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Melting Rate Analysis for Optimization of Fin Configuration in PCM Based Thermal Energy Storage System

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ABSTRACT

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The increase in the energy demands and a higher peak hour electricity tariff makes thermal comfort management of buildings more expensive and critical. Thermal comfort at an optimum cost requires management of building heat load. This leads to the use of Phase Change Materials (PCM) for thermal energy storage system (TESS). The process varies with fin length, position and numbers. The process is complicated requiring either numerical or experimental modelling. Data analysis with statistical methods to understand the melting process under various fin configurations is presented here. Result from open literature has been extracted and equations for liquid fraction are generated using polynomial regression modelling. Melting rate is traced over time to account for the rate in change of the liquid fraction. Analysis showed that, during the initial phase until about 45% liquid melt; the time taken was independent of fin location but increased linearly with fin number. Surprisingly, during the melt process, the fin at top section has a higher melting rate in the initial phase but decreases rapidly. However, this decrease is stabilized and increased by the bottom fins in the later phase when the liquid fraction is in the range of 45% to 90% that simultaneously helps in decreasing the melt time. But this stabilization is affected if the number of fins at the top is more than bottom.

Keywords:

Thermal Energy Storage; regression;
melting rate; Fin Configuration

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1. Introduction

The increase in the energy demands and a higher peak hour electricity tariff makes thermal comfort management of buildings more expensive and critical. For example, thermal management of a data centre is very critical and expensive. Thermal comfort at an optimum cost requires management of building heat load. That is shifting the peak demand to off-peak duration. Thereby, shifting the electrical load requirement. This can be performed by thermal energy storage (TES) [1] with the help of phase change materials (PCM) [2]. In electrical load shifting the conventional heating or cooling system is made to work more during off-peak hours and the thermal energy stored in PCMs

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which will be used during the peak hours [3]. Selection of proper PCM and a heat exchanger with maximum effectiveness are the major parameters that determine the optimum performance of the TES. PCMs are mainly classified into three types [4]

- a) Organic: Paraffin and Non paraffin fatty acid
- b) Inorganic: Salt hydrates and metallic
- c) Eutectic: Organic-Organic, Organic-Inorganic, Inorganic-Inorganic

The PCM for TES is selected based on the following criterion [5]:

- a) melting point in the desired operating temperature range
- b) high latent heat of fusion
- c) high thermal conductivity
- d) low volume changes during phase transition
- e) high specific heat
- f) little or no sub-cooling
- g) chemical stability
- h) low cost

Thambidurai *et al.*, [6] has reviewed various PCMs, from the list of PCMs few PCMs which meets the desired melting temperature are listed Table 1. In most of the cases the macro encapsulation of the PCM is itself considered as a heat exchanger. Only a few studies have been performed with various other configurations such as Shell and tube, shell and tube with fin, packed bed with different shapes of PCM encapsulation (Sphere and Granules) [7-10]. Kurnia *et al.*, [11] evaluated the thermal performance of thermal energy storage with U-tube type heat exchanger with different configurations and also varied the PCM in different regions of the heat exchanger. Tao and He [12] compared the performance of smooth tube shell and tube heat exchanger configuration with internal helically finned tube shell and tube heat exchanger configuration. They have also used a combination of PCMs for performance improvement. It has been concluded that the internal finned tube enhances the performance in the first half of the tube and doesn't have significant effect in the second half. Also, proper combination of PCMs can improve the storage capacity.

Table 1
PCM with desired melting temperature

Sl. No.	Compound	Melting Point (°C)	Heat of fusion (kJ/kg)
1.	n-Heptadecane	19	240
2.	KF.4H ₂ O	18.5	231
3.	55–65% LiNO ₃ .3H ₂ O + 35–45% Ni (NO ₃) ₂	24.4	230
4.	Octadecane + docosane	25.5–27.0	203.8
5.	Paraffin C13–C24	22–24	189
6.	Lactic acid	26	184
7.	Paraffin R20	20-22	172

Mahdi *et al.*, [13] studied the effect of fin length and configuration in the melting rate of PCM in a triplex tube heat exchanger. It was observed that the presence of longer fins in the upper half of the heat exchanger doesn't have significant effect on melting rate and the same was also observed by Ji *et al.*, [14] who had studied the effect of fin length in a rectangular enclosure with two fins under natural convection. Kibria *et al.*, [15] has experimentally studied the effect of flow rate, inlet temperature, tube thickness and tube radius during the charging and discharging of a PCM in a shell

