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Research Article

Experimental Study of Thermal Energy Storage System Using Fin Tube Heat Exchanger and Commercial Phase Change Material

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Abstract: The current experimental study is carried out to investigate the main parameters of Heat Transfer Fluid (HTF), which affects the performance of Thermal Energy Storage (TES). In this study, commercial Phase Change Material (PCM), PlusICE H190 is used to charge the system. The phase change temperature of the used PCM is started at 170^{o}C and completed at 190°C. Thermal energy storage is a rectangular container which consists of a fin tube heat exchanger and the charged PCM. Fin tube heat exchanger is implemented in the construction of the system to compensate the limited thermal conductivity of the selected PCM ($0.512\ \mathrm{W/m.K}$). Five thermocouples K-type are inserted in the domain of the PCM to measure the variations of temperature output with time at different depths. The results show that the inlet temperature (T_{inlet}) = 220°C, which is close enough to the phase change temperature (190°C) of the PCM has the highest energy performance. Also the results illustrates that the phase change region of the PCM is started at 170°C and completed at 190^{o}C with a transitional appearance takes place over a varying temperature difference of 20°C and the average value of heating rate over phase change process remains constant at 0.75°C/min at a flow rate 5.2 kg/min. The results indicates that increasing the HTF mass flow rates leads to decrease the time needed to melt the PCM and influences the melting point to become at relatively lowered value, while in the solidification mode the time decreases as the mass flow rate increases.

Keywords: Heat Transfer Fluid (HTF), melting/solidification, PlusICE H190, Phase Change Materials (PCMs), Thermal Energy Storage (TES), temperature gradient, transitional appearance

INTRODUCTION

The steep rise demand of the conventional energy sources made the energy topics one of the most important issues of our recent times. Moreover, energy demand in the commercial, industrial and utility sectors varies through peak hours which are usually difficult and expensive to supply. The increasing prices of the conventional energy sources, shortage of fossil fuels and the increasing concerns of environmental impact of the conventional energy sources are the main future concerns. Such concerns lead the international community to use renewable energy sources such as solar energy, hydrothermal, biomass and wind energy. The unlimited availability of solar energy source compared with other sources of energy attracted the interest of researchers. The cyclic and time-dependent energy resources are main factors that limit the application of solar energy. Thus, Thermal Energy Storage (TES) systems are mandatory for solar energy system in order to provide energy during nights and overcast periods. Storing the solar energy is necessary to eliminate the mismatch between energy supply and demand and to reduce the discrepancy of solar radiation by nature. Sensible Heat Storage (SHS), Latent Heat Storage (LHS) and the thermo-chemical storage are methods used to store thermal energy. The SHS systems store energy by increasing or decreasing the temperature of the material which depends mainly on the specific heat of material, while LHS systems store energy through transition from solid to liquid or from liquid to vapor phases and *vise versa* at approximately constant temperature. Water, air, oil, rock beds, sand and concrete are common examples of storage Medias

