EUROTHERM112-M-153

An experimental investigation of the heat transfer and energy storage characteristics of a latent heat thermal energy storage system with a vertically-oriented multi-pass tube heat exchanger for domestic hot water applications

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Abstract

This paper presents the experimental performance analysis of a latent heat energy storage system (LHESS) designed for domestic hot water (DHW) applications. The designed, fabricated and characterised thermal store comprised of a vertically-oriented multi-pass tube heat exchanger in a rectangular cross-section container filled with PCM paraffin RT44HC. The experimental investigation evaluated the heat transfer within the system, measured the transient temperature distribution, determined the cumulative thermal energy stored, charging time and the instantaneous charging power. The experimental work was conducted under controlled experimental conditions using different heat transfer fluid (HTF) inlet temperatures and different volume flow rates for store charging. It was found that during charging process natural convection in the melt played a significant role. Higher HTF inlet temperature during charging significantly decreased store charging time. Increasing HTF inlet temperature from 60 to 70 °C shortened the charging time by 3.5 hours, a further increase to 80 °C decreased melting time by a further 2 hours.

Keywords: Latent heat storage, PCM, Thermal energy storage, Natural convection, Multi pass tube heat exchanger, Experimental investigation.

1. Introduction

Reducing energy consumption in buildings and/or substitution with low/zero carbon alternatives is one of the critical components in meeting carbon reduction commitments. In the United Kingdom, it has been estimated that the housing sector alone is responsible for a quarter of the total Carbon emissions of the country [1]. The UK government established a policy of zero carbon homes [2] to ensure that all new dwellings generate as much energy on-site-through renewable sources, such as wind or solar power as they would use for heating, hot water, lighting and ventilation. The policy is part of the UK Government's wider strategy to achieve the CCA (Climate Change Agreement) target of an 80% reduction in CO_2 emissions from 1990 levels, which is used as the baseline, by 2050 [3].

Over the past few decades, considerable research activities have been devoted to improving the use of renewable energy resources. Solar energy is one form of renewable energy that has great potential. Two main applications of solar energy are for electricity generation (via concentrating solar thermal power (CSP) and solar photovoltaic (PV) systems) and for solar heating and cooling (SHC) applications [4].

Solar energy is a natural source of energy, but it is intermittent, transient and unpredictable in nature. Because of the variable intensity and intermittent nature of solar energy across a given interval of hours, days, and seasons, various practical problems arise. This creates a demand for an effective subsystem which is capable of storing thermal energy when available solar energy exceeds demand to allow it to be used during the night or periods of low insolation. A similar problem arises for waste heat recovery systems where availability of waste heat and period of use are not concurrent, creating a need for thermal energy storage (TES) to enable waste heat utilisation [5].

During the design process of the LHESS, different factors must be considered. For example, in residential applications, the charging/discharging time plays a vital role in determining the functionality of the system. System costs and size are also significant considerations. Compactness and good efficiency van be achieved by a high overall heat transfer rate between the HTF and the PCM, this can increase cost and pressure drop from frictional losses in the heat exchanger [6].

There is a need for the development of a simple and low-cost latent heat storage unit for domestic hot water application, which can easily connect with existing solar heating systems or heat pumps without requiring major system modifications. The main focus of the present experimental study is to develop a latent heat storage system for DHW application and examine its performance during charging (melting process). A series of experiments have been conducted to study the effect of the volume flow rate and temperature of the HTF on the melting of paraffin wax (RT44HC) and the quantity of thermal energy stored. The PCM is contained in a store with a vertically-oriented multi-pass tube heat exchanger.

2. Experimental set-up and methodology of tests

2.1 System description

For the present study, a pilot plant test facility was designed and constructed at Loughborough University to investigate the charging and discharging process of a latent heat energy storage system (LHESS). A schematic diagram of the experimental system used to evaluate the performance of a LHESS is presented in Fig. 1. The system is comprised of two main parts, the storage system, and the heating system. The storage system consists of a latent heat storage tank filled with PCM, thermocouples to monitor the PCM's temperature, a data logger and a computer. The tank is a cuboid shape with the outer shell made of 20 mm polycarbonate sheet (k=0.2 W/m. ºC), 560 mm in length, 610 mm in height and 400 mm in width providing a volume of 120 L. A vertically-oriented multi-pass copper tube heat exchanger with a length of 30.0 m, fabricated from 15 mm OD and 1 mm wall thickness copper tube was immersed in the storage tank. The heat exchanger had 4 passes with 24 turns on each pass, the heat exchanger inlet and outlet were both located on the top of the thermal store.

