International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-9 Issue-1, May 2020

Combined Effects of Eccentricity and Internal Fins on the Shell and Tube Latent Heat Storage Systems

Ahmad K AL-Migdady, Ali M Jawarneh, Hussein N Dalgamoni, Mohammad Tarwaneh

Abstract: ***A numerical simulation study was performed on shell and tube configuration for latent heat storage applications where a Phase Change Material "PCM" - N-eicosane -was used to fill the shell side. The effects of smooth tube eccentricity from the shell center were investigated first, two values of eccentricity (ε=0.267, ε=0.533) were compared to the concentric case (ε=0). It was found out that increasing the eccentricity reduces the melting time by 5% and 10% for ε=0.267 and 0.533 respectively. Then the combined effects of eccentricity and attaching fins to the tube within the shell side were investigated for two fin types: straight rectangular fins and flipped triangular fins. The fin addition to the concentric tube reduced the melting time by about 36%, whereas combining the fins - of either type - to the tube of eccentricities of 0.267 and 0.533 reduced the melting by almost 41 % and 48% respectively, when compared to the smooth concentric tube case.***

Keywords: ***Phase Change material, shell and tube configuration, Eccentricity , Latent heat storage, fins.***

I. INTRODUCTION

The global energy demand- which mainly depends on fossil fuels- has been significantly increasing over the past few decades and it will keep growing due to the fast population growth and advanced technologies as well. The thermal energy produced either by solar energy or waste heat recovery systems is utilized in many applications to reduce dependence on fossil fuels and reduce the greenhouse gas emissions. However, the issue of thermal energy storage has emerged as a challenge associated with the thermal energy production and waste heat harvesting. The latent heat thermal energy storage [LHTES] using phase change material was widely used since the charge /discharge process is almost isothermal and it also provides a very high energy density during the melting and solidification processes compared to the traditional sensible heat energy storage. Hence, a much smaller volume of storage is required. [1, 2, 3, 4]

Manuscript received on April 02, 2020.
Revised Manuscript received on April 15, 2020.
Manuscript published on May 30, 2020.

* Correspondence Author

Ahmad K AL-Migdady*, Assistant Professor, Department of Mechanical Engineering, Hashemite University, Zarqa, Jordan,

Ali M Jawarneh, Associate Professor, Department of Mechanical Engineering, Hashemite University, Zarqa, Jordan.

Hussein N Dalgamoni, Assistant Professor, Department of Mechanical Engineering, Hashemite University, Zarqa, Jordan.

Mohammad Tarawneh, Associate Professor, Department of Mechanical Engineering, Hashemite University, Zarqa, Jordan.

The latent heat storage systems [LHS] have low thermal conductivity, typically between 0.2 W/(m·K) and 0.7 W/(m·K), and their performance is limited by such values. However, this challenge can be overcome by implementing innovative solutions to enhance the heat transfer characteristics [5]

The overall performance of latent heat thermal energy storage systems using PCMs can be improved by two main techniques: first, increasing the heat transfer surface area and this can be achieved by: addition of fins with various configurations: size, shapes, spacings [6,7, 8, 9], the insertion of metal matrix like heat pipes [10] and lessing rings [11,12] inserting metal foams into the LHTES unit [13], introducing multiple PCMs into the system [14, 15] and enlarging the fill volume ratio of the PCM [16]. The second technique is concerned with intensifying the thermo-physical properties of the storage system and this includes: dispersion of high conducting nano-particles and/or nano tubes [17,18,19] addition of low density carbon/graphene fibers into the PCM [20, 21], adding porous materials to PCMs [22, 23, 24] and hybrid PCM [25, 26]

In general, the PCM density varies between the solid and liquid states, in fact solid is heavier that liquid, consequently, gravitational effects will influence the melting process and eventually and due to buoyancy effects, more solid is available in the lower section of the shell side that contains the PCM. The performance of LHTES can be enhanced if more heat is directed towards the lower section of the tube side and melting time is reduced. This can be achieved by considering first an eccentric shell and tube configuration. Then, we will consider attaching two types of fins to the tubes within the shell side: rectangular and flipped triangular fins and LHTES performance will be investigated under the combined effects of these fins and eccentricity. Up to the authors' knowledge, no previous investigations on the combined effects of eccentricity and fins- straight and flipped triangular types- were made and this work is study to these cases.

II. GOVERNING EQUATIONS

The heat transfer for this model is transient, non-linear and involves phase change and it is governed by the well-known continuity, energy and Navier-Stokes equations. Solution to this problem involves adopting the following assumptions:

- The PCM density is temperature dependent, whereas all other thermo-physical properties are not.
- Initially the PCM is in solid phase with uniform temperature.
- The outer surface of the shell side is adiabatic.
- The viscous dissipation is negligible.

