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Experimental investigation of heat transfer characteristics in a vertical multi-tube latent heat thermal energy storage system

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Abstract

A vertical multi-tube thermal energy storage system using commercial phase change material (PCM) RT60 has been experimentally investigated. The selection of PCM and experimental rig configurations seek to be suitable to serve as a household thermal energy storage application for the solar energy application. PCM is filled at the annulus of the shell of the cylindrical container and the tubes while heat transfer fluid (HTF) is circulated inside tube to deliver or retrieve thermal energy to or from PCM. Five HTF tubes are configured to achieve heat transfer enhancement in this vertical latent heat thermal energy storage system. Thermocouples are installed at four horizontal cross-sections of the storage unit and at every cross-section thermocouples are positioned at different radial and angular coordinates to capture the transient temperature changes of PCM during the charging and discharging processes. HTF inlet temperature was set at 80 °C in the charging process and 10 °C in the discharging process. The same HTF volume flow rate of 20 L/min was applied in the consecutive charging and discharging processes. The comparative analysis of PCM temperature measurements along the axial, radial and angular directions was conducted. The experimental results showed that natural convection-controlled heat transfer during the charging process, while PCM solidified faster at the bottom liquid PCM region during the early stage of discharging, afterwards conduction dominated heat transfer mode. The analytical study and experimental data stated that the arrangement and positions of HTF tubes have a notable effect on the thermal response of the latent heat thermal energy storage system during the charging and discharging processes.

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Keywords: Phase change material; multi-tube; shell-and-tube; latent heat; natural convection; thermal energy storage

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1. Introduction

Renewable energy has globally made positive impacts on economy and environment, and plays a critical role on the security and diversity of energy supply. However, the availability of most renewable energy resources is variable and uncontrolled, making it essential and attractive to integrate an effective energy storage component with the renewable energy harvesting system. The thermal energy storage system using phase change material (PCM) features higher thermal storage density and nearly constant operating temperature, hence, the wide applications of the latent heat thermal energy storage (LHTES) system are highly expected. But low thermal conductivity of most PCM leads to the undesirable charging and discharging time rates of the LHTES system. Researchers have put huge efforts to improve heat transfer inside the PCM using different enhancement techniques in the LHTES system. Among the various system configurations, the shell-and-tube heat exchanger has continually attracted researchers' interests due to its promising high efficiency and diverse arrangements of PCM and heat transfer fluid (HTF). The heat transfer enhancement techniques employed in shell-and-tube LHTES systems include embedding high conductive additives into PCM [1-3], finned tubes [4, 5], optimized PCM arrangement [6, 7] and multi-tubes [8-10].

Agyenim et al. [11] studied four configurations of the LHTES system, namely, the singular tube, longitudinal finned, circular finned and multi-tube systems. The experimental results showed that the multitube system performed best during the melting process but observed the obvious subcooling in the solidification process. Whereas the longitudinal finned configuration was recommended for the discharge process. Later the same research team [8] studied thermal performance of two horizontal shell-and-tube systems, one was configured with four inner HTF tubes and another with a single HTF tube. The temperature measurements along axial, radial and angular directions were analysed and compared. The results showed that both the multitube and single tube systems have the greatest temperature gradient in the radial direction. The experimental study revealed that separated convective regions formed in the multi-tube system leads to different solid-liquid front shape and more complex liquid PCM flow pattern, compared with the single tube system. Esapour et al. [9] numerically examined the melting characteristics of a horizontal shell-and-tube application with HTF flowing through both the outer tube and inner tubes. The numerical study defined four cases with different inner tube numbers of 1, 2, 3, and 4 and investigated the effects of tube number and HTF flowing parameters on thermal behaviour of the systems by comparing PCM temperature, liquid fraction and melting times in the cases. It concluded that adding inner tubes effectively increased the heat flux at the lower region of the shell and thereby reduced the total melting times. Later Esapour et al. [10] studied the effect of the inner tubes arrangements and found that the distribution of inner tubes significantly influenced the formation of PCM flow vortices thereby affecting the melting process.