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in SHS. Paraffin waxes, eutectic salts, polymers and salt hydrates are the most widely used storage Medias in latent TES. Dincer and Rosen (2011) listed the advantages and disadvantages of these medias are listed in thermal energy storage systems and applications. High transition enthalpy per unit mass, ability to reverse transition, low cost, chemical stability, volume change with transition and transition temperature are the main factors which depends on the selection of a suitable Phase Change Materials (PCMs). PCMs have recently significant attention for TES since the early 1980s. PCMs stores 5 to 14 times more heat per unit volume than sensible heat storage materials such as, water, masonry and rock (Foong *et al*., 2010). The latent heat of solidification/fusion and the temperature at which the phase change occurs are the important parameter of design TES system. PCMs store heat through charging process when they transformed from solid to liquid state and release energy in reverse process. The advantage of this method is that the absorption and releasing energy take place at relatively constant temperature which makes it easier choice to use in different applications. Recently, the TES systems have attracted the interest of the researcher's especially thermal applications such as; space heating, hot water, cooling and generating steam which is important in industrial sector for generating electricity. Recently, a number of studies have been performed to investigate the overall thermal behavior and the effectiveness of various latent heat thermal energy storage systems. Amori (2008) developed a computer program based on finite element method to analyze two dimensional TES unit for different tube diameter, air flow rates and inlet air temperature. Solidification and melting process were taken in their research. They found that utilizing small tube diameter, low flow rates or air inlet temperature near the fusion temperature lead to increase phase change process time. Moreover, the melting time duration is recorded larger than that of the solidification. The simulation performance of TES unit in a real scale PCM-air heat exchanger was developed for different models by Dolado *et al*. (2011). Their models were based on one dimensional conduction analysis, utilizing finite difference method and implicit formulation using the thermo-physical data of the PCM measured in the laboratory. They indicated that, the model was theoretically valid for every air flow rate under internal forced convection and it was experimentally validated for an air velocity range from 0.7 to 2.1m/s and for inlet air temperature range from 8 to 45^{o}C. The comparison between simulation and experimental results proved that a one dimensional model was suitable to a achieve good results of thermal behavior of TES unit. Vaivudh *et al*. (2006) presented TES of solar power plant by small scale experiment for testing the mathematical model. They investigated charging performance of HTFat various flow rates. They found that, the heat transfer rate was rapidly risen HTF temperature that obtained by low flow rate. Also, HTF and storage temperature are parallel decreased during discharge experiment. The calculation was validated with the measurement in charging experiment from room temperature to maximum HTF temperature. An experimental study on melting/solidification characteristics of a paraffin as PCM is conducted in a tube in shell heat exchanger system. Akgün *et al*. (2007) carried out a series of experiments to investigate the effect of increasing the inlet temperature and the mass flow rate of the HTF both on the charging and discharging process of the PCM. The results showed that increasing the inlet temperature HTF lead to decreasing the melting time. Numerical and experimental investigations for heat transfer in triplex concentric tube with phase change material for thermal energy storage were conducted by Jian-You (2008) under different conditions such as; the effect of inlet temperature and flow rate of HTF. Aadmi *et al*. (2015) have investigated, experimentally and numerically, the heat transfer characteristics of TES for PCM melting in a horizontal tube. They used techniques such as conductors like graphite and metal tubes to enhance heat transfer and they proved these techniques effectively. Solé *et al*. (2014) used sugar alcohols as PCMs due to their high storage capacity, safety and economic reasons, their phase temperature make them suitable for medium temperature storage applications such as solar process heat or waste heat recovery applications. Selecting a suitable PCM for applications requires a data of the latent heat, specific heat and phase change transition temperature relevant to a confined application. In industrial application, PCM with phase change (160 to 200^{o}C) are suitable to generate steam. The design of TES systems have to account the lower values of thermal conductivity of the PCM so there are several ways to improve heat transfer in the PCM which are listed in Pointner *et al*. (2014) and Zhou *et al*. (2012). In the present work, energy storage system will be presented and will be focused on PCMs which phase change temperature occurs between (160°C to 200°C). Several types of commercially available PlusICE substances and their thermo-physical properties are listed in Phase Change Material Products Limited (2013). Some of the PlusICE listed products are satisfies the desired phase change transition temperature range between (170 to 190°C). PlusICE H190 is chosen as PCM to be charged in TES container. PlusICE H190 consists of mainly of nitrate, inorganic substance and sodium nitrate as listed in Phase Change Material Products Limited. PlusICE H190 is an attractive material for TES systems. Because of a good value of thermal properties, high latent heat storage capacity of (170 kJ/kg) over a narrow temperature range cans be obtained. It has a transition temperature 191°C and has a limited thermal conductivity, 0.512 W/(m.K). PlusICE H190 is chemically stable under normal condition and it is