Based on the above assumptions the continuity equation becomes

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \vec{u} = 0 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

The momentum equation

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla . (\rho \vec{u}\vec{u}) = \mu \nabla^2 \vec{u} - \nabla p + \rho \vec{g} + \vec{S} \dots\dots (2)$$

The energy equation will be

$$\frac{\partial (\rho H)}{\partial t} + \nabla . (\rho \vec{u} H) = \nabla . (k \nabla T) + S \dots\dots\dots (3)$$

Where ρ: density, $\vec{u}$: velocity vector, p: pressure, μ: absolute viscosity, k: thermal conductivity, H:enthalpy, $\vec{S}$:source term; the momentum sink,

$$\vec{S} = \frac{(1-\alpha)}{\alpha^3 + \sigma} A_{mush} (\vec{u} - \vec{u}_p) \dots\dots\dots\dots\dots\dots (4)$$

α : the liquid fraction, σ: a small scaler value to avoid division by zero, a preset value of to 0.001 was chosen for σ, A_{mush}= the mushy zone constant, it is a measure of the damping amplitude and it predicts the PCM behavior during melting/solidifications. The value of the mush zone constant was set to 10^5 but it can vary between 10^4 -10^7 . $\vec{u}_p$: the pull velocity, it accounts for the solidified material movement away from the computational domain.

The total enthalpy H is the sum of the sensible enthalpy *h* and the latent heat *ΔH*

$$H = h + \Delta H \dots\dots\dots\dots\dots\dots\dots\dots (5)$$

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \dots\dots\dots\dots\dots\dots (6)$$

using the latent heat of the material *(L_f)*, the latent heat content *(ΔH)* will be

$$\Delta H = \alpha L_f \dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

The latent heat content varies from *0* for solid state to L_f for liquid state.

The liquid fraction (α)

$$\alpha = \begin{cases} 0 & for\ T < T_s \\ \dfrac{T - T_s}{T_l - T_s} & T_s < T < T_l \dots\dots\dots\dots\dots\dots\dots (8) \\ 1 & for\ T > T_l \end{cases}$$

The model was created and solved using ANSYS FLUENT 14.5; the enthalpy porosity method was used to solve the PCM melting. In this technique, the enthalpy balance is performed at each iteration to compute the melt fraction (α) and cell volume fraction in the liquid phase. Besides, the melt region of the PCM which is represented by the mushy zone is considered as porous medium with liquid fraction varying from 0 for a total solid phase to 1.0 for a total liquid phase.

III. NUMERICAL PROCEDURE

In this work, a two-dimensional shell and tube configuration was modeled using ANSYS FLUENT 14.5, model details are shown in figure, shell side is filled with PCM. The computational geometry is shown in figure 1: copper was chosen for the inner tube material with inner and outer radii ($R_{t,i}$,$R_{t,o}$) of 4 mm and 5 mm respectively, the outer circular shell is also made of copper and its inner and outer radii ($R_{s,i}$,$R_{s,o}$) are 20 mm and 21 mm respectively. The centers of the shell and tube are at a distance δ apart, Obviously, the shell and tube are concentric when δ =0.

The eccentricity parameter ε is defined as

$$\varepsilon = \frac{\delta}{R_{s,i} - R_{t,o}}$$

Smooth and finned inner tube cases are considered; two types of fins were attached to the inner tube as shown in figure: rectangular fins and flipped triangular fins. In each case, 10 equally

Smooth and finned inner tube cases are considered; two types of fins were attached to the inner tube as shown in figure: rectangular fins and flipped triangular fins. In each case, 10 equally radially spaced fins are considered. The rectangular fin is 4.0 mm long and 1.0 mm wide, whereas the flipped triangular fin is fin is 4.0 mm long and its width varies from 0.5 mm at the inner tube tip to 2.0 mm. Fig. 1 illustrates the details of the geometry.

The space between the two tubes is filled with N-eicosane; properties are summarized in table 1.

Table 1, Thermal and physical properties of N-eicosane

Property	Value	Unit
Density of ρ	770 kg/m^3	kg/m^3
Heat capacity , c_p	2460	kJ/kg.K
Thermal conductivity, k	0.1505	W/m.K
Absolute Viscosity, μ	0.0385	kg/m.s
Melting temperature T_l	308	K
Solidus temperature T_s	310	K
Latent heat , L_f	247.60	kJ/kg
Thermal expansion Coef., β	0.0009	k^{-1}

Initially, the system was subcooled to 305 kelvins. However, during the simulation the surface of the inner tube is maintained at constant temperature of 329 kelvins and the outer tube is well insulated. Due to symmetry about the vertical axis and in order to save computation time, half of the domain was chosen for simulation. A mesh of about 8200 grids for all the cases was good enough for the specified geometry. Besides, several values of time step were considered (Δt= 0.1s,0.05s ,0.02 s) and a value of Δt = 0.05s was chosen.