and tube heat exchanger configuration without any fins. It was concluded that the inlet temperature and the tube radius have significant impact on the charging and discharging of PCM whereas the flow rate doesn't have significant impact and tube thickness has no impact in the charging and discharging of PCM. Khan and Khan [16] has experimentally studied the effect of flow rate and inlet temperature of HTF during discharging phase of PCM. The experiment is conducted in a shell and tube heat exchanger configuration with four longitudinal fins. It was concluded that the conduction is predominant in the middle portion of the fin than that of the upper and lower portions. It was also concluded that decreasing the inlet temperature and increasing the flow rate can increase the mean discharge power. The same has been observed by Raul *et al.*, [17] who had used vertical multi-tube shell and tube heat exchanger configuration. In addition to these parameters Raul *et al.*, [17] has varied the initial PCM temperature and found that the increase in initial PCM temperature helps in increasing discharge efficiency. Abdi *et al.*, [18] has numerically analysed the melting process of the PCM (Lauric acid) in cavity with vertically oriented fins. The PCM is filled in a cube shaped cavity with a volume of $0.72 \times 10^{-3} \text{ m}^3$. The material for the cavity and the fins is taken as aluminium. The simulations were performed for various fin numbers (1, 3 & 5) and fin length (2.5%, 5% & 7.5% of cavity height). The fin volume fraction varies from 0% to 12.5%). The melting process is analysed based on melting time, energy stored, heat transfer rate, overall heat transfer coefficient and mean power. The cavity is heated in the bottom surface with different temperatures corresponding to Stefan number of 0.55, 0.43 and 0.36. From the results it was observed that the configuration with long and a greater number of fins will be suitable for high-intermittent thermal demand. The configuration with short and a smaller number of fins will be suitable for low-continuous thermal demand. Karami and Kamkari [19] has investigated the effect of inclination angle in finned enclosures under natural convection. It was observed that the melting time was minimum when the inclination is zero degrees that is vertical in orientation. This observation is also in line with that of Abdi *et al.*, [18]. It is concluded that the enclosure should be oriented to allow natural convection currents. Han *et al.*, [20] studied the effect of natural convection in shell-and-tube heat exchanger in different orientations. The PCM was placed in the tube in one configuration and in the shell in one configuration. It was observed that the heat storage and PCM melting rate is more when the PCM is placed in tube than the other configuration in horizontal configuration. Ji *et al.*, [21] has numerically investigated the influence of inclined fins in natural convection during the melting process of PCM (RT42). The simulation was performed in a 2-D model in which the PCM is filled in a rectangular cavity of length 120mm and width 100mm. The cavity consists of two horizontal fins of thickness 2mm and pitch 32mm attached to the heater plate placed at the left side of the cavity. Simulations were performed for three fin lengths (30mm, 60mm & 90mm) and five angles of inclination namely, 0° , $+15^\circ$, $+30^\circ$, -15° & -30° . For a given fin length and heat flux, the fins facing upwards ($+15^\circ$ & $+30^\circ$) did not improve the melting rate and in the case of fins facing downwards, the -15° inclined fin had a better melting rate than that of the -30° inclination. Fin length less than 50% of the cavity width doesn't have effect in the melting rate. When the input heat flux is increased the influence of inclined fins in the melting of PCM decreases. Zennouhi *et al.*, [22] has studied the influence of inclination angle of the cavity in the melting rate of the PCM under natural convection. It was observed that the strength of the vertical flow structures increases when the inclination angle is reduced from 90° to 0° . Agyenim *et al.*, [23] has compared the performance of circular and longitudinal fin in a cylindrical heat exchanger. It was concluded that the circular fin doesn't provide significant increase in the melting rate than that of the longitudinal fin. Tao and He [24] had studied the PCM melting rate in a horizontal concentric tube and the influence of fins in the PCM melting rate. It was observed that the natural convection enhances the melting rate in the upper half of the tube. In order to improve the melting rate in the lower half of the tube fins were placed. Providing fins with proper parameters

such as thickness, height and number of fins can improve the uniformity of the melting process. Sciacovelli *et al.*, [25] has proposed tree shaped fins with single and double bifurcation configuration to improve the efficiency of the TES system. It has been found that the melting time is low for Y shaped fins with wide angles between the branches. Banaszek *et al.*, [26,27] has studied the performance of spiral heat exchanger with two coaxial spiral cylinders. In one-cylinder PCM is stored and in the second cylinder heat transfer fluid is passed. Nor Azwadi Che Sidik *et al.*, [28] performed a comprehensive review of nano fluid PCM for performance enhancement of energy storage system. Ahmad Tajuddin Mohamad *et al.*, [29] studied the effect of graphene on inorganic salt hydrated PCM for thermal physical enhancement.

Thus, from the above review, it is seen that the thermal correlations seem to vary with type of configuration, it proposed to see if the choice of statistical methods to analyse the results available in open literature would throw light in the understanding of the melting process. In order to test the above hypothesis, 13 cases presented in literature is analysed and presented in the following sections.

