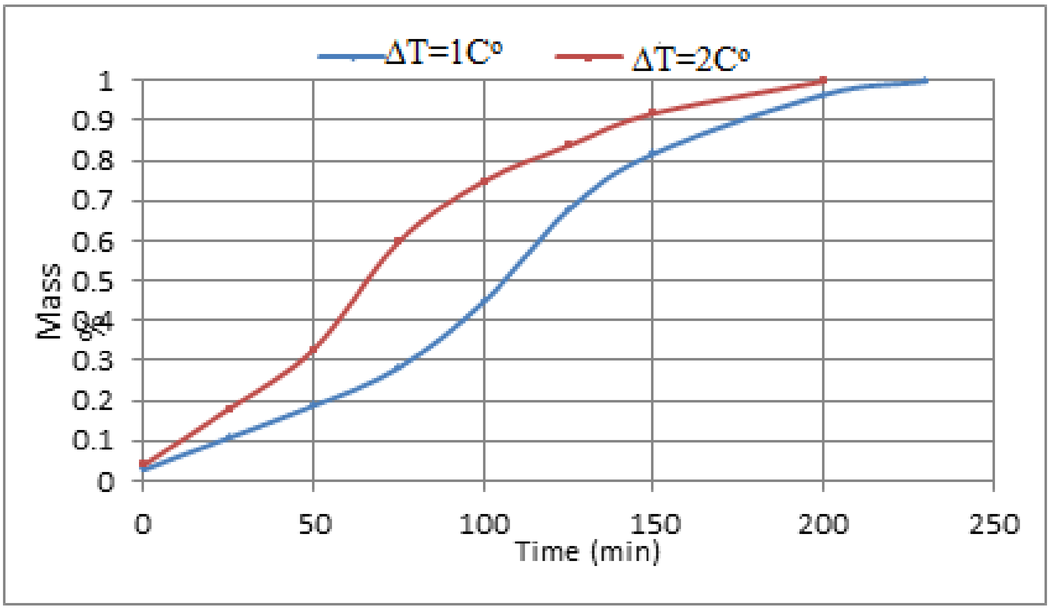

Fig. 13: solidified mass ratio vs time for different Dt mushy

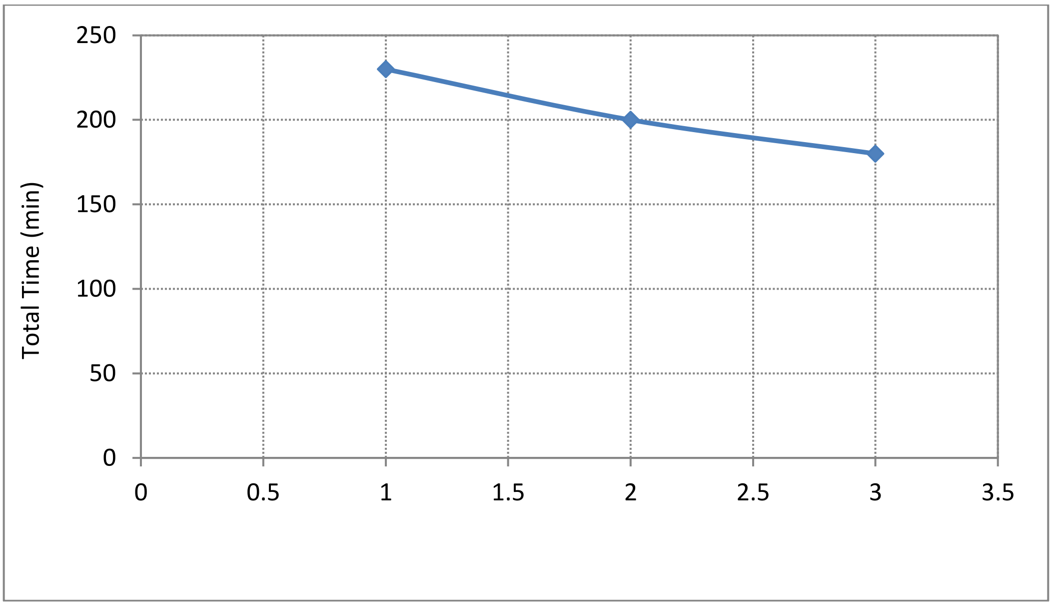

Fig. 14: total solidification time vs. different Dt mushy

Conclusion

A finite volume numerical model was developed to investigate the freezing behavior of phase change material (PCM) around a circular finned tube with cylindrical embedded fins. The model successfully captured the transient evolution of the solid–liquid interface and the variation of the melted PCM fraction over time, overcoming the challenges associated with the nonlinear moving boundary problem. Dimensionless results showed good agreement with available reference data, confirming the accuracy and reliability of the proposed approach. The parametric analysis revealed that the thermal discharge performance of the latent heat storage system can be significantly enhanced by increasing fin diameter and thickness, the number of fins, and the temperature difference between the tube wall and PCM. Additionally, employing a more compact tube arrangement was found to improve heat transfer and reduce discharge time. These findings demonstrate the effectiveness of finned tube configurations in enhancing latent heat energy storage performance and provide useful guidelines for the optimal design of PCM-based thermal energy storage systems.

References

[1] Abderrahmane, A., Hatami, M., Younis, O., & et al. (2022). Effect of double rotating cylinders on the MHD mixed convection and entropy generation of a 3D cubic enclosure filled by nano-PCM. European Physical Journal Special Topics .

[2] Al-Abidi, A. A., Bin Mat, S., Sopian, K., Sulaiman, M. Y., & Lim, C. H. (2012). Review of thermal energy storage for air conditioning systems. Renewable and Sustainable Energy Reviews, 16(8), 5802–5819 .

[3] Bonacina, C., Comini, G., Fasano, A., & Primicerio, M. (1973). Numerical solution of phase change problems. International Journal of Heat and Mass Transfer, 16(10), 1825–1832 .