The heating systems comprises a 250 L hot-water storage cylinder [7] with heat exchange fluid (water) circulated through a closed dynamic temperature control system (Peter Huber Kältemaschinenbau, Germany, type: Unistat 510w [8]) to provide heating during charging. External Pt100 sensor probes were used to set the temperature in the tank to the required HTF temperature. The circuit contains a series of flow control valves and circulation pumps (Pedrollo PQm, 0.37 KW [9]) utilised to circulate and control the direction of HTF flow between the hot water tank and the LHTES. A turbine pulse flow rate sensor (Gems™ FT-110 Series, Hall effect [10]) was employed to measure the volume flow rate of the HTF with an accuracy of ± 3% of the reading. The accuracy of the flow rate sensor was confirmed by measuring the time required to fill a 10-litre container using different flow rates.

Thirty-two T-type thermocouple probes ($\mathbf{T}_1$-$\mathbf{T}_{32}$) (accuracy ± 0.2 ºC) were located in the PCM store as shown in Fig.2. These thermocouples were used to provide qualitative information on the temperatures and the phase change process within the thermal storage system. Two additional PT1000 sensors (with an error temperature ± 0.1 ºC) were located at the inlet and the outlet of the heat exchanger to measure the inlet and outlet temperature of the HTF. The first thirty thermocouples were located on a 3d grid pattern at five heights (The vertical distance between each thermocouple at each location is 100 mm) and six different zones (referred to as 1, 2, 3, 4, 5 and 6) as shown in Fig.2. The spatial distribution of the vertical and horizontal locations of the thermocouple probes were selected within the PCM store to provide three-dimensional measurements of the PCM temperature.

Thermocouple probe $\mathbf{T}_{31}$ was located at the bottom of the tank, near to the edge as an indicator of the state of charging of the store; being at the very bottom of the tank, when $\mathbf{T}_{31}$ recorded temperatures above the PCM melting temperature, the entire PCM in the tank had melted. Thermocouple probe $\mathbf{T}_{32}$ was used to record the ambient temperature.

In order to record the volume flow rate and temperature readings, a data logger (Datataker DT85 [11]) was used to record and transfer data to a computer. Temperatures were recorded during the melting process at five seconds intervals. dEX® Logger Software was used to record data and display the results on the computer screen updated every five seconds.

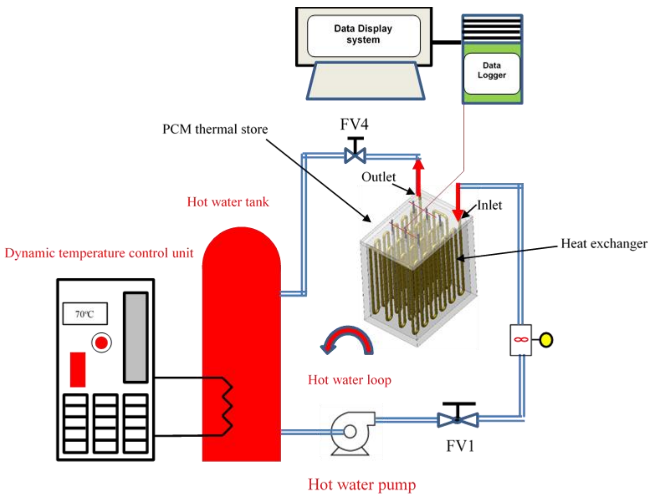


Fig.1 Diagram illustrating key components of the experimental apparatus developed to assess charging of a LHESS.