2. Polynomial Regression Model

The data presented in Mahdi *et al.*, [13] for the 13 cases with various configurations was extracted. The system consists of a triple co-axial tube that has heat transfer fluid (HTF) flowing through the innermost and outermost region. The mid portion has the PCM (Rubitherm RT82) and fins projecting from both inner and outer tubes into the top and bottom portion of the annular region that contains the PCM. In their work, the location and number of fins in the PCM region (from both inner and outer HTF) has been varied for the first six cases keeping the fin length as a constant. But for the remaining seven cases, the fin length was also varied along with the number of fins and angular location. The schematic representation of the finned triplex-tube heat exchanger model along with the fin orientation axes and the size of the fins are presented in Figure 1. For a more detailed information the readers are invited to refer to Figure 2 and Table 1 of Mahdi *et al.*, [13].

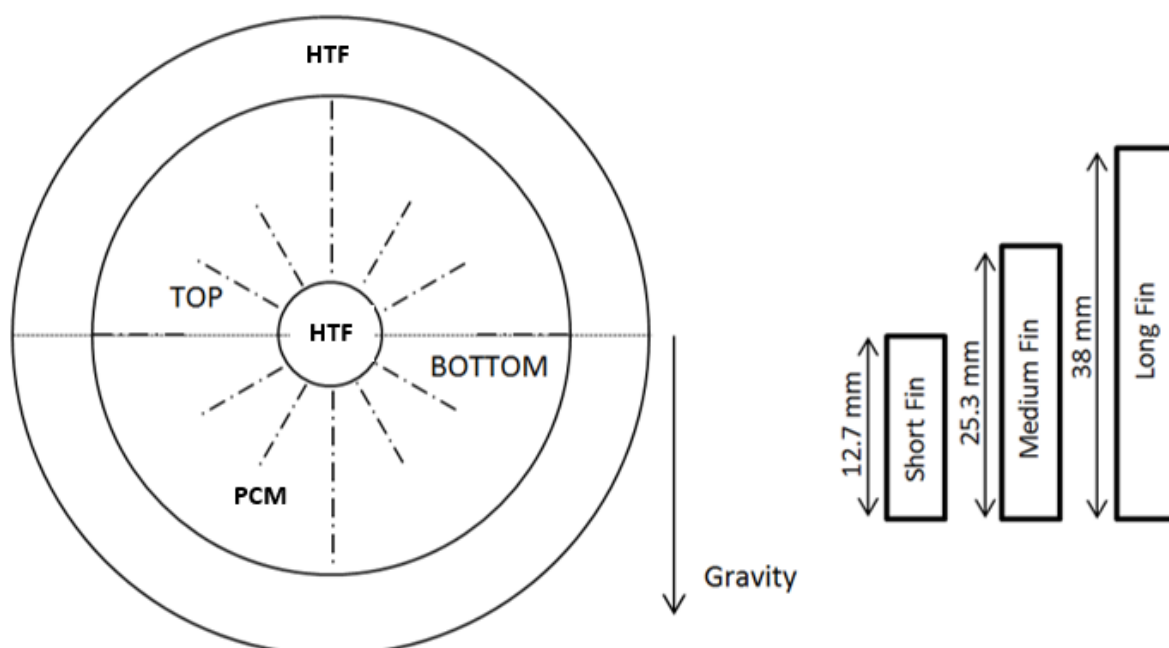


Fig. 1. Schematic representation of finned triplex-tube heat exchanger with fin length

Analysis is done based on the various configurations that achieve the same time to melt the PCM fully. The nomenclature for designating the fins are Number of fins in the order top and bottom followed by the length as Large, Medium and Small as subscript. Table 2 summarizes the cases considered with relevant nomenclature. For example, Case 2 it is 3_L1_L, meaning three long fins at the top and one at the bottom (Figure 1).

Table 2
 Nomenclature for Cases Studied

Case	Nomenclature	Case	Nomenclature
1	1 _L 1 _L	7	3 _S 3 _L
2	3 _L 1 _L	8	3 _M 3 _M
3	5 _L 1 _L	9	3 _L 3 _S
4	1 _L 1 _L	10	5 _S 5 _L
5	1 _L 3 _L	11	5 _M 5 _M
6	1 _L 5 _L	12	5 _L 5 _S
		13	3 _M 5 _L

The numerical data of the liquid fraction history presented graphically in Mahdi *et al.*, [13] was extracted using an online tool. From the extracted data of all the thirteen cases a polynomial regression was performed in excel and the various constants of the polynomial in Eq. (1) were obtained with time as independent variable and liquid fraction as dependent variable. The function was generated to ensure that the correlation with reference to the extracted data is greater than 0.99. From this correlation the liquid fraction at various time instants were computed and presented in Table 3. This was necessary to compute the rate of melting that will be discussed in the later section.

