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A comparative study of the effect of wall heat flux on melting and heat transfer characteristics in phase change material thermal energy stores arranged vertically and horizontally

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Abstract. An experimental investigation was carried out to analyse the heat transfer characteristics during melting of phase change material (PCM) RT44HC in thermal energy stores arranged vertically and horizontally to assess the effect of different values of wall heat flux on the development of melt fraction, solid/liquid interface location and temperature distribution. A test cell consisting of a rectangular cross section enclosure was constructed from polycarbonate sheet, copper plates and mica heaters. Both left and right sides of the store were subject to uniform wall heat fluxes of 675, 960 and 1295 W/m². Thermocouples were used to measure the temperature at different locations inside the phase change material (PCM) and on the surface of the copper plates. The study included visualization of the melting process and measurement of the temperature distribution at the vertical mid-plane of the store. Images of the melting process were analysed with an image processing technique to determine the melt fraction at selected times. It was observed that as the heat flux input increased the total melting time reduced, the reduction in melt time for the horizontally oriented store was about 12.5-15.0 % when compared to the vertically oriented store as a result of the intensification of natural convection flows. Heat conduction was the dominant mode of heat transfer during the early stage of melting, followed by short transition period after which convection dominates during the rest of the melting process. The experimental results provide a set of benchmark data for validation of numerical codes.

Keywords: Phase Change Heat Transfer, Natural Convection and Melting.

1. Introduction

Thermal energy storage (TES), specifically latent heat thermal energy storage using phase change materials (PCM) has a greater heat storage capacity for a given volume when compared with sensible heat storage systems if operational temperatures are close to the phase transition temperature. They offer the advantage of near-isothermal heat storage and release processes. They may have a role to play in supporting the achievement of future decarbonisation of heat [1] as they can increase utilisation of time constrained heat production, e.g. from solar based technologies that only generate heat during daytime when exposed to sufficient solar radiation. PCMs have been used in many fields such as solar energy storage systems, space heating and cooling and thermal performance improvement of building envelopes. Predicting the temperature distribution, melt fraction, rate of heat transfer and the stored energy during the PCMs melting/solidification, are the most important parameters to analyse when trying to maximize the performance of thermal energy storage system using PCMs [2].

When used with a solar thermal system to ensure long-term thermal performance of any PCM thermal store, the size and shape of the PCM store must correspond to the required energy storage capacity, with the melting temperature of the PCM selected to make best use of the daily insolation at a given location, and the solar collector characteristics [3]. Common shapes of PCM stores which have been used in different applications are cylindrical or rectangular stores and spherical capsules. A survey of

previously published papers dealing with LHTES reveals that rectangular stores are commonly employed for PCMs due to the number of different engineering applications requiring thermal engineering storage [4]. Constant wall flux (CWF) and Constant wall temperature (CWT) are the main boundary conditions which are applied to the stores being representative of applications including waste heat recovery, solar thermal storage and cooling systems for electronic devices [5], [6], [7] and [8].

H.El Qarnia [9] carried out a numerical investigation of the heat transfer by natural convection during melting of n-eicosane phase change material contained in a rectangular enclosure. The wall was heated by three discrete protruding heat sources (simulating electronic components). The numerical results show the impact of key parameters (Rayleigh number, heat sources positions and aspect ratio) on the cooling capacity of a PCM based heat sink. Z. Gong et al [10] simulated free convection melting of phase change material in a rectangular cavity with isothermally heated vertical walls using the streamline up wind Petrov-Galerkin finite element technique. The enthalpy-porosity model was employed to account for the development of the flow at the solid/liquid interface. The results showed that inverting the store at an appropriate time during the melting process was an effective technique for enhancement of free convection in the liquid phase change material, with a 50 % increase in the energy charge rate during the melting process obtained. J. Zhao et al [11] carried out a 2-dimensional visualization experiment for the contact melting process of a phase change material in a rectangular cavity at different tilt angles ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$). The results show that the shortest total melting time was when the tilt angle is 60° .

Although many researchers have studied the role of natural convection during the melting process in rectangular stores as mentioned above, there is a lack of knowledge regarding how the arrangement (vertical or horizontal) and wall heat flux affect phase change duration

In the present paper, the melting process of a phase change material in a rectangular store is investigated with heat supplied through the left and right vertical walls at 3 constant heat flux levels. Temperatures are measured within the PCM and at the heating plate using 18 thermocouples. The movement of the solid/liquid interface and the melt fraction are determined by taking images of the PCM through the transparent front wall of the store.