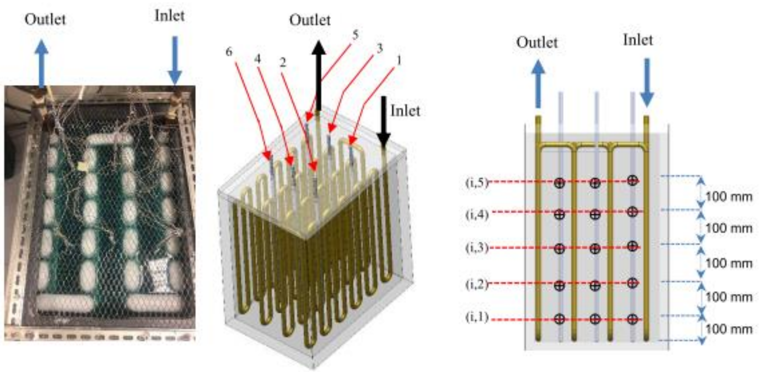


Fig.2 Prototype LHESS unit and an illustration to show the horizontal and vertical locations of the thermocouples in zones 1, 2, 3, 4, 5 and 6.

2.2 Calculation methods and data analysis

2.3 Mean power and energy stored

The total power input/output to the PCM is equal to the energy input /output from the hot/cold HTF assuming that there is negligible heat loss from the store.

$$\dot{Q}_{input} = \dot{m}\, C_{p,HTF}\, (T_{in} - T_{out}) \quad (1)$$

Where $\dot{m}$ is the mass flow rate of the HTF, $C_{p,water}$ is the specific heat capacity of water evaluated at the average temperature of the HTF, and T_{in}, T_{out} are the inlet and outlet temperatures of the HTF, respectively.

The cumulative energy input to the store ($Q_{cumulative}$) was calculated by summing the energy delivery to the store over (evaluated for each time period between readings) the time required for charging as given by Eq (2):

$$Q_{cumulative} = \sum_{i=0}^{i=n} \Delta t\, \dot{m}\, C_{p,water}\, (T_{in} - T_{out}) \quad (2)$$

To verify the calculations of energy stored, they were compared to the theoretical energy storage capacity of the PCM. The theoretical heat storage capacity of the unit was determined to account for both sensible and latent heat components. Which was estimated using Eq (3):

$$Q_{stored} = m_{pcm}\, [C_{p,pcm,s}(T_m - T_i) + \Delta h_m + C_{p,pcm,l}(T_f - T_m)] \quad (3)$$

Where m is the mass of the PCM in the LHESS, $C_{p,s}$ and $C_{p,l}$ are the specific heat capacities for the solid and liquid PCM, T_m is the melting temperature of the PCM, T_i *and* T_f are the initial and final temperature of the PCM in the store.

3. Results and discussion

3.1 Charging mode

For charging, the initial temperature of the LHESS was allowed to cool to the ambient temperature, around 22 ºC. The charging process commenced when the measured temperature difference between all thermocouples within the store was less than 1ºC and ended when the reading of thermocouple $\mathbf{T}_{31}$ increased to 50 ºC.

3.1.1 Effect of the volume flow rate of HTF on charging time

The parametric investigation of the effect of HTF volume flow rate on the melting time was conducted at four HTF volume rates: 2.5 L/min, 5.0 L/min, 7.5 L/min and 10.0 L/min and at a fixed inlet temperature 70 ºC.

Fig.3 illustrates the HTF inlet and outlet temperature, power input, cumulative energy stored and the maximum theoretical storage capacity for each experiment. It is clear that the charging time was affected by the HTF volume flow rate.

It can be seen from Fig.3. that the HTF outlet temperature rises rapidly at first during sensible heat storage, reaches a constant value for a certain period of time during latent heat storage and then increases towards the HTF inlet temperature with the remaining energy stored as sensible heat.

The experimentally determined input power rates for all tested flow rates are presented in Fig. 3 (a, c, e and g). At the start of each experiment, the inlet temperature of the HTF was approximately 70 ºC, while the outlet temperature was almost at the initial temperature of the PCM. The considerable difference between T_{in} and T_{out} measured indicates the input power at the beginning of the experiment was high, this was however due to flushing cold HTF out of the heat exchanger. The input power rate then decreases rapidly and reflects the the heat transfer to storage. Towards the end of the tests, the input power diminishes when the PCM is all melted and the outlet temperature stabilizes indicating a low rate of heat input.

Fig.3 (b, d, f and h) presents the cumulative heat stored for the four flow rates, obtained by summing the energy stored within each data acquisition time step. The heat stored in the LHESS increases rapidly at the start of charging due to flushing of cold HTF from the system, a near constant period of charging then occurs and when temperature between water and PCM decreases after phase change increases at a reducing rate to the end of the experiment.

