Experimental Study of Melting and Solidification of Paraffin Wax with Dispersion of Al_2O_3 in Rectangular Enclosure

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Abstract

In this experimental based research work, the performance of Thermal Energy Storage System (TESS) during charging (melting) and discharging (solidification) processes were studied under varying conditions. The results from the CFD simulations for these conditions were published earlier. Here, the experimental results had been discussed. Paraffin wax concentration was varied to form the TESS. Al_2O_3 was included as nano-material with a varying concentration – 0% (Base Model), 1% (Variant-1), 2% (Variant-2) and 3% (Variant-3). It was observed that the Variant-1 had provided better performance for Configuration A under the heat load of 125 W and 175 W in the melting process. During the solidification process for the Configuration B, Base Model had better performance than the variants with nano-fluids. Results from CFD simulations as well as experimental procedure were in good agreement for this research work.
Keywords- TESS, Melting - Solidification, CFD

I. INTRODUCTION

Energy is the backbone of all human activities on the earth. In recent years, energy demand has increased due to the high-energy consumption in different fields (e.g. Electricity Generation, Industry, Transportation, Household, etc). Fossil fuels have served and fulfilled all human needs from energy for long era, these fossil fuels caused huge damages for the environment that led to the most of the recent environmental problems, which are the global warming and the danger of ice melting in north and south poles. In addition, the prices of these fossil fuels increased in last years and it is expected to continue increasing in coming years because energy demand is increasing while fossil fuels in reserves are decreasing. Therefore, other sources of energy must be developed in order to take the role of fossil fuels.

Renewable energies are expected to play the major role for energy supply in the near future. Renewable energies have main characteristics that are the contrast of that for fossil fuels. Renewable energies are sustainable and do not cause any pollution for the environment while fossil fuels are not sustainable and cause an extensive pollution that damages the environment. Renewable energies are solar energy, wind energy, bio energy, geothermal energy, tidal energy and hydropower. Approximately all these forms of energy are hampered by their high costs. Moreover, solar energy, wind energy and tidal energy are characterized by their intermittent nature, as they are not available all the time. This intermittent problem can be solved by energy storage. Renewable energy plays an important role from the political point of view. Countries with no or minor energy resources from fossil fuels found the renewable energy as a very prestigious opportunity for a new era of dependency on their own renewable resources for energy instead of importing their energy needs from other countries.

Sina Lohrasbi et.al [1] had investigated the methods to optimize the discharging process of latent heat thermal storage system (LHTESS) with the help of V-shaped fins. In the discharging process, the expedition of the solidification process is critical and the authors had included the solidification expedition and maximum energy storage capacity as the primary variables in their study. The impact of thermo-physical properties of the PCM with the dispersion of nano-particles (TiO2) was studied by R. K. Sharma et.al [2]. They had considered Palmitic Acid as the PCM with 0.5, 1.3 and 5% mass fraction of TiO2 in their study. Nitesh Das et.al [3] had modeled the vertically oriented latent heat thermal energy storage system as 2-dimensional axi-symmetric in their CFD simulations. The melting process of PCMs were simulated using the enthalpy-porosity method. The inclusion of the Graphene in to the PCMs resulted in reduction of melting rate by upto 22%. The impact of the orientation – vertical and horizontal – in a shell-and-tube thermal storage system was studied by Saeid Seddegh et.al [4]. Based on the results from their study, they had concluded that the horizontal unit to be effective for the charging process, when the top half melts. However, the effectiveness of the horizontal unit to reduced when the bottom half melts during the charging process. Rasool Kalbasi et.al [5] had conducted optimization study for heat removal from portable electronic components with the help of thermal energy storage systems. They had compared the thermal performance for a rectangular and square shaped TESS for the identical operating conditions. They had identified that the rectangular TESS provided better performance in terms of melting time as compared to the square TESS. A mixture of Sodium Nitrate and Potassium Nitrate as the PCM in a thermal storage system that was under the natural convection effects was studied by J Vogel et.al [6]. In their study, the simulations were performed using the enthalpy-porosity technique. By this approach, the complexities that are associated with multi-phase simulations are avoided. A finite volume based numerical simulation for investigating the charging process in a horizontally placed tube was conducted by Kamal A R Ismail et.al [7]. The authors had developed the numerical solver for this 2-dimensional geometry. The results obtained from these simulations were compared against the experimental data for validation. For this transient simulations, the authors had identified 0.01 s as time-step size. D. Cano et.al [8] had studied the heat recovery from a hydrogen cycle's residual energy with the help of a tube-in-tube heat exchanger that utilized thermal energy storage system. They conclude that the countercurrent mode of operation resulted in efficient energy transfer in the tube-in-tube heat exchanger thermal energy storage system. Thermal conductivity enhancement for the Lauric Acid – to be used as PCM – was investigated by Sivasankaran Harish et.al [9]. The authors had added Graphene Nano-Platelets (GNP) of 5-10 nm in size with the Lauric Acid in order to enhance the thermal conductivity of the PCMs. The synthesis of Lauric Acid in to the porous Expanded Vermiculite (EVM) as form stable PCM was studied by Ruilong Wen et.al [10]. This resulted in Lauric Acid as PCM while Expanded Vermiculite (EVM) was acting as the supporting material. With this synthesis, the stability of PCM was found to be increasing. Reema Jadhav et.al [11 and 12] studied selection of Phase Change material, selection of nanomaterial and stability of nanomaterial. Numerical analysis of phase change material in details.