2. Experimental apparatus

A rectangular cross section store filled with phase change material RT44HC [12] that can be subjected to uniform wall heat flux from both left and right vertical sides has been fabricated from transparent polycarbonate to allow the accurate measurement of the effect of input wall heat flux intensity on the transient solid-liquid interface movement and temperature distribution within the PCM.

The developed experimental test rig shown in Figure.1 comprises the rectangular PCM store, insulation, power supply, voltage transformer, thermocouples, temperature control unit, data acquisition system, DSLR camera and a computer

The rectangular store was formed from 12 mm thick transparent polycarbonate sheet [13] which allows observation of the melt fraction of the RT44HC with time. The internal dimensions were 176 mm height, 200 mm width and 100 mm depth (vertical store) and 76 mm height, 200 mm width and 200 mm depth (horizontal store) as shows in Figure.2. Thin 2 mm copper plates [14] with area of 100 x 200 mm form the right and left vertical sides of the store to which Mica heating pads are mounted to provide uniform wall heat flux to the plates.

In order to record the development and movement of the solid/liquid interface during melting, a Canon 24.2 Megapixel digital camera, Canon EOS 80D [15] with a 18-55mm lens was used to take photographs every 30 minutes. A light source behind the store was used to make the solid/liquid interface more visible.

12 T-type thermocouples formed from 0.26 mm diameter wires with a calibrated accuracy of $\pm 0.1^\circ\text{C}$ were placed in 4 columns and 3 rows in the vertical middle plane of the store as shown in Figure 3. These were connected to a datalogger and temperatures recorded during the melt process.