The multi-tube LHTES system studies reviewed above are all horizontally configured and Seddegh et al. [12] concluded that for a shell-and-tube system, thermal responses of the horizontal and vertical units are significantly different during a melting process. Moreover, Agyenim et al. [8] summarized two approaches employed by researchers to study the multi-tube shell-and-tube system, one is the theoretical model of simplifying the multi-tube physical system to a single tube system and another is the numerical solution of calculating a zone within a cross-section of the multi-tube system. Based on their experimental study, Agyenim et al. stated that further validations are needed for the theoretical model of employing a single tube system to represent the multi-tube system. The present study investigates a vertical shell-and-tube experimental setup with five inner HTF tubes configured to achieve the higher heat transfer rate between PCM and HTF. The five inner HTF tubes are arranged in such a way that one tube concentrates with the central axis of the cylindrical storage unit and the other four outer tubes rotate about the central axis by an equal angle interval of 90 degree. The experimental study of thermal characteristics and heat transfer mechanism of such a system serves as the starting point to investigate the optimal arrangement of the multi-tube LHTES system.

2. Experimental setup

2.1. Apparatus and PCM

Fig. 1a shows the schematic drawing of the experimental system which consists of a charging loop and a discharging loop. Two 2.4 kW electric immersion heaters with thermostats for temperature control are installed in the hot water tank with a volume of 108 L. For a charging process HTF (water) from the hot water tank is circulated by a vertical centrifugal pump to the shell-and-tube LHTES component to melt the PCM, then flows back to the hot water tank.

A 20 kW chiller maintains the cold water at a required temperature in the cold tank with a volume of 1575 L. For a discharging loop HTF is circulated from the cold water tank by a horizontal centrifugal pump to the shell-and-tube heat exchanger to solidify the PCM. A positive displacement flow meter is installed at the heat exchanger inlet to measure the volume flow rate of HTF. Type T thermocouples are used to measure the water temperatures at the inlet and outlet of the heat exchanger.

The heat exchanger container is made of transparent polypropylene with a thickness of 6 mm and thermal conductivity of 0.1 w/m·K. The inner diameter and height of the vertical cylindrical container is 0.35 m and 0.5 m, respectively. Five vertically-oriented copper tubes with outside diameter of 19.05 mm and a thickness of 1.02 mm go through the container as the HTF tubes. The positions of HTF tubes are shown in Fig. 1b. The storage unit contains 35 kg PCM which is stored between the inner tubes and the cylindrical shell. The outer surfaces of the container are insulated by 25 mm thickness insulation sheets with a thermal conductivity of 0.036 W/m·K.

Type T thermocouples with an accuracy of ±0.2 °C and sheath diameter of 1.5 mm are employed to measure PCM temperatures in the test. Fig. 1b shows the positions of the thermocouple sensors in the storage unit. The thermocouple sensors are fixed at levels 1-4 to measure PCM temperature variations along the height of the container during the experiments. At each height level, five thermocouples A, B, C, D, E with varying radial and angular positions are deployed in order to investigate effects of the HTF tube arrangement on PCM temperature variations at the horizontal cross-section of the storage unit. The cables of all thermocouples and the flow meter are connected to multiple channels temperature data loggers which are plugged into the computer to record the test data.

The PCM used by the experiments is paraffin wax RT60 which is the commercial product from Rubitherm GmbH with melting temperature range of 55-61 °C. Its latent heat of fusion, specific heat and thermal conductivity are 130,000 J/kg, 2000 J/kg·K and 0.2 W/m·K, respectively. The density of liquid PCM(at 80 °C) is 770 Kg/m3 while that of solid PCM(at 15 °C) is 880 Kg/m3 [13].