II. PROBLEM STATEMENT

A TESS of rectangular cross section with a dimension of 50 mm X 200 mm X 80 mm was considered for this research work.

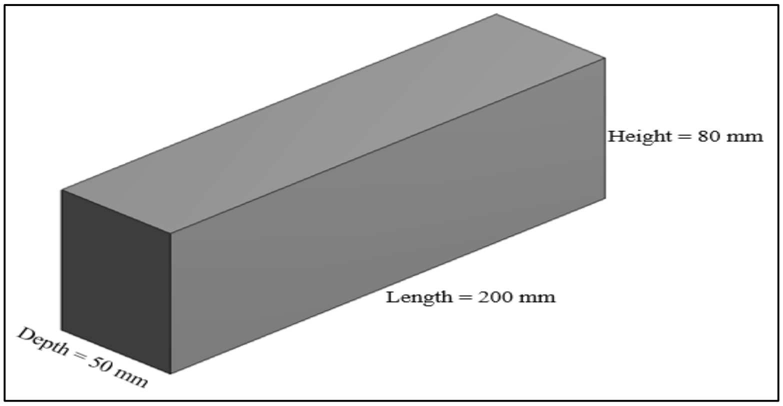

Fig. 1: Geometrical Description of TESS

This thermal energy storage system had been filled up with the phase change material (PCM) of paraffin wax at a solid state. The heat input to the TESS was supplied through the electrical energy in the experimental studies. For this project work, the two thermal loads were investigated 125 W and 175 W. This heat load was applied over a surface of 200 mm X 80 mm cross-section as shown in the following figure, colored in Blue.

Three configurations – Configurations A, B and C – were defined based on the thermal loads and thermal conditions. The heat supply area for the Configuration A and Configuration B were the same. But, for the Configuration C, the heat supply area was 100 mm X 80 mm, half of the heat supply area from Configuration A and B. With this partial heating for the identical heat supply, the PCM melting rate as well as melting time was expected to be influenced. And, investigation of this particular mechanism was one the primary objective of this research work.