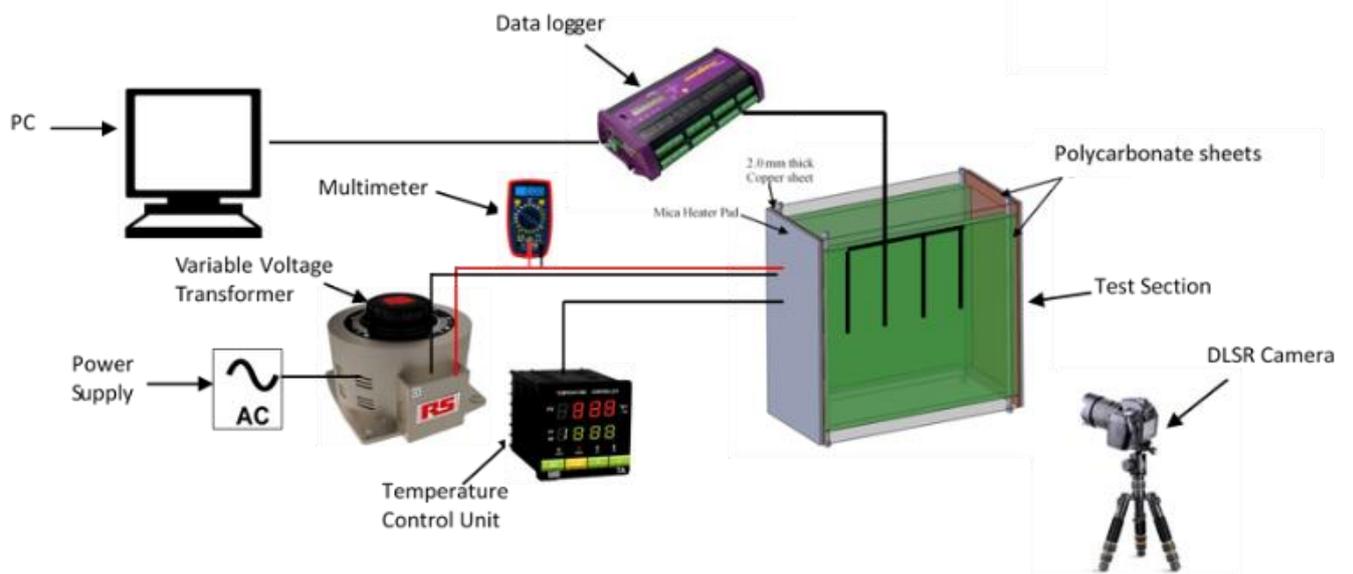


Figure 1. Schematic diagram of the experimental test rig

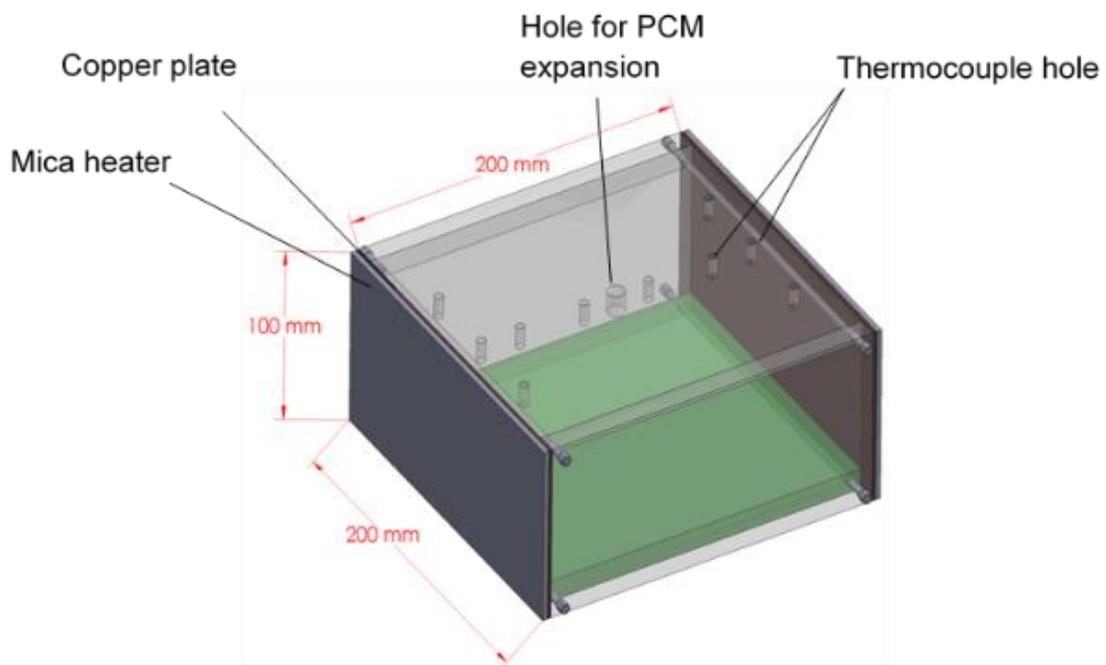


Figure 2. Isometric projection of the horizontal rectangular store

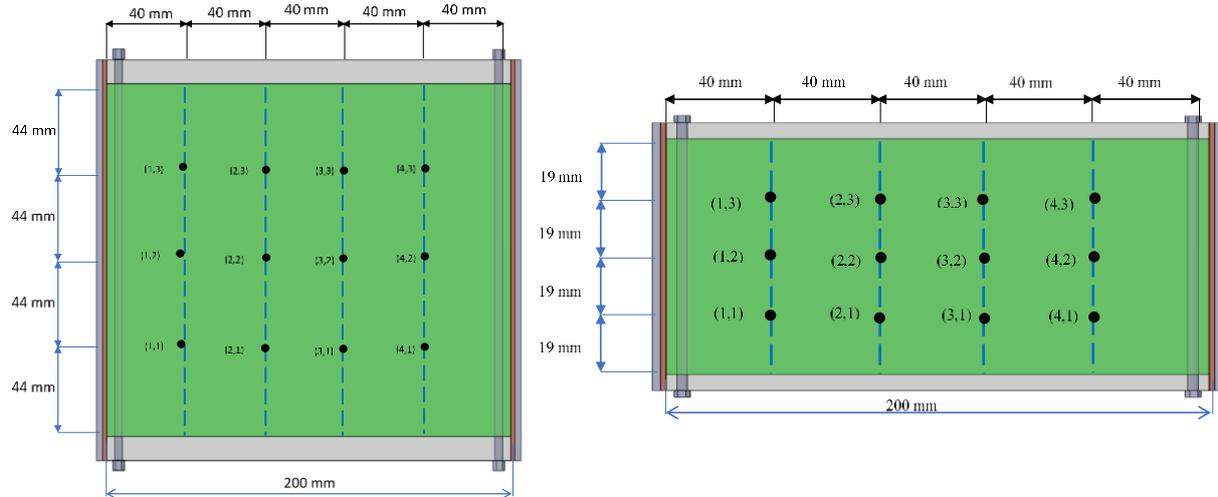


Figure 1 Thermocouples locations in the mid plane of the vertical and horizontal PCM stores.