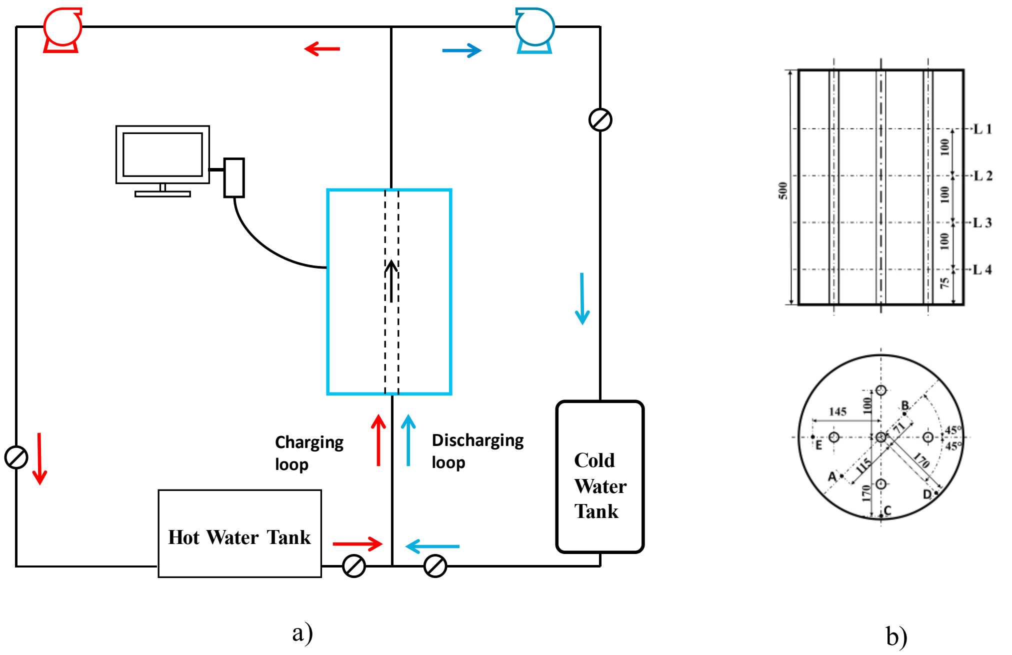

Fig. 1. (a) the schematic drawing of the experimental system; (b) locations of thermocouples and HTF tubes(unit: mm).

2.2. Experimental procedure

The initial PCM temperature was set to around 15 °C by flowing cold water through the HTF tubes. The water was heated up to 80 °C for the charging process in the hot water tank. Then, the charging process was launched by circulating the hot water with a flow rate of 20 L/min from the bottom end of the storage unit to investigate the thermal performance of the vertical multi-tube LHTES system. Following the total melting of PCM and the stabilized temperature readings of all the thermocouples, the discharging process was performed by injecting water with temperature of 10 °C and a flow rate of 20 L/min from the bottom end of the storage unit to retrieve the thermal energy. The discharging process was finished when PCM was totally solidified and the temperatures of solid PCM stabilized.

3. Results and discussion

3.1. Charging process

3.1.1. Temperature evolution at the height levels

Fig. 2(a-e) shows the PCM temperature variations over height levels at thermocouple group A, B, C, D, and E of the cylindrical storage unit during the charging process. In each of the thermocouple groups PCM temperatures initially increase by almost the same rate across the height levels. The temperature curve slopes of groups C and D are more flat at this stage. This reflects that thermal conduction along the radial direction dominates heat transfer mode in the solid PCM as the temperature increasing rates do not relate to the height levels and groups C and D are more far away from HTF tubes along the radial direction. With the charging process continuing, temperature curves in the every thermocouple group are observed to diverge, being dependent on height levels. This can be interpreted by the continuing expansion of the individual molten layer formed along the surface of each HTF tube leading to the emergence of natural convection flow, transporting more energy to the top region of the PCM, in turn resulting in higher temperature recordings even for solid PCM at the higher level behind the solid-liquid front. According to Fig. 1b, at each height level thermocouple D is the most far away from HTF tubes and expected to indicate when this level is melted totally. Temperature profile of thermocouple D in Fig. 2d shows that at the level 1, after 6.1 hours charging separated PCM liquid layers formed along HTF tubes merge into a whole liquid pool, which then expands downwards until PCM totally melts at the charging time 26.0 hours. Multiple heat sources enhance the heat transfer rate and result in complex shape evolution of solid-liquid front during the PCM melting process. For every group of thermocouples, temperature plots have similar shape across the height levels. The thermal characteristics of the PCM melting progress are highly influenced by the liquid PCM convection flow.