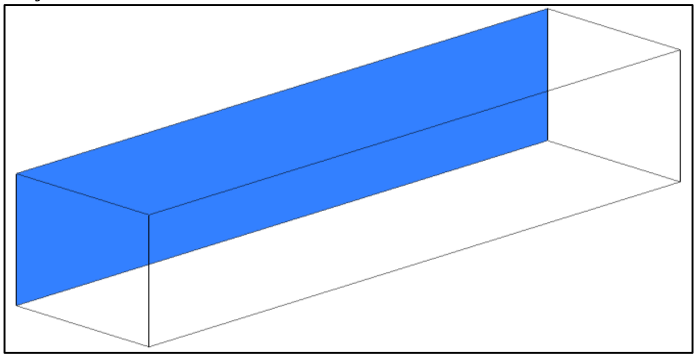

Fig. 2: Configuration – A

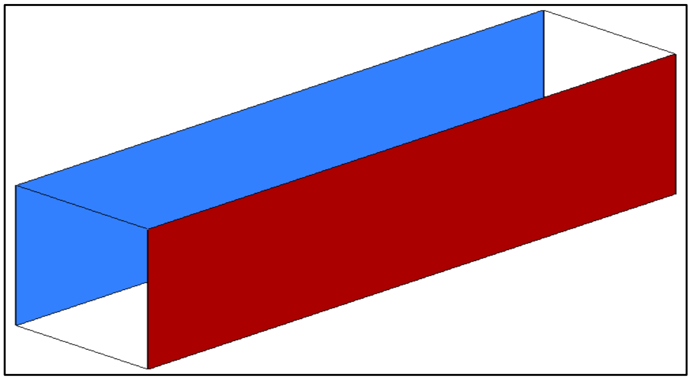

Fig. 3: Configuration – B

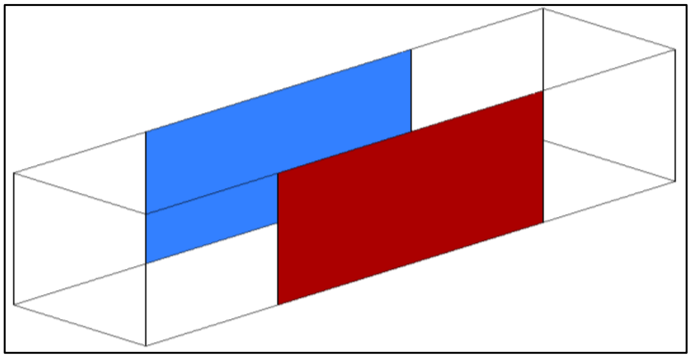

Fig. 4: Configuration – C

The major focus of this research was to study the factors that influence the melting and solidification process. One of such factor was the atmospheric conditions that surrounds the thermal energy storage systems (TESS). Heat loss from the TESS to the surrounding would delay the melting process while the melting could be accelerated if there had been a heat gain from the surrounding to the TESS. In this research work, this was studied by applying three thermal conditions.

Case 1: Adiabatic conditions on TESS boundaries

Under this conditions, the TESS was assumed to be sufficiently insulated that there were no heat transfer between the surrounding (atmospheric conditions) and the TESS.

Case 2: atmospheric temperature on the opposing wall

For these thermal conditions, the wall opposite to the heat supplying surface was applied with surrounding temperature (300 K) while the remaining TESS surfaces were sufficiently insulated to prevent any heat transfer between the surrounding and the TESS.

Case 3: Partial exposure

The impact of partial exposure to the surrounding was studied here, with half of the surface area as compared to the previous case was exposed to atmosphere (300 K).

III. EXPERIMENTAL STUDY

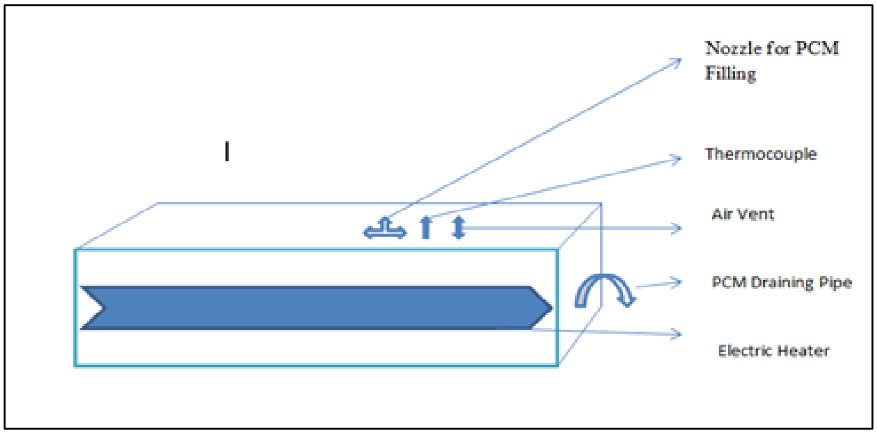

Fig. 5: Block Diagram of Experimental set up

An experimental apparatus has been designed and accurately measure the instaneous solid liquid interface evolution and temperature distribution within the PCM. The container was a rectangular enclosure with inside dimension 50mm width, 80mm height and 200mm depth. The right wall of the enclosure was held at constant temperature using 200W heater. The other five walls of the enclosure were insulated by using 25mm thick glass wool to avoid heat losses. Temperature of PCM measured by K- type thermocouple. Feed provided to fill the PCM. Air vent also available to remove air bubbles from the enclosure. Drain is available to just check out rectangular enclosure full filled by PCM or not.

Tests were carried out on the different thermal conditions and different heat load conditions (125W, 175W) to observe heat transfer enhancement effect on melting (charging) and solidification (discharging) performance of paraffin wax. Dispersion of nano-materials to improve thermal conductivity of paraffin wax in LHTES system was studied.