where,

$$\phi = \beta_1\tau^4 + \beta_2\tau^3 + \beta_3\tau^2 + \beta_4\tau \tag{1}$$

ϕ – Liquid fraction (0 – 1 non-dimensional)

τ – Time instant (Seconds)

β_i – Coefficients ($i = 1 - 4$)

Table 3
 Liquid fraction for Cases

Time (min)	Case Number											
	1 & 4	2	3	5	6	7	8	9	10	11	12	13
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.23	0.30	0.40	0.30	0.40	0.28	0.27	0.28	0.40	0.40	0.41	0.40
40	0.48	0.62	0.70	0.61	0.71	0.56	0.58	0.56	0.74	0.77	0.70	0.77
60	0.75	0.84	0.86	0.90	0.92	0.86	0.87	0.78	0.98	0.97	0.87	1.00
80	0.96	0.96	0.94	1.00	1.00	1.00	1.00	0.91	1.00	1.00	0.95	1.00
100	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00

3. Analysis of Variance ANOVA

Analysis of variance (ANOVA) is a statistical technique that is used to identify the impact of one or more factors by comparing number the means of different samples. Here, a 2^k factorial design is proposed. Where, 2 represent the levels ‘low’ and ‘high’ taken by the factors and k represents the number of factors considered. By considering the fin position and number of fins to be factors (A and B), the analysis of variance is used to identify their order of significance on the melting process. The

factors considered along with its value are presented in Table 4. ANOVA was performed based on the melting time. The design of experiment table (2^k design) is given in Table 5. The melting time was obtained from the regression Eq. (1) for the corresponding fin configuration. The equations to evaluate the significance of the factors are from Durakovic [30] and presented below.

For 2^2 design:

$$Total\ Variation = SS_A + SS_B + SS_{AB} \quad (2)$$

where,

$$SS_A\ (Sum\ of\ Squares\ of\ A) = 2^2 q^2_A \quad (3)$$

$$SS_B\ (Sum\ of\ Squares\ of\ B) = 2^2 q^2_B \quad (4)$$

$$SS_{AB}\ (Sum\ of\ Squares\ of\ AB) = 2^2 q^2_{AB} \quad (5)$$

$$q_A\ (Effect\ of\ A) = \frac{(Deflection\ of\ Model * Corresponding\ Level\ of\ A)}{4} \quad (6)$$

$$q_B\ (Effect\ of\ B) = \frac{(Deflection\ of\ Model * Corresponding\ Level\ of\ B)}{4} \quad (7)$$

$$q_{AB}\ (Effect\ of\ AB) = \frac{(Deflection\ of\ Model * Corresponding\ Level\ of\ AB)}{4} \quad (8)$$

$$Significance\ of\ A = \frac{SSA}{Total\ variation} \quad (9)$$

$$Significance\ of\ B = \frac{SSB}{Total\ variation} \quad (10)$$

$$Significance\ of\ AB = \frac{SSAB}{Total\ variation} \quad (11)$$

Table 4
Factors considered for ANOVA

Sl. No.	Factor	Description	Low	High
1	A	Fin position	Bottom	Top
2	B	Number of fins	2	4

Table 5
Design of experiment for ANOVA

Sl. No.	Factors		Time (min)
	A	B	
1	Low	Low	78
2	High	Low	94
3	Low	High	76
4	High	High	92

Table 6 presents the effect due to the factors such as fin position, 'A', number of fins, 'B' and the interaction 'AB'. The F-distribution value for alpha Type I error with numerator and denominator DOF are 1 and 2 respectively is $F(0.01,1,2) = 98.50$. The factors with Fo value greater than 98.50 is considered to have significant influence in the melting time. In general, the ANOVA assumes that 'larger the better'. Which means that it would provide the best combination for large melting time. However, we have to interpret the opposite of the above, since we need a shorter melting time. It is seen from Table 6. that the factor A that refers to fin position is the important factor with the level 'High' i.e. fins at top portion of the annual region containing the PCM yield a higher melt time. Hence, for the least melt time the fin needs to be positioned at the bottom portion of the annual region containing the PCM. Similarly, the factor B, the number of fins has a negative effect. This means that lower number of fins will have higher melting time. Thus, for shorter melt time we need higher number of fins positioned at the bottom portion of the annual region containing the PCM. As will be seen in the next section the profile of the volume fraction varies over time depending on the fin length and location although the ultimate aim would be final melt time. Looking beyond ANOVA, a further data mining was done to estimate the melt rate coined as '*melt-velocity*' and discussed in detail in the next section.