3.1.2. Temperature variations in the cross-section

Fig. 3(a-b) presents the comparison of the PCM temperature records at three position pairs, A to B, C to D, and C to E at level 2 during the charging process. The comparisons make sense upon the rotational symmetry of the storage unit and the assumption that each of five HTF tubes has the same flowing and thermal conditions during the tests. Temperatures of positions A and B which are at different radial distances from the central HTF tube are considered to be influenced by three HTF tubes adjacent to A and B, respectively. While the temperature comparison of positions C and E reflect the effect of the outer tube on the PCM section between the outer tube and the inner surface of the storage container. Moreover, the temperature plot of positions C and D presents the thermal response difference along the angular direction resulted from the arrangement of multiple HTF tubes. At a horizontal cross-section, the distances to HTF tubes determine the melting sequence but when the whole level is melted the radial temperature gradients across this level decrease gradually. This can be observed in Fig. 3 that the temperature differences between position pairs A to B, and C to D drop to being very small once liquid PCM temperatures stabilize. This indicates when the whole liquid PCM pool forms at a height level, thermal stratification emerges in the liquid PCM region, preventing the natural convection flow from circulating up to the height level. Moreover, the temperature recordings in Fig. 3 tell that as expected, position of the thermocouple D is last melted, indicating the lower melting rate at periphery section of PCM in the container. This can be explained by two reasons: the periphery section of PCM is farther away from heat sources and the heat loss to outside of the container.