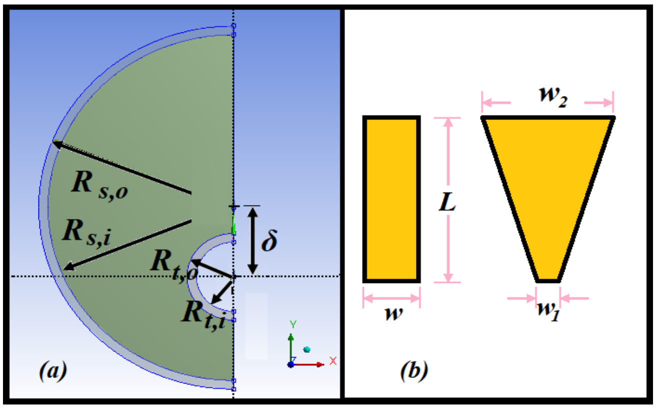

Fig. 1, (a) shell and tube geometry (b) fin geometry

The numerical technique was validated by comparing an independent simulation model with the work of Darzi [27].
A shell a tube system with inner and out diameters of 20 mm and 40 mm respectively and solid boundary thickness of 1.5 mm was modeled. The inner tube surface was heated to 329 K during the whole simulation while the outer shell boundary was well insulated. Figure shows comparison of the melt fraction evolution with time between the two works and a satisfactory agreement between the current study and that of Darzi et al [27].

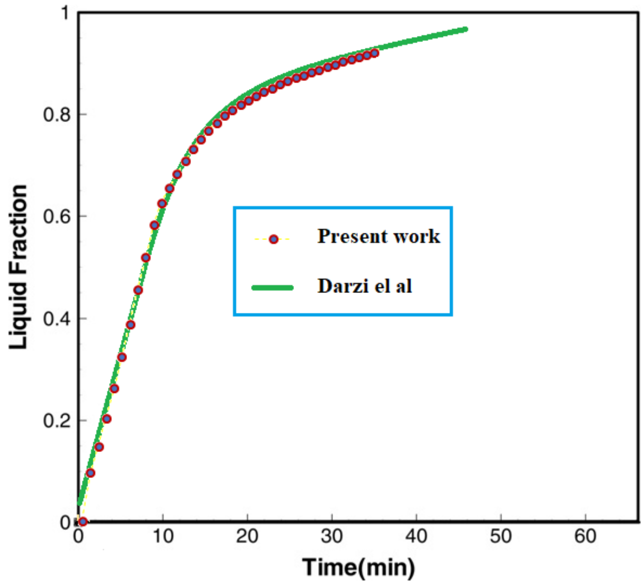

Fig. 2, Progress of melt fraction with time, present work, vs Darzi et al [27]

IV. DATA AND RESULTS

A. Latent heat storage with smooth tube

Fig. 3 illustrates the melting and temperature contours in LHS with smooth tubes at different times for different eccentricities [0,0.267, and 0.533]. Initially, heat is transferred from the hot surface to the adjacent PCM causing its temperature to rise and eventually starts melting once the melting temperature is reached. It can be noted that a small molten region is formed around the hot surface with almost same melting rate regardless of the tube eccentricity. Heat conduction dominates the heat transfer at this stage. Now, two distinctive regions of PCM are present: molten PCM in liquid phase and Non-melted PCM in solid phase. The solid region receives heat from the molten liquid by convection and heat transferred within the solid matrix by conduction. As melting continues, the molten region gets bigger and the hot fluid ascends to the top side of the molten region and the cold fluid descends downward due to buoyancy effects induced by density gradients that are caused by temperature difference. As a result, convection currents and vortices are formed and due to circulation, mixing is enhanced as well as heat transfer within the molten PCM. In fact, melting rates are significantly improved in the upper region where temperature gets higher after melting due to sensible heating. Whereas, a boundary layer exists around the hot surface and weak currents are present in the lower region and the sloid-liquid interface moves slowly.
LHS with eccentric tubes will have larger amount of PCM above the heating tube than that of a concentric tube and consequently, the fluid fraction will be larger. In the lower region, conduction dominates the heat transfer due to the weak flow currents, it is quite obvious that the temperature in lower section is proportional to the eccentric distance and thus the melting rate in significantly increased with the eccentricity and melting time was reduced by almost 5% and 10% for $\varepsilon = 0.267$ and 0.533 respectively when compared to the concentric smooth tube case. Figure 6 demonstrates this behavior.