Table 6
 ANOVA based on melting time

Factor	Effect	SS	DOF	MSF & MSE (SS/DOF)	F = MSF/MSE
A	16	256	1	256	128
Errors (B and AB)	-2	4	2	2	
Total DOF (N-1) = 4-1			3		

where,

SS is Sum of Squares,

DOF is Degrees of Freedom,

MSF is Mean Square of Factors and

MSE is Mean Square of Errors.

4. Melt Velocity

During phase change, there are two modes of heat transfer that is conduction when the PCM is solid and natural convection when the PCM starts to melt. However, the present focus is to only analyse the mathematical model without reference to the thermal physics.

It was seen from the literature that the liquid fraction trace over time is almost similar with a near linear pattern initially and shifts to an exponential profile. Using the Eq. (1) with unique β values for each configuration as tabulated in Table 3 a first order derivative of this profile with respect to time is computed and plotted in Figure 2 through Figure 6. Thus, a new approach of studying the rate at which the liquid fraction changes with time is extracted and analysed. This is given the term '*melt-velocity*' to understand the gradient (acceleration/deceleration) during the melt process.

Cases 1, 2, 3 and 12 have the same melt time of 95 min and the melt-velocity of these cases are presented in Figure 2. Case 4 is identical to case 1 in configuration. Case 3 configuration is 5_L1_L and case 12 is 5_L5_S respectively. The melt-velocity is higher initially due to the higher number of fins. On the contrary case 2 (3_L1_L) has a lower melt-velocity compared to case 3 and 12 due to lesser number of fins but the melt-velocity accelerates due to the presence of top fins till the melt fraction is about 35%. It is expected that case 3 should be better than case 2. But the total melt time is the same with

a drastic deceleration after 54% liquid concluding that the fins at the top do not help in stabilizing the melt-velocity at the later stages. The 54% liquid is of equal mass of solid due to density difference. The process decelerates as the solid at the bottom is not aided by a greater number of large fins and the further heat transfer is purely by internal conduction of liquid-solid. In so far as case 2 is considered it has only one large fin at the bottom but three large fins at the top.

Cases 5, 6, 7 and 11 have the same melt time of 75 min and the melt-velocity of these cases are presented in Figure 3. The case 5 and case 7 configurations are 1_L3_L and 3_S3_L respectively. The higher velocity is attributed to 3 large fins at the bottom. Large fins at the bottom not only start at a higher melt-velocity, but also stabilize during the major portion of the melt process that is from 20 to 75%. Case 5 and 7 has same melt-velocity after the liquid fraction is 54% as both the cases have fin dominance in the bottom and has same fin configuration in the bottom. In both these cases the profile is quadratic dominant followed by $2/3$ rd cubic and $1/3$ rd linear. Case 6 configuration is 1_L5_L , due to the presence of the five number of long fins at the bottom the initial velocity is high and the one long fin at the top. Hence in the initial phase the PCM at the bottom is fully melted and on long fin at the top is unable to aid in melting the PCM at the top at the same rate causing heavy deceleration. Case 11 configuration is 5_M5_M and is similar to the observation made in 6 and top fins though more than case 6 do not help in stabilizing the melt-velocity at the later stages.

For the cases shown in Figure 4, the time taken to melt is 95 min for case 2, 85min for case 8 followed by 75min for case 5. For case 2 it is 3_L1_L , for case 8, 3_M3_M and case 5, 1_L3_L . The observations are as follows: The fish type profile (fraction 0 to 54%) created by case 2 and 5 due to the exact opposite of fin number and placement in top and bottom. As mentioned in the start of section, though the profiles may be different the total time taken up to this point was 36min for both cases 2 and 5 respectively. Case 8 having medium configuration has melt time in between. Case 5 and 8 have the same profile after the melt fraction is 24% aided by bottom fins.