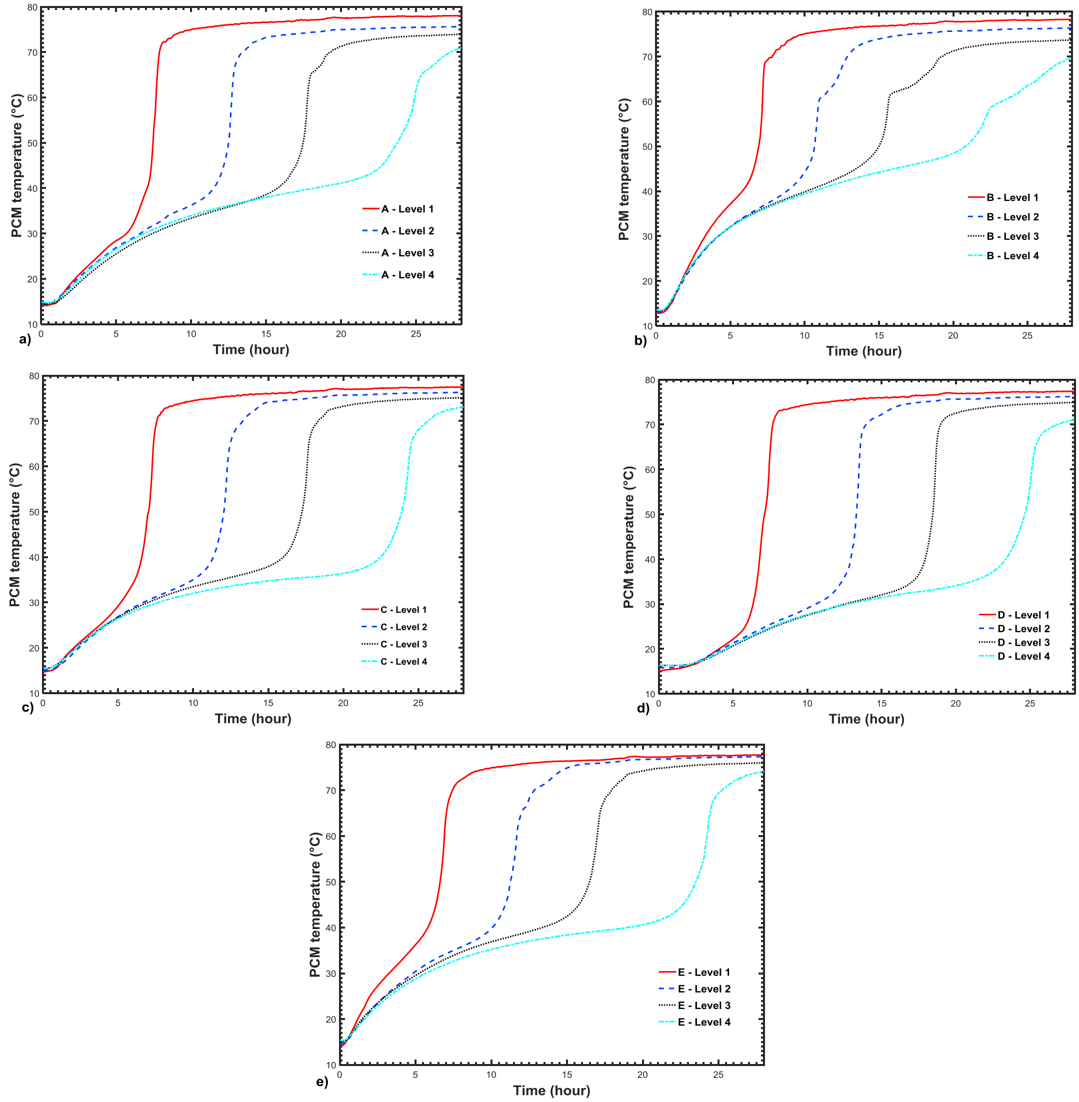

Fig. 2. (a) PCM temperature variations over time at position A during the charging process; (b) PCM temperature at position B; (c) PCM temperature at position C; (d) PCM temperature at position d; (e) PCM temperature at position E.

The comparisons indicate that the locations and arrangement of HTF tubes play an important role on the PCM temperature evolution at the horizontal cross-section, prompting the importance of optimizing HTF tube arrangements for the multi-tube configuration.

3.2. Discharging process

3.2.1. Temperature evolution at the height levels

Fig. 4(a-e) presents the PCM temperature variations over time at positions A, B, C, D, and E of the cylindrical storage unit during the discharging process, which was performed with HTF inlet temperature of 10 °C and flow rate of 20 L/min, immediately following the completion of the charging process. It took around 46 hours for PCM to

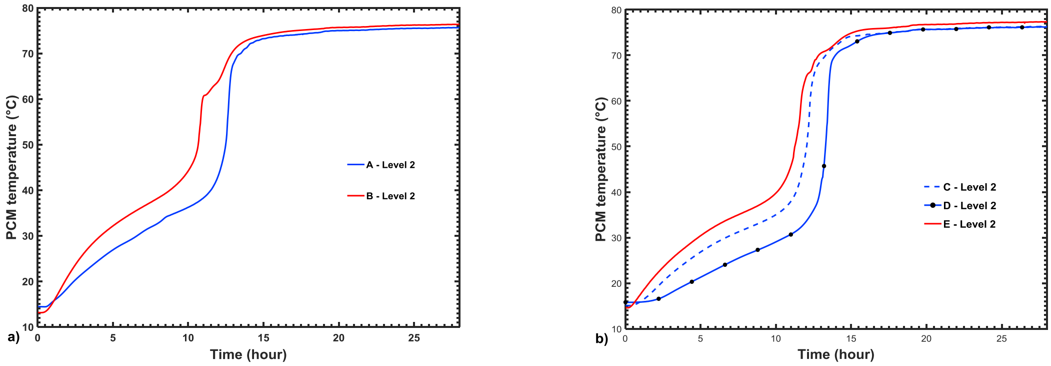

Fig. 3. (a) PCM temperature comparisons of positions A to B; (b) PCM temperature comparisons of C to D and E.