B. Latent heat storage with embedded fins

Fins are used to enhance the heat transfer and obtain more uniform temperature distribution and reduce the melting rate. Fins increase the surface are of the hot surface and more heat is transferred into the PCM. Referring to figures [4,5] heat transfer starts immediately from the hot tube and fin surfaces to the PCM and melting begins upon reaching the melting point, a small region of the melt is formed in the vicinity of the hot surfaces and it keeps growing. Conduction is dominant in the early stages of the melting process and as the molten region propagates buoyancy effects drive the hot liquid upward and cold liquid downward and consequently vortices and convective currents are generated. Convection dominates the heat transfer process and mixing is enhanced and as a result, melting is significantly improved when compared to the smooth tube case.
Combining the eccentricity with fins further improves the heat transfer and melting and more uniform melting rates and temperature distributions are achieved.
The melting rate and temperature profiles in the PCM in the two fin types cases were very similar, as it shown in figure (7 and 8) in both fin configurations melting times was reduced by 36%, 41 % and 48 % for eccentricities of 0, 0.267 and 0.533 respectively. further parametric investigations need to be made on different container size, fins size and number and PCM type to have clear relation between fin type and melting rate as well as temperature profiles.

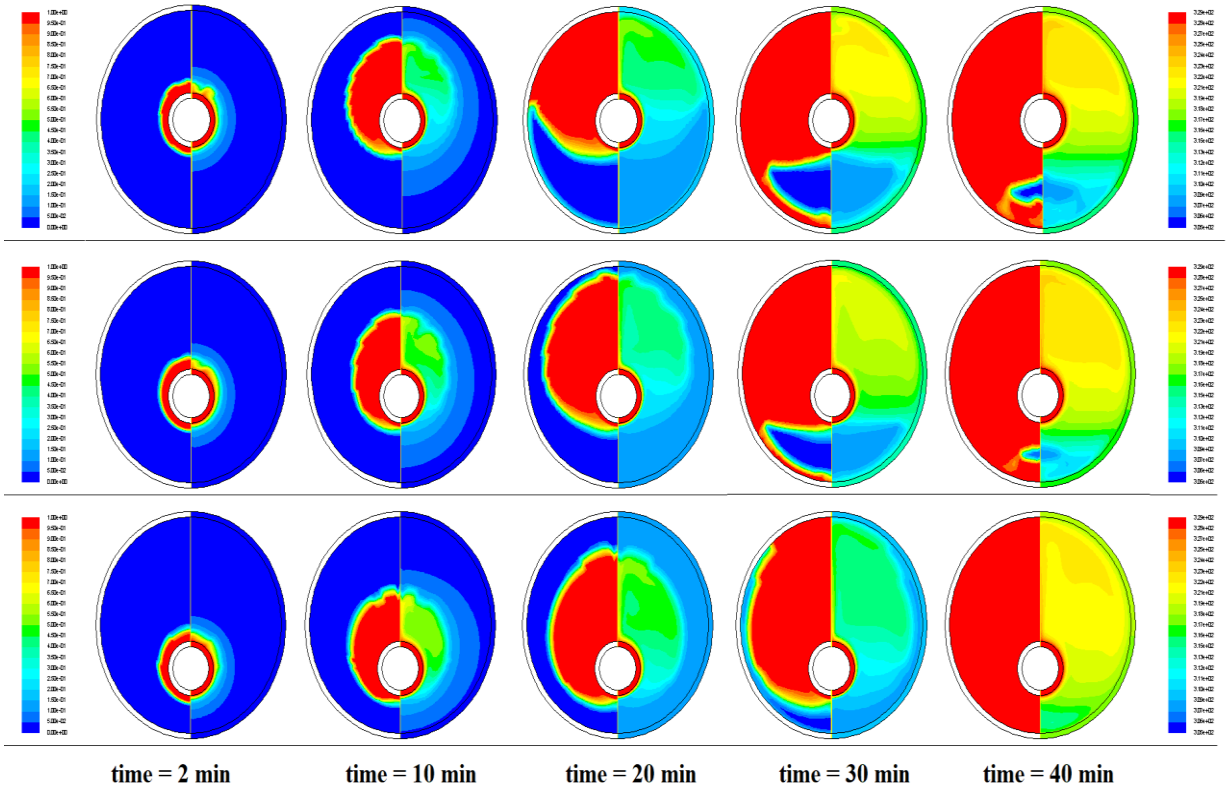

Fig. 3, Time evolution of melt fraction (left side) and Temperature (right side) contours for smooth tube at different eccentricities (ε=0.0, 0.267, 0.533 ,1st, 2nd and 3rd rows respectively)