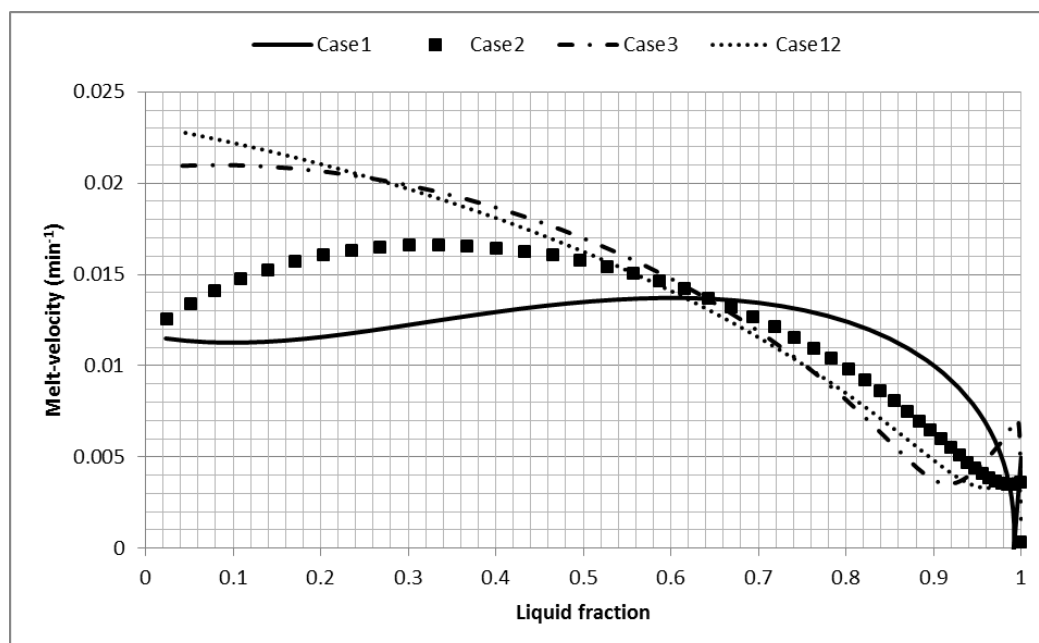


Fig. 2. Melt-velocity for cases with overall melting time 95 minutes

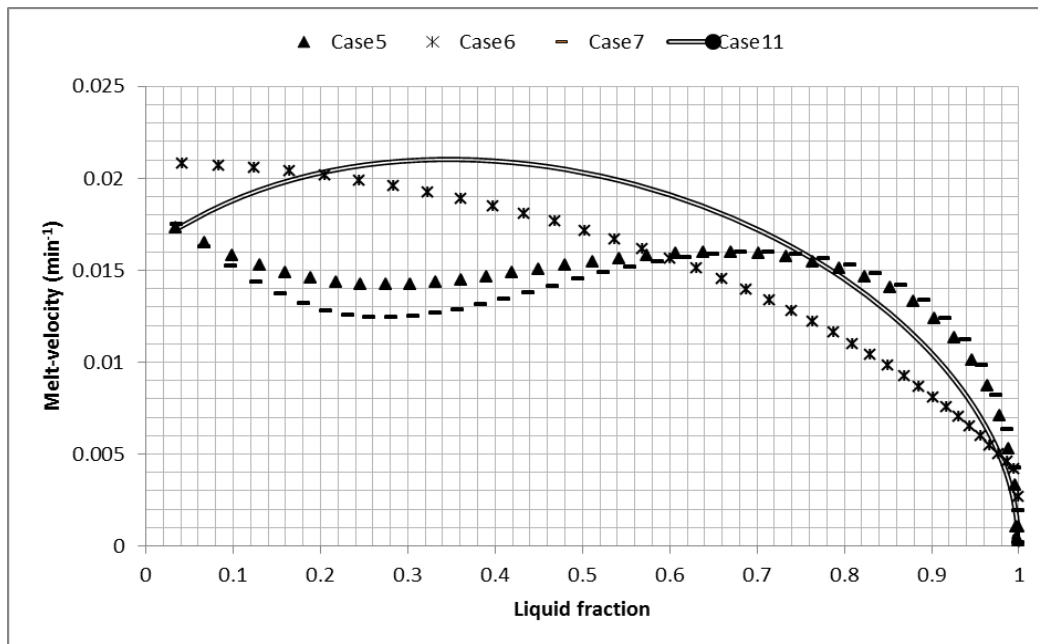


Fig. 3. Melt-velocity for cases with overall melting time 75 minutes

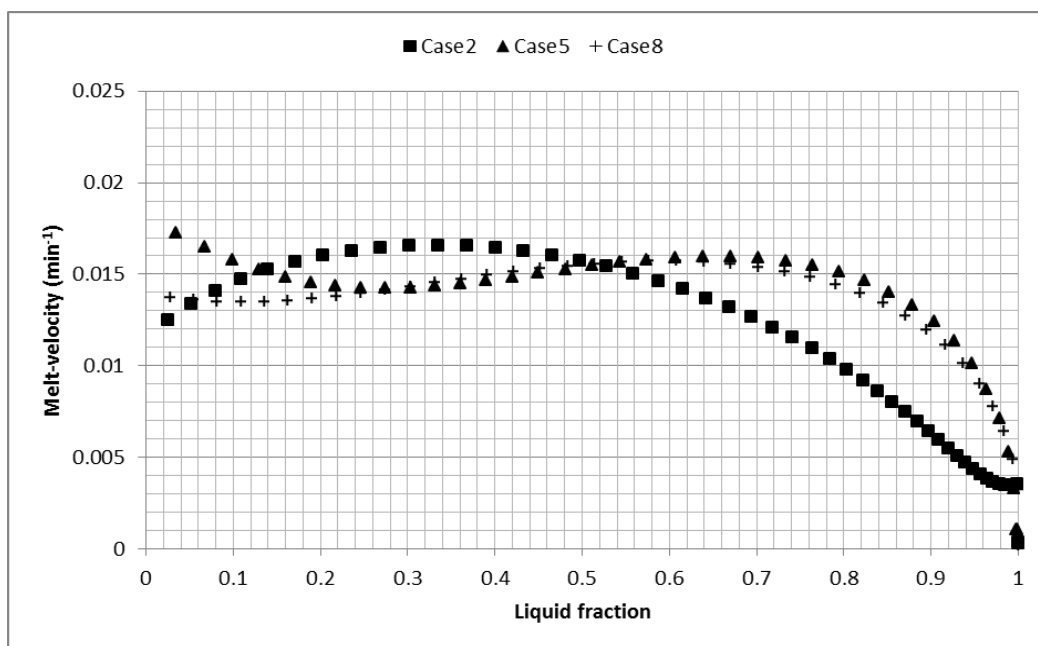


Fig. 4. Melt-velocity for cases with overall melting time 95-75-85 minutes

For the cases presented in Figure 5, the melting time is 105 min (case 9) and 95 min (case 2). The configuration for cases 9 and 2 is 3_L3_S and 3_L1_L respectively. Case 2 and 9 has almost same initial value since both the configurations has three long fins at the top. But case 9 is worse due to the fact it has three small fins at the bottom and is inefficient compared on one long at the bottom in case 2.

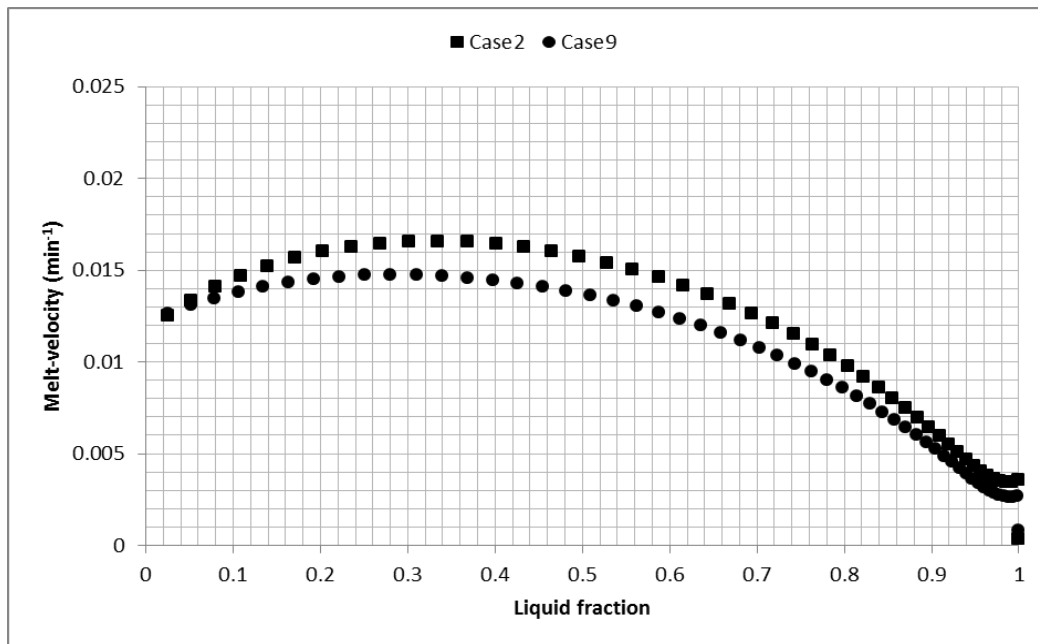


Fig. 5. Melt-velocity for cases with overall melting time 95-105 minutes

The melting time for case 7 is 75 min, case 10 is 65 min and case 13 is 60 min. The configuration for cases 7, 10 & 13 are 3_S3_L , 5_S5_L & 3_M5_L . Comparing cases 7 & 10, it can be seen that the increase in the initial melt-velocity is because of the increase in the number of fins. The deceleration of case 7 is stabilized and a slight acceleration of melting was observed during 30 to 70% shown in Figure 6. The deceleration of case 10 is stabilized and after 70% liquid fraction from thereon both cases 7 and 10 have the same melt-velocity. The five small fins configuration at the top in the case 10 is replaced with three medium fins to form case 13. The introduction of lesser number medium sized fins at the top helps the bottom fins in better stabilization of the melt-velocity and reduces the overall melt time.