The calculated cumulative energy stored for this experiment was 7.8 kWh; and is closely aligned with the theoretical storage capacity, providing confidence in the experimental results. The total charging time to bring the tank from an average temperature of 20 ± 2 °C to 70 ± 2 °C was 350 minutes for a volume flow rate of 2.5 L/min and 300 minutes for volume flow rate 5.0 L/min.

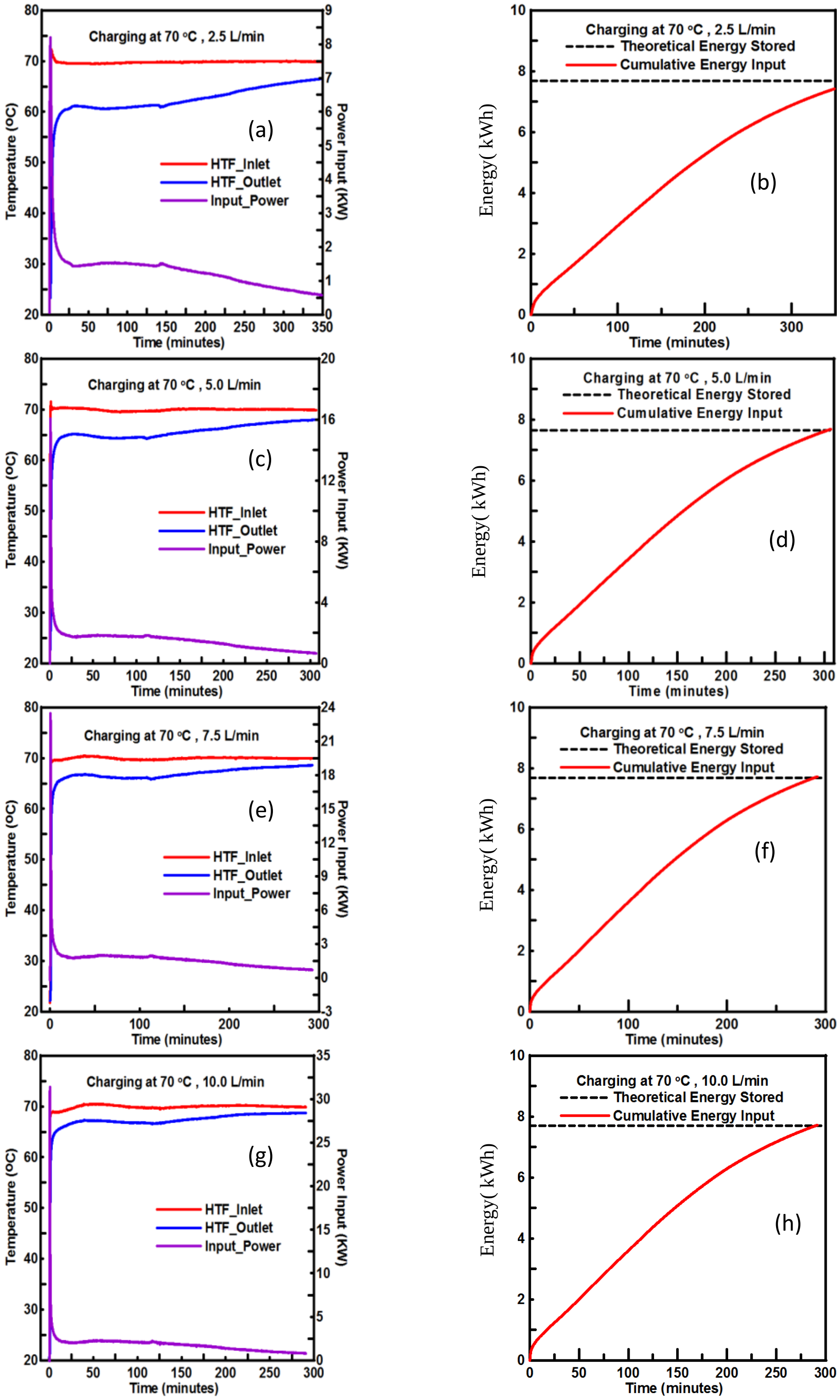


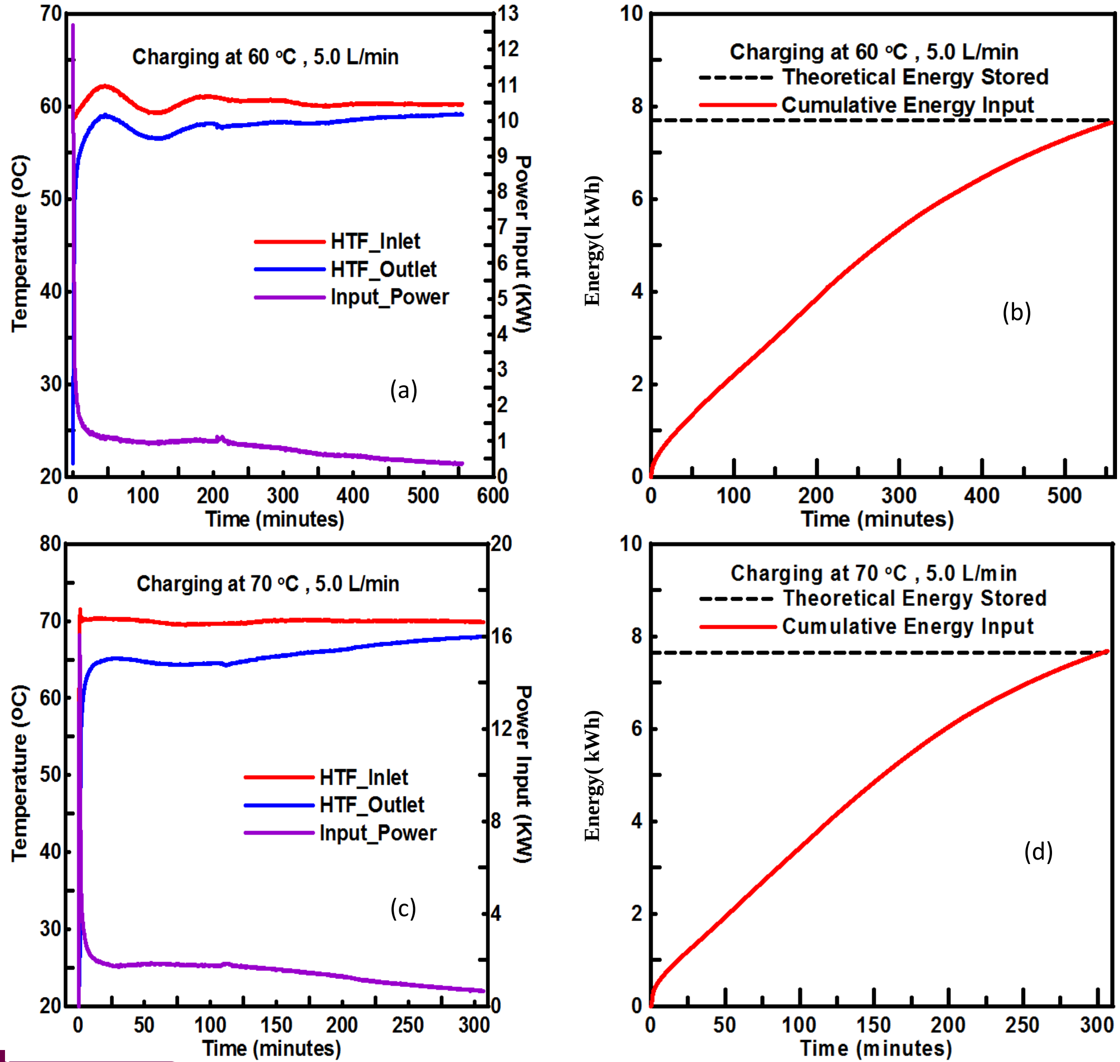
Fig.3. Power input and cumulative energy stored during charging for HTF inlet temperature of 70 ºC and volume flow rates 2.5 L/min, 5.0 L/min, 7.5 L/min and 10.0 L/min.

3.1.2 Effect of HTF inlet temperature on charging

An analysis of the effect of HTF inlet temperature on the overall charging process was conducted using three inlet HTF temperatures 60 ºC, 70 ºC and 80 ºC. Fig. 4. presents the calculated power input, measured HTF inlet and outlet temperatures, cumulative energy stored and maximum theoretical storage capacity for each experiment. The volume flow rate used was 5.0 L/min.