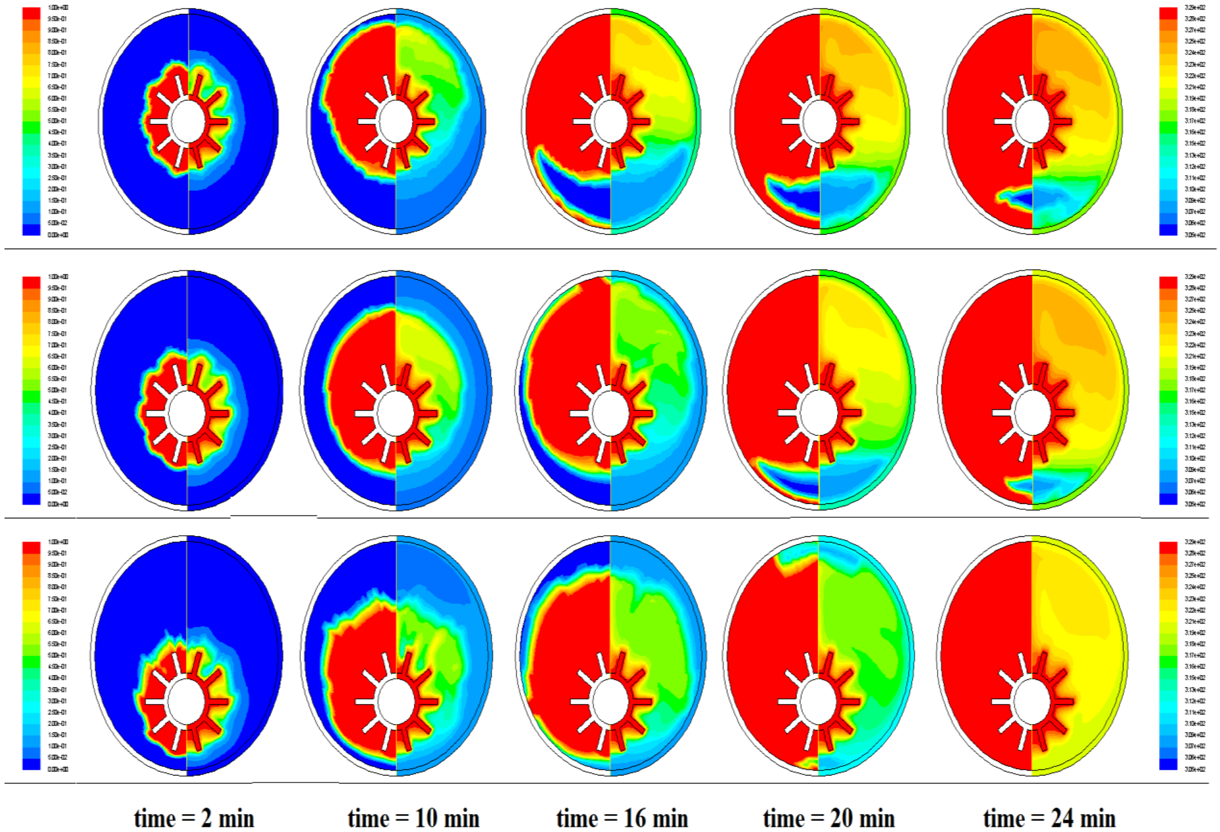

Fig. 4, Time evolution of melt fraction (left side) and Temperature (right side) for straight finned tube at different eccentricities (ε=0.0, 0.267, 0.533 ,1st, 2nd and 3rd rows respectively)