The mass of paraffin wax is filled in the rectangular container of LHTES system. By using temperature setting it has set 365K. Heater is started by supplying current. Melting process of paraffin wax is started due to supplying heat supply by using heater in rectangular container. There are 200 W heater available in system but heat load 125W provided using dimerstat and wattmeter. Time taken by melting process is recorded with interval of 5 minutes. By using drain we had confirmed Paraffin wax fully melted or not. The solidification process was started directly after the completion of melting period. The solidification process was initiated directly by disconnect the current supply to heater. The time required for solidification process of pure paraffin wax is measured and recorded with interval of 5 minutes. Procedure is followed to investigate the heat transfer enhancement in paraffin wax with dispersion of Al_2O_3 nanoparticles by mass concentration of 1%, 2% and 3% and different thermal conditions(configuration A, configuration B and configuration C) and heat load (125W and 175W).

IV. RESULTS AND DISCUSSIONS

In the following graph, the temperature at the measuring-point for the 4 variants at heat supply of 125 W during the melting process had been plotted.

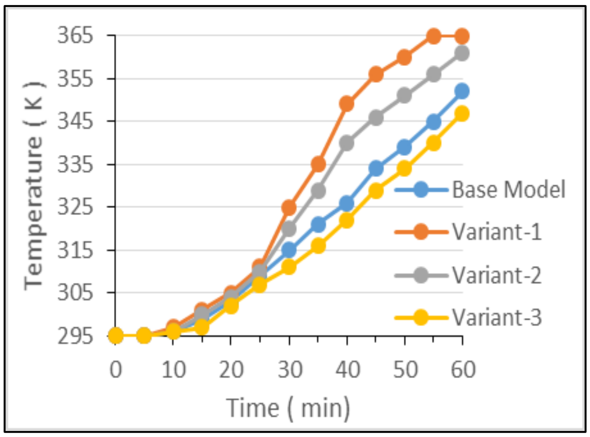

Fig. 6: Experimental temperature measurement during melting for Configuration A under 125 W heat supply

Variant-1 with 1% Al_2O_3 concentration had high temperature as compared to the remaining configurations. With the increase in the temperature, the melting process could be initiated at the earliest. So, the Variant-1 has better performance here.

In another observation, as the nano-fluid concentration was increased from 0% (Base Model) to 1% to 2% Al_2O_3, the temperature also increased at the measuring point. However, as the nano-fluid concentration was increased to 3%, there was a drop in the temperature.

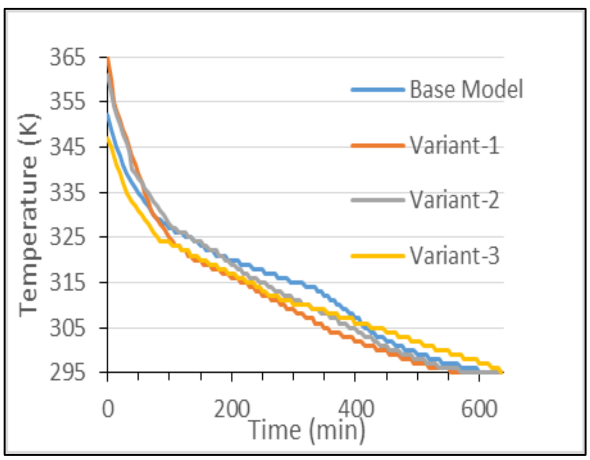

Fig. 7: Experimental temperature measurement during solidification for Configuration A under 125 W heat supply

During the solidification for the same operating conditions, the temperature for Variant-1 reduced sharply as compared to other variants. This would result faster energy observing capacity. For the geometrical configuration B, Variant-1 showed better performance during both the melting as well as solidification process as can be observed from the following two graphs.

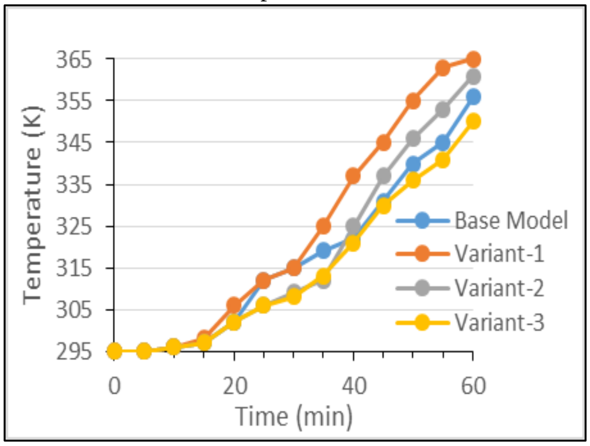

Fig. 8: Experimental temperature measurement during melting for Configuration B under 125 W heat supply

During the melting process, Configuration B had high temperature at the 15 minute observation time as compared to Configuration A. However, a sharp increase in temperature with the observation time was noted for the Configuration B whereas in the Configuration A, the rise in temperature was more linear.