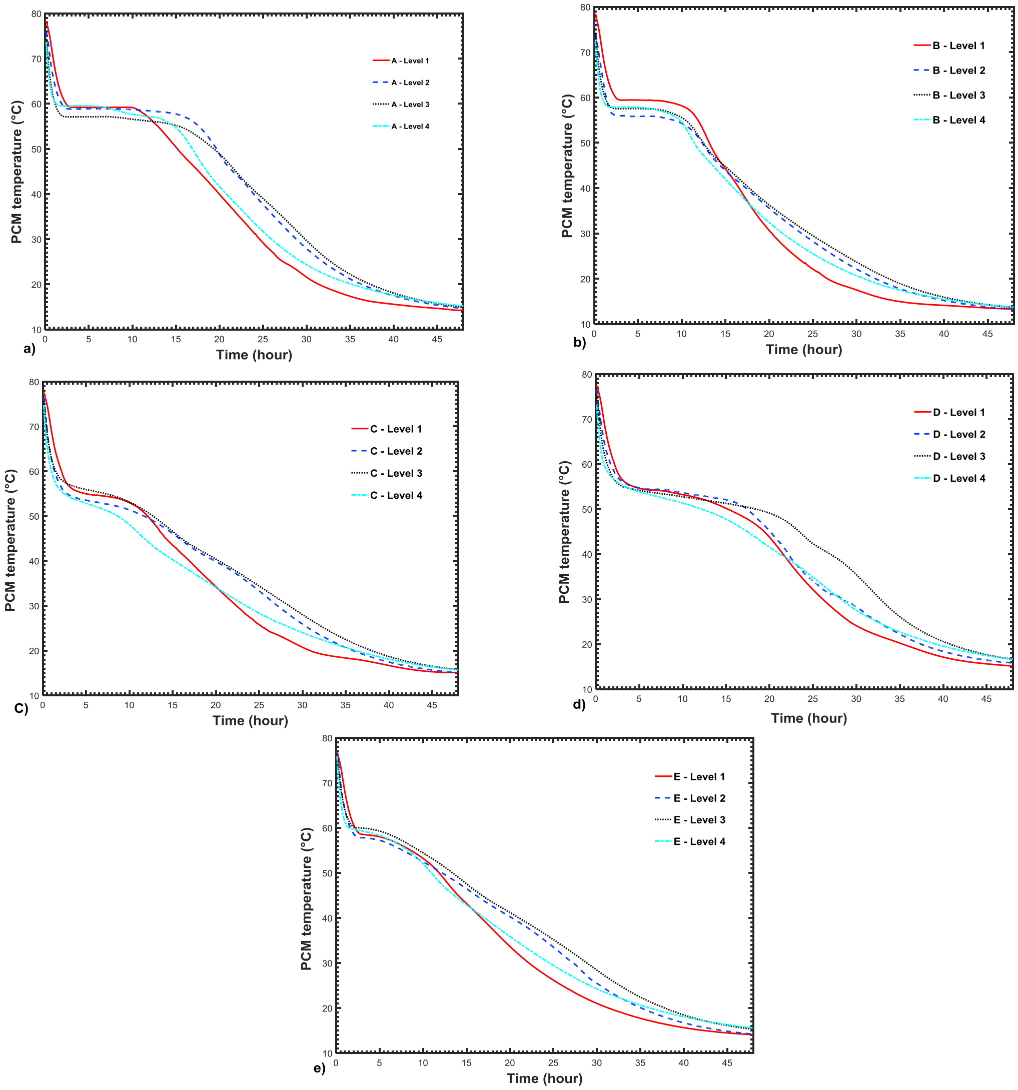

Fig. 4. (a) PCM temperature variations over time at position A; (b) PCM temperature variations at B; (c) PCM temperature variations at C; (d) PCM temperature variations at D; (e) PCM temperature variations at E.