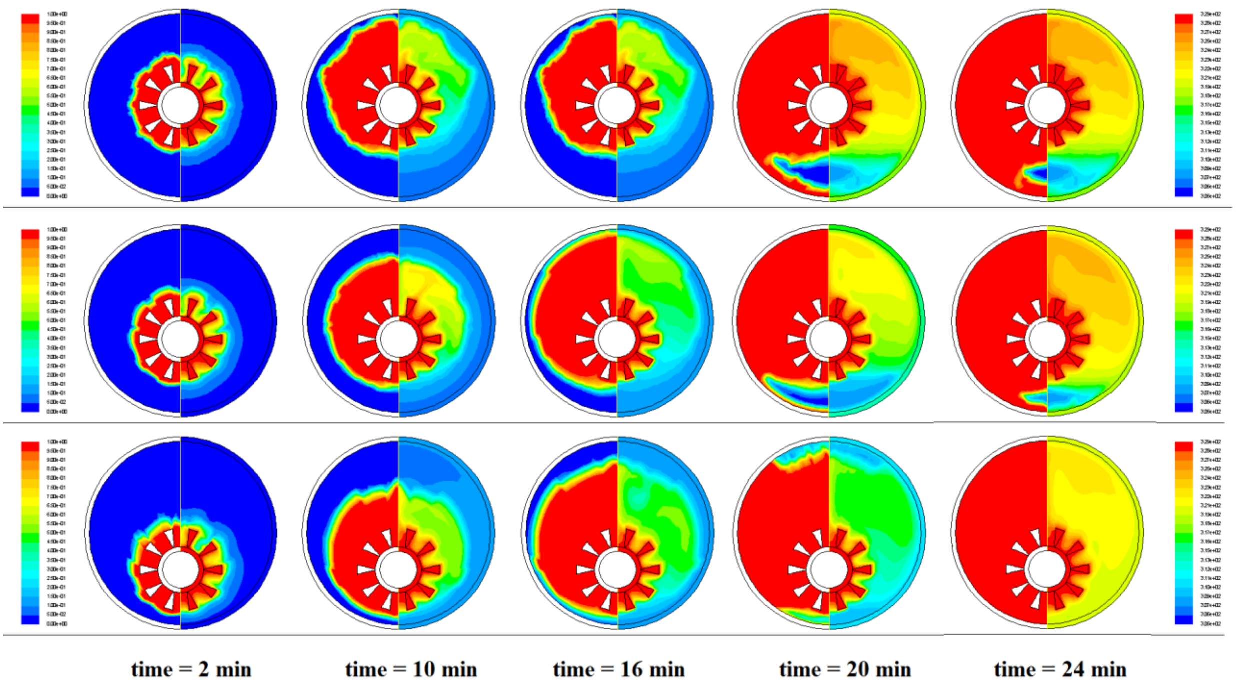

Fig. 5, Time evolution of melt fraction (left side) and Temperature (right side) for flipped triangle finned tube at different eccentricities (ε=0.0, 0.267, 0.533 ,1st, 2nd and 3rd rows respectively)

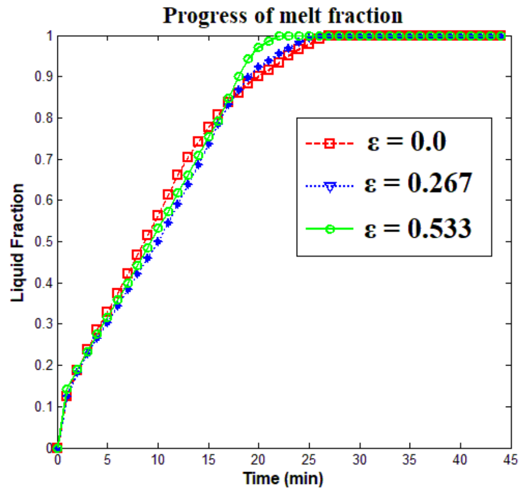

Fig. 6, Time evolution of melt fraction for smooth tube at different eccentricities (ε=0.0, 0.267, 0.533)

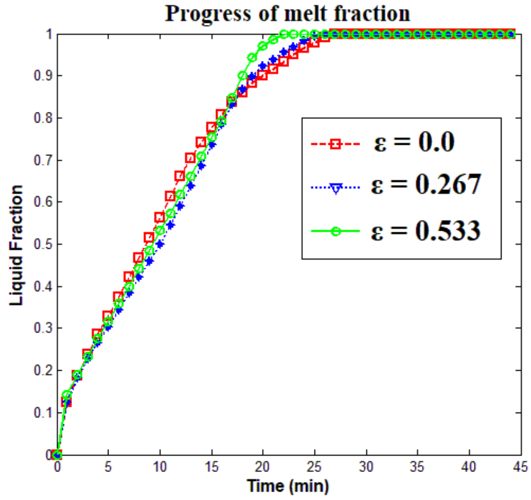

Fig. 7, Time evolution of melt fraction for tube with straight fins at different eccentricities (ε=0.0, 0.267, 0.533)

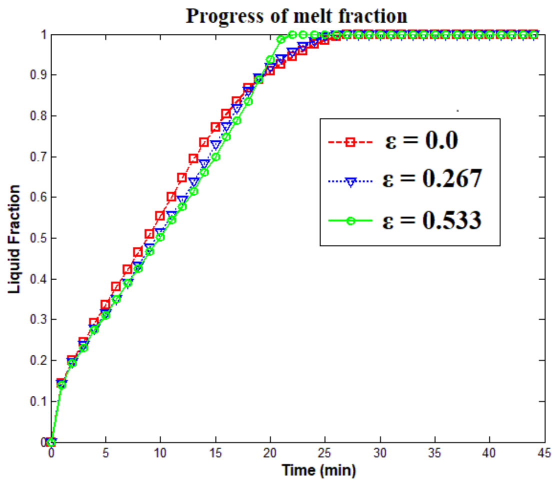

Fig. 8, Time evolution of melt fraction for tube with FT fins at different eccentricities (ε=0.0, 0.267, 0.533)

V. CONCLUSION

The shell and tube configuration for heat storage applications using PCM was successfully numerically investigated: first smooth tubes with different eccentricities were considered and it was found out that the melting time was reduced with increasing the eccentricity downward. Then two types of fins were attached to the tube within the shell side and results predicted that the combined effects of fins and eccentricity will further reduce the melting time and also make the temperature distribution more uniform. At the beginning of melting, conduction dominates the heat transfer in all regions, however and as time advances, natural convection becomes more significant in the upper section while conduction still dominating the heat transfer process in the lower section. Melting rate becomes higher in the upper section due to convection currents and improved circulation.