3. Melt front evolution

To evaluate the percentage melt fraction and the location of the moving solid/liquid interface, a colour digital image was taken of the store front wall every 30 minutes. The colour image was converted to a binary image which contains either zero or one corresponding to black and white pixels in a two-dimensional matrix. Using the MATLAB image processing toolbox [16] the instantaneous liquid fraction was calculated based on the number of zeros and ones. The percentage liquid fraction was evaluated by dividing the number of zeros by the total number of array elements in the matrix.

4. Results and discussion

1.1. Development of the solid/liquid interface

Details of melt front development during the melting process in the rectangular store reveal the heat transfer characteristics during the process. Figure. 4 presents a series of photographs obtained during the melting of RT44HC in the vertically and horizontally oriented rectangular stores at time intervals of 30 min with a uniform wall heat flux of $q''=960 \text{ W/m}^2$ imposed at the left and right walls. In these photographs, white and black areas represent the solid and liquid phases, respectively. Symmetry is observed in the entire domain for both stores. Melting can be characterized into four distinct regimes, (I) conduction dominated melting regimes [0-60 minutes], (II) mixed convection-conduction melting regime [90-180 minutes], (III) convection melting regime [210-240 minutes], (IV) variable height (or shrinking solid melting regime) [270-360 minutes]. The solid/liquid interface was almost vertical at the initial stage of heating because the region influenced was adjacent to the heating surfaces and the heat transfer was predominantly by conduction. This mode of heat transfer prevails while the viscous forces oppose the fluid motion, the melt front remains almost uniform in width and parallel to the hot wall (Figure. 4 a and b). With the elapse of time, more RT44HC was melted, and the hotter liquid paraffin flowed upwards due to buoyancy, when the buoyancy force becomes large enough to overcome the viscous force natural convection is initiated in the liquid region. The resulting convection currents lead to a change in the profile of the solid/liquid interface at the top of the melt layer. The buoyancy driven fluid circulation creates a concave curve at the top of the melt front (Figure. 4 c-e). As melting continues, natural convection flow strengthens and the effect on the melt front becomes more pronounced. The increasing curvature of the melt front in the upper part of the store provides evidence of this. With increasing melt layer thickness, a single dominant vortex in the liquid PCM is established. In the lower part of the vertical store, the shape of the interface is almost linear, its angle of tilt increasing as the solid PCM shrinks. This pattern of melting continues until the solid PCM melts completely.