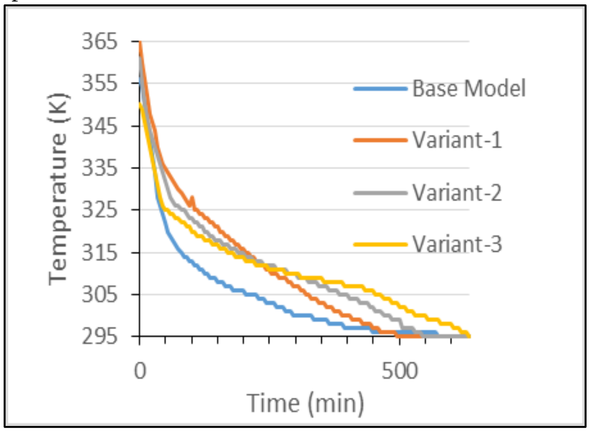

Fig. 9: Experimental temperature measurement during solidification for Configuration B under 125 W heat supply

In the solidification process, the temperature at the measuring-point was lower for the Base model in comparison to nano-fluid concentration (Variant-1 to Variant-3). So, even though the heat supply as well as Paraffin concentration remained identical, the solidification process was greatly influenced by the geometrical configurations (Configuration A and Configuration B).

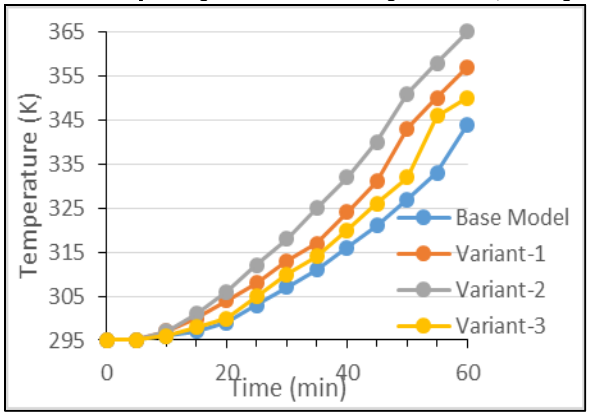

Fig. 10: Experimental temperature measurement during melting for Configuration C under 125 W heat supply

Variant-2 had high temperature at the measuring-point for the geometrical configuration C under the heat supply of 125 W. This was followed by Variant-1. For the Configuration C during melting process, Al_2O_3 concentration with the Paraffin resulted in higher temperature as compared to the Base Model (pure Paraffin).

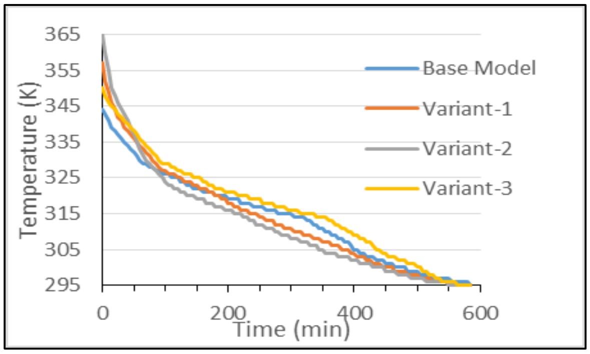

Fig. 11: Experimental temperature measurement during solidification for Configuration C under 125 W heat supply

In the solidification process, Variant-2 showed better performance in terms of heat rejection as can be observed in the above figure. The heat rejection from Varinat-3 was found to be slower in comparison to the remaining variants.

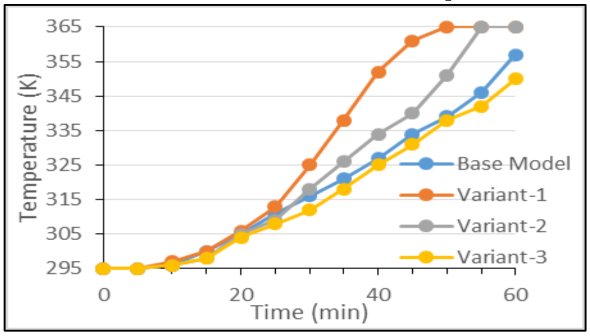

Fig. 12: Experimental temperature measurement during melting for Configuration A under 175 W heat supply

With the heat supply had been increased to 175 W, the performance of the nano-particle mixed Paraffin cases continue to show improvement over the pure=Paraffin (Base Model) for the Configuration A during the melting process. This was evident in the following graph.