A significant increase in heat transfer rate was observed when increasing the HTF inlet temperature. The higher inlet temperature provides s larger temperature differences between the HTF and the PCM, sthe pipe wall temperature rises more quickly transferring more heat to the PCM, which promotes faster melting at the beginning of the charging process [12]. Increasing HTF inlet temperature from 60 ºC to 70 ºC and 80 ºC leads to reduction in total melting time by 44.8 % and 63.7 %, respectively. The increase in HTF inlet temperature, leads to incresed sensible heat storage after phase transition resulting in an increase in the overall heat stored.

The impact of increasing the HTF inlet temperature is significant in comparison to increasing the HTF volume flow rate, i.e increasing the Stefan number has a higher impact than increasing the Reynold number.



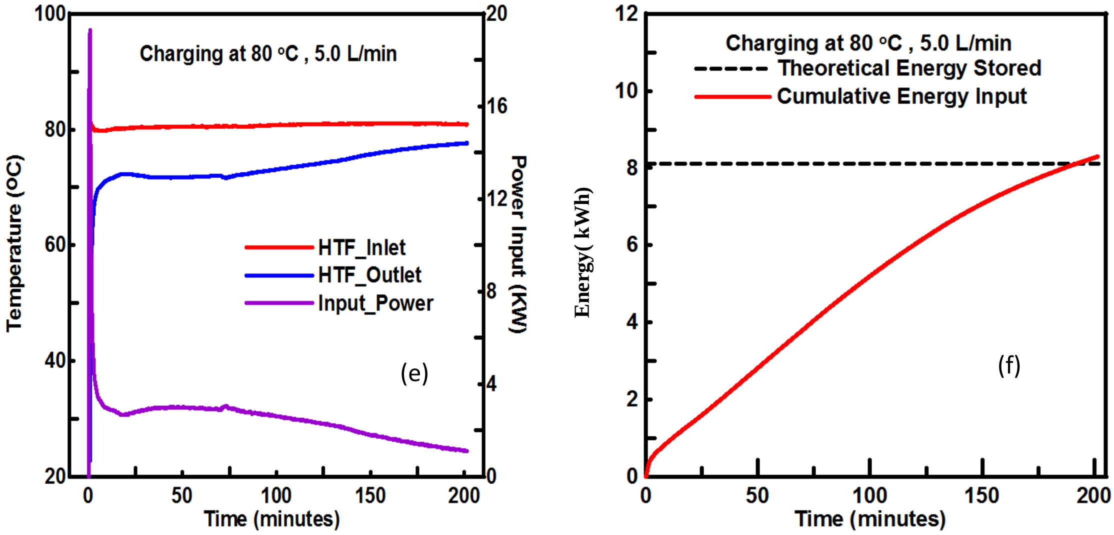


Fig.4. Power input and cumulative energy stored during charging at a volume flow rate of 5.0 L/min and HTF inlet temperatures of 60 °C , 70 °C and 80 °C.

4. Conclusion

In the present study, an experimental system was built to characterise the thermal performance of compact vertically-oriented tube-in-tank latent heat thermal energy storage system using paraffin (RT44HC), for domestic hot water applications. A series of experiments were conducted to investigate the heat transfer mechanism and performance at different HTF inlet temperatures and volume flow rates during charging. The following conclusions were derived from the present study:

- Initially, the heat transfer in the PCM is dominated by conduction, during charging as the liquid fraction increases, natural convection in the PCM becomes the dominant mode of heat transfer.
- At an inlet temperature of 70 °C, increasing the volume flow rate from 2.5 L/m to 5.0 L/m and 7.5 L/m, was reduced the total PCM melting time by 12 %, 16.3 % respectively.
- Increasing HTF volume flow rate to 10.0 L/min, resulted in a minimal further reduction in melt time.
- At a constant volume flow rate 5.0 L/min, increasing the HTF inlet temperature from 60 °C to 70 °C and 80 °C, the total PCM melting time was reduced by 44.8 % and 63.7 %, respectively.

Acknowledgement

The authors are grateful to the Engineering and Physical Sciences Research Council (EPSRC) for funding this work through Grant reference EP/N021304/1.

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