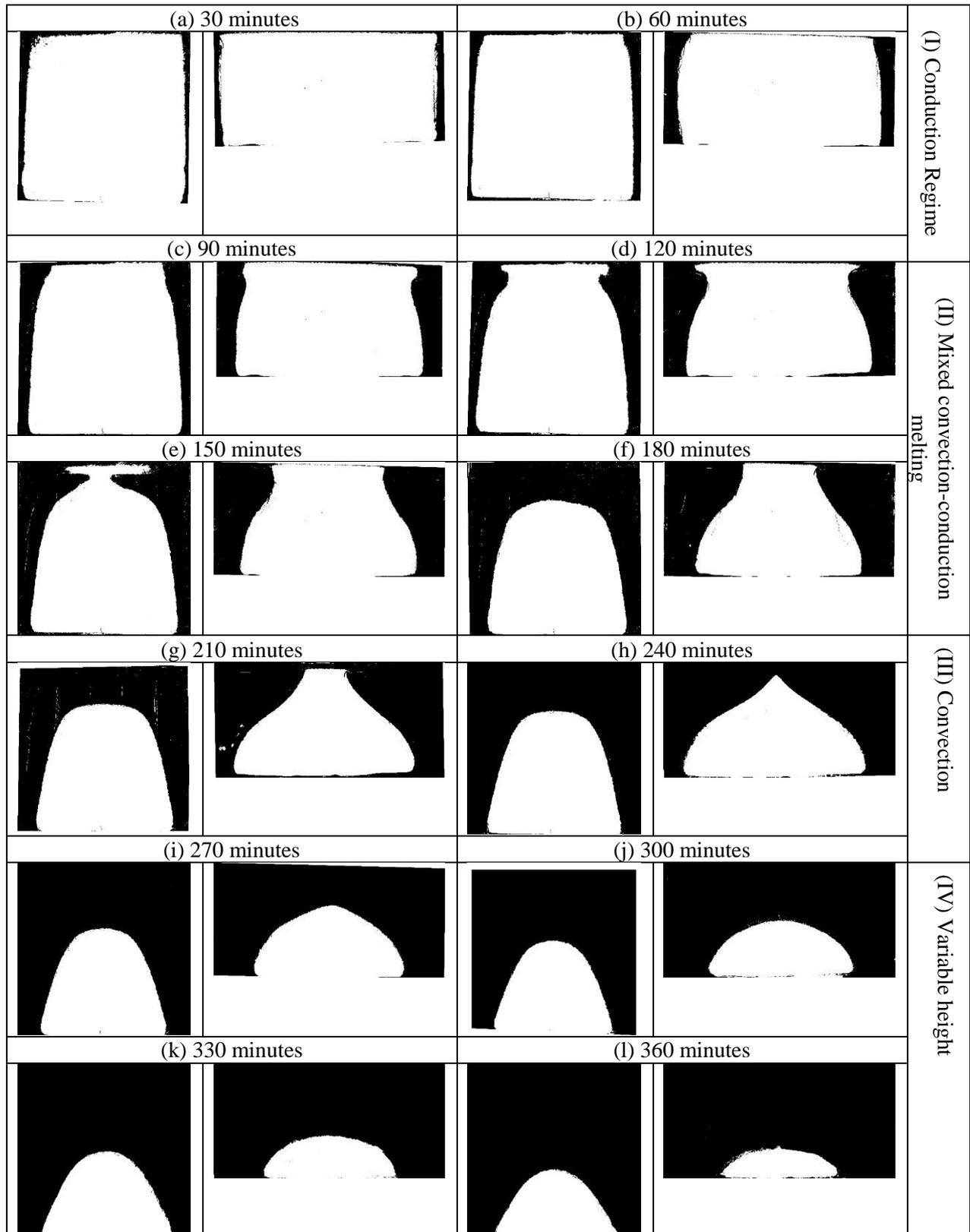


Figure 4 Melting front progression in RT44HC in the vertical and horizontal rectangular stores for a wall heat flux $q''=960 \text{ W/m}^2$, black regions represent the PCM in the liquid state and the white regions are the PCM in the solid state

The melt fraction calculated at 30-minute intervals for different values of wall heat flux are presented in Figure.5. It can be seen as the wall flux increases, the time for total melting decreases, this is expected due to the increased rate of heat transfer to the store. The increased power input also led to an

increase in the average temperature of both the PCM and the heating surface. For the vertical store, increasing the input power from 675 W/m^2 to 960 W/m^2 to 1295 W/m^2 , reduces the total time for the melting process by 27.27 % and 43.18 % respectively. For the horizontal store, the time for completion of the melting process decreases from 420 min to 330 min as the wall heat flux increase from 675 W/m^2 to 960 W/m^2 and from 570 min to 420 min as the wall heat flux increase from 960 W/m^2 to 1295 W/m^2 .