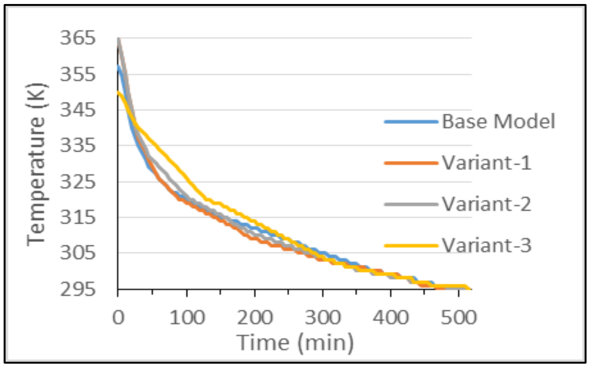

Fig. 13: Experimental temperature measurement during solidification for Configuration A under 125 W heat supply

During the solidification process, apart from Variant-3, the remaining variants showed nearly identical performance under this heat load.

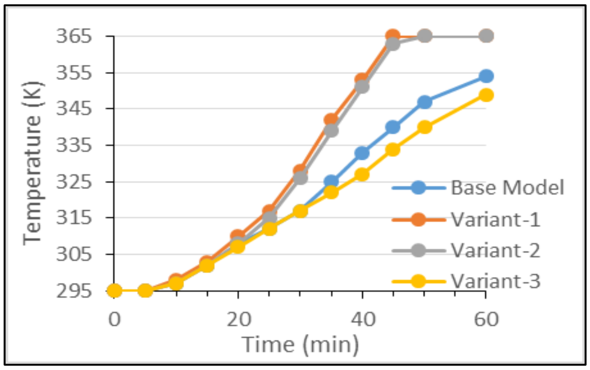

Fig. 14: Experimental temperature measurement during melting for Configuration B under 175 W heat supply

For the 175 W heat supply to the Configuration B, Variants 1 and 2 had distinct improvement in the performance while melting as can be seen in the above figure.

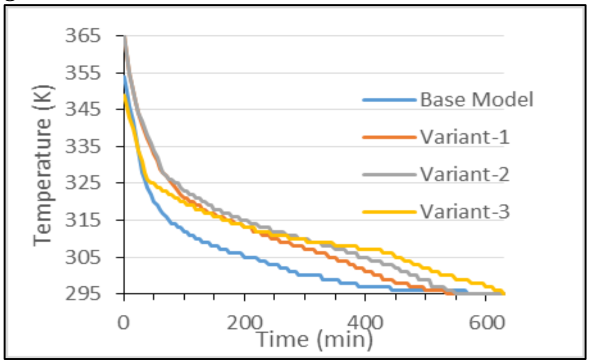

Fig. 15: Experimental temperature measurement during solidification for Configuration B under 175 W heat supply

However, the Base Model (pure Paraffin) provided better heat rejection characteristics for the Configuration B under the heat load of 175 W.

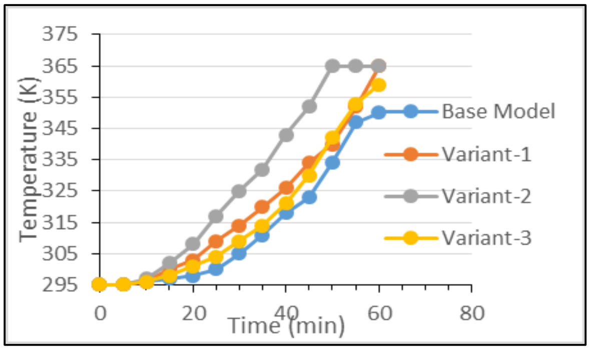

Fig. 16: Experimental temperature measurement during melting for Configuration C under 175 W heat supply

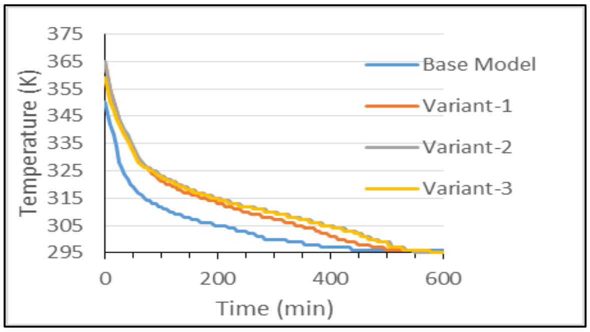

Fig. 17: Experimental temperature measurement during solidification for Configuration C under 175 W heat supply

A similar trend of Base Model having better heat rejection than the Paraffin mixed with Al2O3 was observed for Configuration C during the solidification process. This implies that the inclusion of nano-particles adversely affected the solidification process.