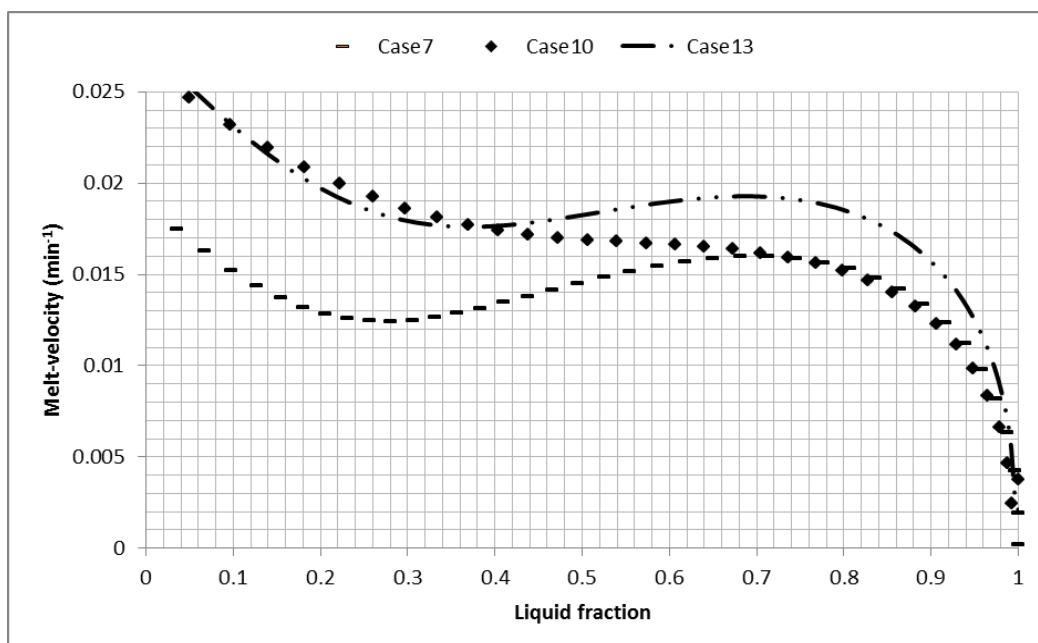


Fig. 6. Melt-velocity for cases with overall melting time 75-65-60 minutes

Thus, in order to increase the melting during the initial phase, the placement of fins in the top is essential, but it must not be dominant, as during the later stages, the bottom fins help in stabilization and in reducing the melt time.

5. Conclusion

The advantages of the triplex tube heat exchanger (TTHX) is that it houses the PCM in the annular region thus having an increased surface area of heat transfer. This helps in faster phase change with a lower temperature heat transfer fluid. This type finds application in process industries such as food, chemical and dairy products. From the numerical and experimental results presented in open literature, it was seen that the thermal correlation seemed to vary with the configuration. Hence, in this work data analysis approach has been implemented in the melting process of a PCM with various fin configurations using the available results from open literature.

An analysis of variance resulted in understanding the significance of the position and number of fins. It was found that the positioning the fins at the bottom portion of the annulus has a significant effect on the melting time followed by the numbers. It was found that the best configuration was to have a greater number of fins at the bottom region. But it was found from the various cases, the melting rate also changed during the duration of the melting process. Hence the melting rate has been analysed to better understand the process.

The melting rate profile is a combination linear, quadratic and cubic terms. Though the profile is predominantly cubic in nature, it is seen depending on the fin number, size and position, the strength of the cubic term is 2/3rd of quadratic by weight and the linear is 1/3rd the quadratic by weight ('S type profile') or certain cases have a very strong cubic term with a the quadratic term at half its weight. However, as the melt fraction is greater than 75% the profile is exponential that decreases at an increasing rate. This S type profile occurs for those cases that have strong bottom fin dominance and also has a shorter duration to melt. Another generic observation is that in the initial melting phase i.e. from 0 to 45%, the time taken varies linearly with the number of fins 3 or 5 irrespective of its position though they may have different melt velocity profiles.

It was seen that though the melt velocity is initially higher with increase in the number of fins, surprisingly certain configurations do not aid in reducing the melt time. The initial melt velocity and its stability decide the overall melting time. The fins at the top accelerate the melt velocity during the initial phase while the bottom fins try to stabilize the melt velocity for a longer duration thereby reducing total melt time. However, the effect of bottom fins in stabilizing is affected if the number of fins at the top is higher.

In conclusion it is seen that the bottom dominant fin configuration with lesser number in top help in the overall reduction in the melt time. As fins at the top are necessary to aid in the melting at the initial phase but becomes detrimental if the number of fins is higher. Thus, it can be seen that pure data analysis with statistical tools helps in understanding the physics of the problem. Incorporation of artificial intelligence with a more data set will help in designing a good configuration for PCM based TES system.

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