Eccentricity towards the lower side provide more PCM in the upper region and hence more area are dominated by natural convection and consequently higher melting rate is obtained. The inclusion of fins efficiently transfers and distributes thermal energy and as a result more uniform temperature profiles are present in within the shell side and better natural convection characteristics are achieved and eventually significant improvements in melting rate are obtained.

REFERENCES

1. F. Agyenim, N. Hewitt, P. Eames and M. Smyth, "A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)," Renewable and Sustainable Energy Reviews, vol. 14, pp. 615-628,, 2010.
2. M. M. Farid, A. M. Khudhair, S. A. K. Razack and S. Al-Hallaj, "A review on phase change energy storage: materials and applications," Energy Conversion and Management, vol. 45, pp. 1597-1615,, 2004.
3. M. Kenisarin and K. Mahkamov, "Solar energy storage using phase change materials," Renewable and Sustainable Energy Reviews,, vol. 11, pp. 1913-1965, 2007.
4. B. Zalba, J. M. Marín, L. F. Cabeza and M. Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications," Applied Thermal Engineering, vol. 23, no. 3, pp. 251-283, 2003.
5. Zhao CY, Lu W, Tian Y., "Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs)," Solar Energy , vol. 84, no. 8, p. 1402-1412, 2010.
6. U. STRITIH, "An experimental study of enhanced heat transfer in rectangular PCM thermal storage," International Journal of Heat and Mass Transfer, vol. 47, pp. 2841-2847, 2004.
7. C. GUO and W. ZHANG, "Numerical simulation and parametric study on new type of high temperature latent heat thermal energy storage system.," Energy Conversion and Management, vol. 49, pp. 919-927, 2008.
8. Z. Liu, X. Sun and C. Ma, "Experimental investigations on the characteristics of melting processes of stearic acid in an annulus and its thermal conductivity enhancement by fins," Energy Conversion and Management,, vol. 46, pp. 959-969, 2005.
9. R. Velraj, R. V. Seeniraj, B. Hafner, C. Faber and K. Schwarzer, "Experimental analysis and numerical modelling of inward solidification on a finned vertical tube for a latent heat storage unit," Solar Energy, vol. 60, no. 5, p. 281–290., 1997.
10. J. R. Turnpenn, D. W. Etheridge and D. A. Reay, "Novel ventilation cooling system for reducing air conditioning in buildings: part I: testing and theoretical modelling," Applied Thermal Eng.ineering, vol. 20, no. 11, p. 1019–1037, 2000.
11. R. Velraj, R. V. Seeniraj, B. Hafner, C. Faber and K. Schwarzer, "Heat transfer enhancement in a latent heat storage system," Solar Energy, vol. 65, no. 3, pp. 171-180, 1999.
12. R. A. H. Albaldawi , A. K. Shyaa and B. M. H. Hammendy , "Experimental Study on the Effect of Insertion of Copper Lessing Rings in Phase Change Material (PCM) on the Performance of Thermal Energy Storage Unit," Al-Khwarizmi Engineering Journal, vol. 11, no. 4, pp. 60- 72 , 2015.
13. C. Y. Zhao, "Review on thermal transport in high porosity cellular metal foams with open cells," International Journal of Heat and Mass Transfer, vol. 55, pp. 3618-3632, 2012.
14. H. MICHELS. and R. PITZ-PAAL, "Cascaded latent heat storage for parabolic trough solar power plants. Solar Energy," Solar Energy, vol. 81, pp. 829-837, 2007.
15. J. Wang, Y. Ouyang and G. Chen, "Experimental study on charging processes of a cylindrical heat storage capsule employing multiple-phase-change materials," International Journal of Energy Research, vol. 25, pp. 439-447, 2001.
16. P. Chandrasekaran, M. Cheralathan and R. Velraj, "Effect of fill volume on solidification characteristics of DI (deionized) water in a spherical capsule – an experimental study," Energy, vol. 90, p. 508–515., 2015.
17. J. L. Zeng, Z. Cao, D. W. Yang, L. X. Sun and L. Zhang, "Thermal conductivity enhancement of Ag nanowires on an organic phase change material," Journal of Thermal Analysis and Calorimetry, vol. 101, no. 1, p. 385–389, 2010.
18. A. Karaipekli, A. Biçer, A. Sarı and V. V. Tyagi, "Thermal characteristics of expandedperlite/paraffin composite phase change material with enhanced thermal conductivity using carbon nanotubes," Energy Conversation and Management, vol. 134, p. 373–381, 2017.
19. M. Nabavitabatabayi, F. Haghighat, A. Moreau and P. Sra, "Numerical analysis of a thermally enhanced domestic hot water tank," Applied Energy, vol. 129, p. 253–260, 2014.
20. A. Karaipekli, A. Sarı and K. Kaygusuz, "Thermal conductivity improvement of stearic,acid using expanded graphite and carbon fiber for energy storage applications,," Renewable Energy, vol. 32, no. 13, p. 2201–2210., 2007.
21. J. Fukai, M. Kanou, Y. Kodama and . O. Miyatake, "Thermal conductivity enhancement of energy storage media using carbon fibers," Energy Conservation and Management, vol. 41, no. 14, p. 1543–1556., 2000.
22. W. Wang , X. Yang , Y. Fang , J. Ding and . J. Yan, "Enhanced thermal conductivity and thermal performance of form-stable composite phase change materials by using b-aluminum nitride.," Applied Energy, vol. 86, no. 78, p. 1196-1200., 2009.
23. Y. Tian and C. Zhao , "A numerical investigation of heat transfer in phase change materials (PCMs) embedded in porous metals," Energy, vol. 36, p. 5539-5546., 2011.
24. P. Srivatsa , R. Baby and C. Balaji, "Numerical investigation of pcm based heat sinks with embedded metal foam/crossed plate fins.," Numerical Heat Transfer, Part A: Applications, vol. 66, p. 1131-1153, 2014.
25. B. Tang, H. Wei, D. Zhao and S. Zhang, "Light-heat conversion and thermal conductivity enhancement of PEG/SiO2 composite PCM by in situ Ti4O7 doping,," Solar Energy Materials and Solar Cells, vol. 161, p. 183–189, 2017.
26. R. Lazzarin, M. Noro, G. Righetti and S. Mancin, " Application of hybrid PCM thermal energy storages with and without al foams in solar heating/cooling and ground source absorption heat pump plant: An energy and economic analysis," Applied Sciences, vol. 9, no. 5, p. 1007, 2019.
27. A. R. Darzi,, M. Farhadi and K. Sedighi, "Numerical study of melting inside concentric and eccentric horizontal annulus," Applied Mathematical Modelling, vol. 36, p. 4080–4086, 2012.