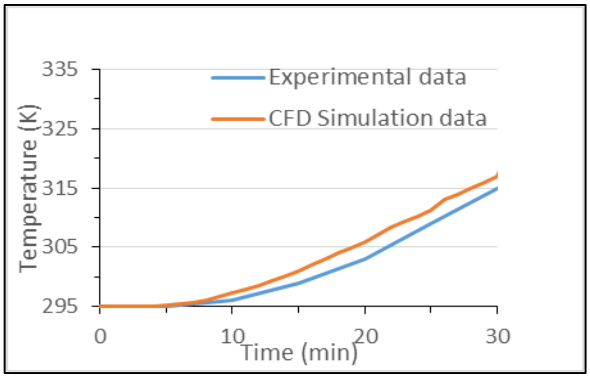

Fig. 18: Comparison of temperature at the monitoring-point during the melting process for Base Mobel under 125 W

The temperature predictions from the experimental procedure had been compared from the CFD simulation results in the following graphs.

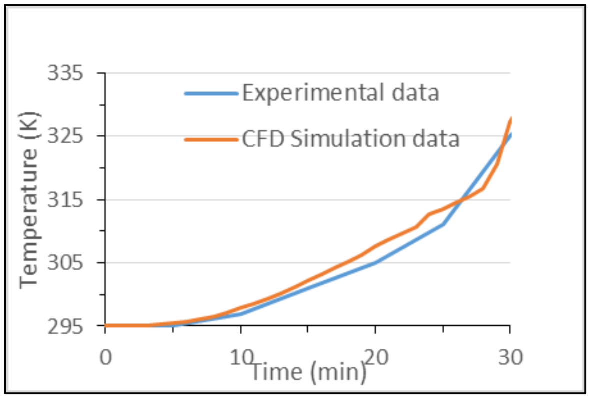

Fig. 19: Comparison of temperature at the monitoring-point during the melting process for Configuration A under 125 W

The detailed description of CFD simulation methods as well the results obtained from those simulations had been discussed in Reema Jhadhav [1].

As can be observed in the above figure, the temperature prediction at the monitoring-point between the experimental and CFD simulation procedure matches closely for the Configuration A. Similar trends for Configurations B as well as C were observed as shown in the following figures. From this it was concluded that the temperature predictions during melting and solidification process of Paraffin Wax from experimental and CFD simulations were in close agreement.

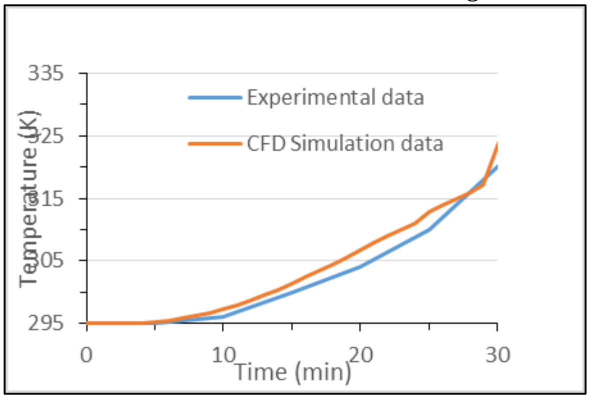

Fig. 20: Comparison of temperature at the monitoring-point during the melting process for Configuration B under 125 W

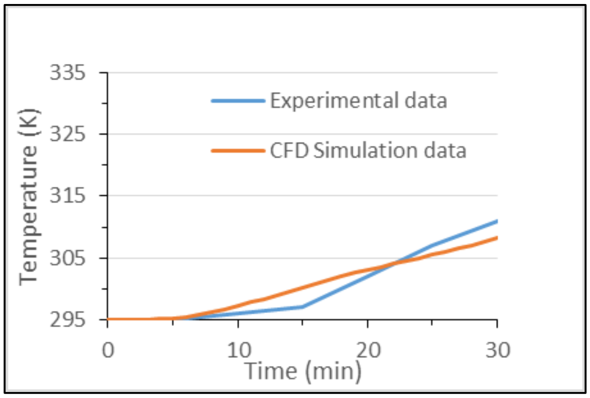

Fig. 21: Comparison of temperature at the monitoring-point during the melting process for Configuration C under 125 W

V. CONCLUSIONS

For the melting process under the heat load of 125 W, Variant-1 had shown superior performance for geometrical configurations A and B.