solidify and attain the steady temperatures. As it can be seen that during the initial stage of discharging, temperatures of every thermocouple group decrease rapidly due to large temperature difference between HTF and PCM. For each of groups A, B, C, D, E, temperature drops more rapidly at the lower levels, meaning higher solidification rates in the lower part of liquid PCM. But the time point for each of thermocouple groups A, B, C, D, E to enter solidification range does not depend on the height level. This indicates natural convection flow disappears gradually along with solidification of liquid PCM, playing a less important role on PCM solidification process. Then heat conduction takes control of the heat transfer, resulting almost the same temperature reading across the height levels at the ending of discharging.

3.2.2. Temperature variations in the cross-section

Fig. 5a-b presents the comparison of the PCM temperature records of three position pairs, A to B, C to D and E at level 2 during the discharging process. According to Fig. 5, temperatures of liquid PCM of every position pair drop quickly during the initial discharging process. Once PCM reaches solidification range and afterwards, positions more closer to HTF tube(s) in each comparison group, B (compared to A), C (compared to D), and E(compared to C) decrease more quickly. The temperature evolution trends reflect that thermal conduction dominates heat transfer when PCM temperature drops to the solidification point thus the influence of distances to the HTF tube(s) becomes more pronounced.

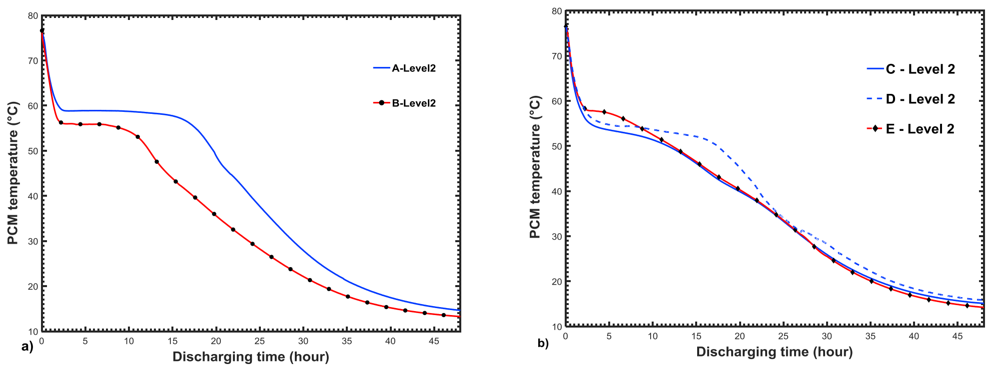

Fig. 5. (a) PCM temperature comparisons of position A to B; (b) PCM temperature comparisons of C to D and E.

4. Conclusions

The heat transfer characteristics of a vertical cylindrical LHTES system with multiple inner HTF tubes was investigated. The centrosymmetric arrangement of inner HTF tubes seeks to achieve the enhanced heat transfer effect during the consecutive charging and discharging processes. The PCM temperature variations along the height, radial and angular directions were analyzed and based on the experimental study. The following conclusions can be drawn:

- Separated liquid PCM layers along the surfaces of HTF tubes expand more quickly at the PCM upper region due to the effect of natural convection flow and merge into a whole liquid PCM pool in the PCM top section. Henceforth, liquid PCM develops along the height and radial directions until PCM totally melts. Multiple heat sources and natural convection flow enhance the heat transfer rate between PCM and HTF and lead to complex evolution of solid-liquid front shape during the PCM melting process;
- At the horizontal cross-section PCM thermal behaviour is highly influenced by the relative positions to HTF tubes, prompting the importance of optimizing HTF tube arrangements in the multi-tube storage unit;
- At the initial discharging stage solidification rates are higher in the lower part of liquid PCM but the consistently steady thermal status of liquid PCM compresses natural convection flow, therefore conduction heat transfer dominates PCM solidification process.

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