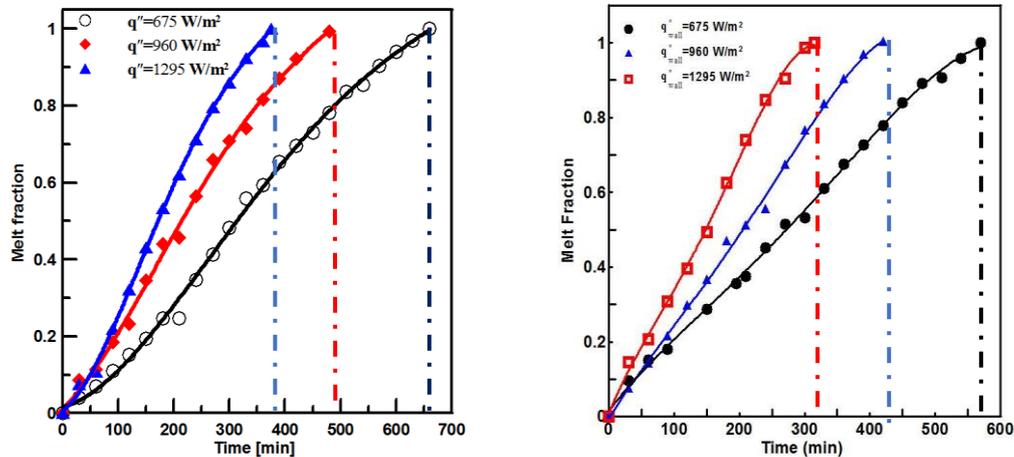


Figure 5 Melt fraction development versus time for 3 wall heat flux levels

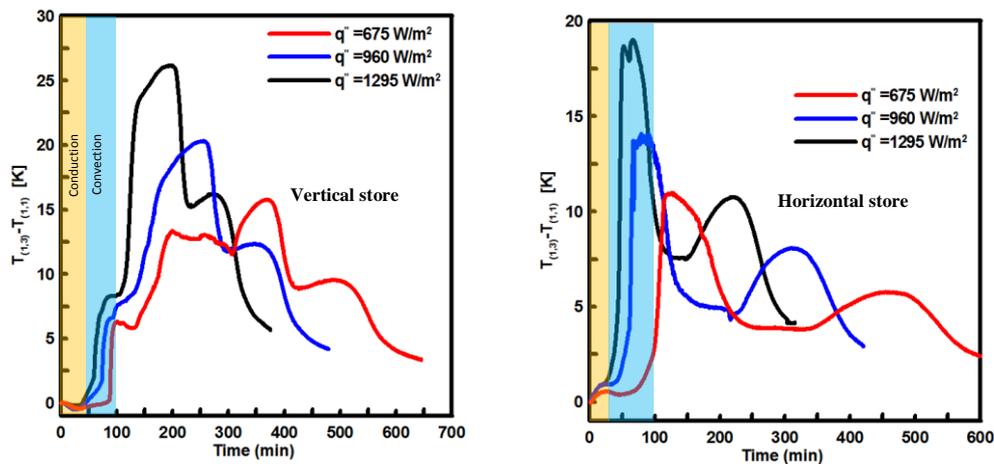


Figure 6. The measured time dependent temperature difference recorded by thermocouples located at position $T_{(1,3)}$ (top) and $T_{(1,1)}$ (bottom) for 3 wall heat flux levels

Figure 6 presents the differences in temperature recorded by thermocouples located in positions $T_{(1,3)}$ (top of the vertical mid-plane of the store) and $T_{(1,1)}$ (bottom of the vertical mid-plane of the store) for the three values of wall heat flux for vertical and horizontal stores.

In the first 50 minutes, the rise in the measured temperature differences are similar for all flux values due to conduction in the solid PCM being the main heat transfer mechanism. At $t=50$ minutes, the thermocouple in the upper location shows a much greater temperature rise than those in the bottom location due to the onset of natural convection in the melted liquid PCM, which increases the local heat transfer rate between the solid and liquid PCM in the upper section of the store. The value of the increase in temperature difference is an indicator of the strength of the local heat transfer rate at the solid/liquid interface. The higher values of wall heat flux increase the rate at which the temperature difference is established suggesting a faster onset of convection and a higher rate of convection at higher wall heat fluxes. When the RT44HC melted fully, natural convection increased mixing in the liquid paraffin, leading to the gradual decrease in the temperature difference.

5. Conclusion

An experimental investigation was performed to examine the heat transfer during the melting process of phase change material (PCM) RT44HC in a vertically and horizontally oriented rectangular cross section store to understand the effect of different values of wall heat on the development of the melt fraction, solid/liquid interface location and temperature distribution. The images of the melting process were analysed using an image processing technique to measure the melt fraction development with time. The following conclusions are drawn:

- Conduction is the dominant mode of heat transfer during the early stage of melting which is followed by short transition period before convection dominates the remainder of the melting process.
- It was observed at higher values of wall heat flux, the total melting time reduced.
- The reductions in melting time for the horizontally oriented store is about 12.5-15.0 % when compared to the vertical oriented store as a result of the intensification of natural convection flows.

Finally, the experimental measurements provide a set of benchmark data suitable for validation of numerical simulation tools

6. Acknowledgements

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