Under the same heat load for Configuration B, the Base Model (pure Paraffin) had shown better solidification characteristics as compared to the remaining variants.

Expectedly, for the heat load of 175 W, Variant-1, showed better melting performance.

The results between the experimental and CFD simulation methods were in agreement for this research work.

REFERENCES

[1] Sina Lohrasbi, Mofid Gorji Bandpy, D D Ganji,"Response Surface Method Optimization of V-Shaped Fin Assisted Latent Heat Thermal Energy Storage System during Discharging Process" Alexandria Engineering Journal, Volume 55, pp 2065-2076, 2016;
[2] R K Sharma, P Ganesan, V V Tyagi, H S C Metselaar, S C Sandaran, "Thermal Properties and Heat Storage Analysis of Palmitic Acid-TiO2 Composite as Nano-Enhanced Organic Phase Change Material (NEOPCM)" Applied Thermal Engineering, Volume 99, pp 1254-1262, 2016;
[3] Nitesh Das, Yasuyuki Takata, Masamichi Kohno, Sivasankaran Harish, "Melting of Graphene Based Phase Change Nono-Composites in Vertical Latent Heat Thermal Energy Storage Unit" Applied Thermal Engineering, Volume 107, pp 101-113, 2016;
[4] Saeid Seddegh, Xiaolin, Alan D Henderson, "A Comparative Study of Thermal Behavior of a Horizontal and Vertical Shell-and-Tube Energy Storage using Phase Change Materials" Applied Thermal Engineering, Volume 93, pp 348-358, 2016;
[5] Rasool Kalbasi, Mohammad Reza Salimpour, "Constructal Design of Phase Change Material Enclosure used for Cooling Electronic Devices" Applied Thermal Engineering, Volume 84, pp 339-349, 2015;
[6] J Vogel, J Felbinger, M Johnson, "Natural Convection in High Temperature Flat Plate Latent Heat Thermal Energy Storage Systems" Applied Energy, Volume 184, pp 184-196, 2016;
[7] Kamal A. R. Ismail, Fatima A. M. Lino, Raquel C. R. Da Silva, Antonio B. de Jesus, Louryval C Paixao, "Experimentally Validated Two-Dimensional Numerical Model for the Solidification of PCM Along a Horizontal Long Tube" International Journal of Thermal Sciences, Volume 75, pp 184-193, 2014;
[8] D. Cano, C. Funez, L. Rodriguez, J. L. Valverde, L. Sanchez-Silva, "Experimental Investigation of a Thermal Storage System using Phase Change Materials" Applied Thermal Engineering, Volume 107, pp 264-270, 2016;
[9] Sivasankaran Harish, Daniel Orejon, Yasuyuki Takata, Masamichi Kohno, "Thermal Conductivity Enhancement of Lauric Acid Phase Change Nano-Composite with Graphene Nano-Platelets" Applied Thermal Engineering, Volume 80, pp 205-211, 2015;
[10] Ruilong Wen, Zhaohui Huang, Yaoting Huang, Xiaoguang Zhang, Xin Min, Minghao Fang, Yangai Liu, Xiaowen Wu, "Synthesis and Characterization of Lauric Acid/Expanded Vermiculite as Form-Stabilized Thermal Energy Storage Materials" Energy and Buildings, Volume 116, pp 677-683, 2016;
[11] Reema R. Jadhav, Sameer. Y. Bhosale and A. V. Waghmare "Heat Transfer Enhancement during Charging and Discharging of Pure Paraffin Wax with Dispersion of Nanomaterial" International Engineering Research Journal (IERJ) Special Issue Page 788-792, Ju
[12] Reema Jadhav, Prof.S.Y.Bhosale, Prof. A.V. Waghmare and Prof. H.N. Deshpande "NUMERICAL ANALYSIS OF MELTING MECHANISM IN A RECTANGULAR THERMAL ENERGY STORAGE" JETIR (ISSN-2349-5162) August 2017, Volume 4, Issue 08.