[4] Henze, R. H., & Humphrey, J. A. C. (1981). Enhanced heat conduction in phase-change thermal energy storage devices. International Journal of Heat and Mass Transfer, 24(3), 450–474 .

[5] Khan, M. M. A., Saidur, R., & Al-Sulaiman, F. A. (2018). Evaluation of solar collector designs with integrated latent heat thermal energy storage: A review. Solar Energy, 166, 334–350 .

[6] Lakshmi Narasimhan, N., & Srinivasan, G. (2018). Analysis of a thermal storage unit containing multiple phase change materials dispersed with high conductivity particles. Journal of Mechanical Science and Technology, 32(1), 373–380 .

[7] Mourad, A., Aissa, A., Zabaat, M., & et al. (2022). Recent advances on the applications of phase change materials for solar collectors, practical limitations, and challenges: A critical review. Journal of Energy Storage, 49, 104186 .

[8] Patankar, S. V. (1980). Numerical heat transfer and fluid flow. McGraw-Hill .

[9] Qasem, N. A. A., Sahoo, S., & et al. (2022). Effect of a rotating cylinder on convective flow, heat and entropy production of a 3D wavy enclosure filled by a phase change material. Applied Thermal Engineering, 205, 118818 .

[10] Rathod, M. K., & Banerjee, J. (2013). Thermal stability of phase change materials used in latent heat energy storage systems: A review. Renewable and Sustainable Energy Reviews, 18, 246–258 .

[11] Reddy, K. S., Mudgal, V., & Mallick, T. K. (2018). Review of latent heat thermal energy storage for improved material stability and effective load management. Journal of Energy Storage, 15, 205–227 .

[12] Riahi, S., Jovet, Y., Saman, W. Y., Belusko, M., & Bruno, F. (2019). Sensible and latent heat energy storage systems for concentrated solar power plants, exergy efficiency comparison. Solar Energy, 180, 104–115.

 |

[13] Seddegh, S., Wang, X., Henderson, A. D., & Xing, Z. (2015). Solar domestic hot water systems using latent heat energy storage medium: A review. Renewable and Sustainable Energy Reviews, 49, 517–533 .
[14] Soares, N., Costa, J. J., Gaspar, A. R., & Santos, P. (2013). Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energy and Buildings, 59, 82–103.