AUTHORS PROFILE

Ahmad K AL-Migdady, Currently an assistant professor at the department of mechanical engineering at the Hashemite university, Zarqa, Jordan, received his Master's and PhD degrees in Mechanical engineering from the City College of New York/CUNY, New York, NY, USA in 2001 and 2012 respectively and Bachelor's degree in mechanical engineering from Jordan University of Science and technology "JUST", Irbid, Jordan in 1998. He has more than 10 years of teaching and research experience. He is a member of Jordan Engineers Association. Research interests include: thermal power, thermo-fluids, nano-scale fluid mechanics using molecular dynamics, computational fluid mechanics and heat transfer, renewable energy and thermal energy storage.

Ali M Jawarneh, Currently an associate professor at the department of mechanical engineering at the Hashemite university, Zarqa, Jordan. He received his PhD degrees in Mechanical engineering from Concordia University, Montreal, QC, Canada in 2004 and Master's and Bachelor's degree from the University of Science and technology, Irbid, Jordan in 1996 and 1993 respectively. Research interests include, experimental and computational fluid mechanics and heat transfer, swirl flow and renewable energy.

Hussein N Dalgamoni, Currently an assistant professor at the department of mechanical engineering at the Hashemite university, Zarqa, Jordan. He received his PhD degrees in Mechanical engineering from State University, of New York at Binghamton, Binghamton, NY, USA in 2019, Master's degree in mechanical engineering from Jordan University of Science and technology, Irbid, Jordan in 2007 and Bachelor's degree in Mechanical engineering from Mutah University, Karak, Jordan in 2003. Research interests include, renewable energy, experimental and computational fluid mechanics and heat transfer, Low-scale fluid mechanics.

Mohammad Tarawneh, Currently an associate professor at the department of mechanical engineering at the Hashemite university, Zarqa, Jordan. He received his Master's and PhD degrees in Mechanical engineering from Jordan University, Amman, Jordan in 2004 and 2008 respectively. and Bachelor's degree from Yarmouk University, Irbid, Jordan in 1987. Research interests include, experimental and computational fluid mechanics and heat transfer, renewable energy, refrigeration.