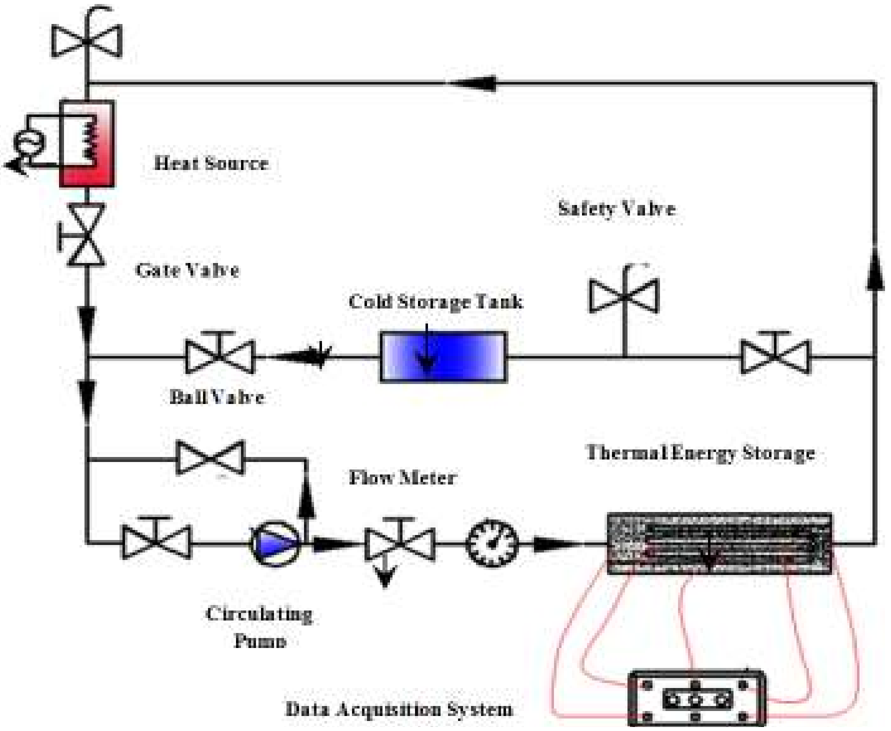

Fig. 1: Schematic diagram of the thermal energy storage set-up

compatible with metal container as listed in Phase Change Material Products Limited (2013). The objective of the present study is to analyze the thermal behavior of the selected PCM, PlusICE H190 and to investigate the performance of thermal energy storage container under different conditions for melting and solidification processes.

EXPERIMENTAL SETUP

Olimat *et al*. (2013) presented a schematic diagram of the TES system shown in Fig. 1. This system is divided into two main cycles, charging cycle and discharging cycle. The main components of charging cycle is the heat source which heats the HTF, while the cold storage tank is the main part of discharging cycle which extracts heats from the melted PCM. Fin pipe heat exchanger is installed in TES container to heat transfer between the PCM and the HTF. The container is made of stainless steel with thickness 4.0 mm and with rectangular shape. The rectangular container has a volume of 73 L and it is placed horizontally. To enhance the heat transfer, internal fins which made of stainless steel are placed vertically inside the container as shown in Fig. 2 to be effective and to increase heat transfer area. 26 pieces of fins with thickness of 1.0 mm and with 1.0 cm fin spacing are used. In order to reduce the heat transfer to environment the outer walls of thermal energy storage container were insulated. The walls and floor were insulated with thick 5.0 cm ceramic fiber made in USA and gladded with 0.5 mm aluminum foil thick. To set the inlet heat transfer temperature at desired value and to control the volume flow rate, the heat source is supplied with thermostat to control the temperature, lamp for power indication, safety valve for excess pressure. Flow meter with resolution 0.1% full scale range which is made from Krohne company model H250 and several gate valves were used for regulating the volume flow rate. Transient temperature distributions at different depth for the phase change material domain were measured using five K-type thermocouples with accuracy ±0.4%. Oil gear pump with motor rated 2.0 hp and 900 rpm was used to circulate the oil within the cycles. Electrical

Fig. 2: Thermal energy storage container

Table 1: Thermophysical properties of phase change material (Plus ICE H190) and heat trasfer fluid

Material	Phase change temperature (°C)	Density (kg/m^3)	Latent heat capacity (kJ/kg)	Volumetric heat capacity (MJ/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Viscosity (Pa.s)$\times 10^{-4}$
PCM	191	2300	170	1.51	1510	0.512	-
HTF	-	766.8	-	-	2470	0.1248	9.45

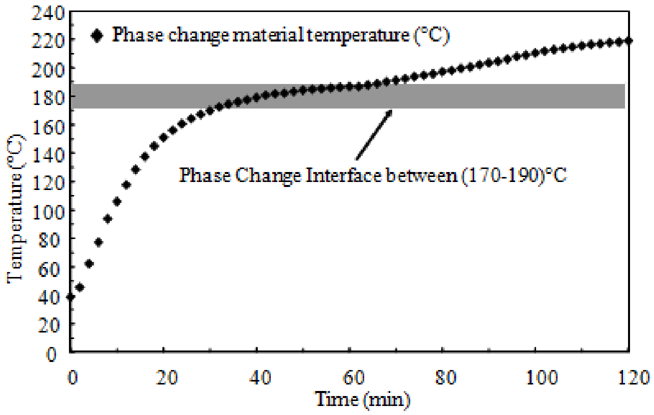

Fig. 3: Time variations of PCM temperature during melting process at the elevation, depth = 7.0 cm for mass flow, ṁ = 5.2 kg/min

heater with capacity 9.0 kW was used to heat the oil. The Thermo-physical properties of the HTF and PCM used are listed in Table 1 by Radco (2013) and Phase Change Material Products Limited (2013) respectively.

RESULTS AND DISCUSSION

During the phase change process, heat is exchanged between the HTF and the phase change interface within the PCM, at the phase change temperature. The thermal heat storage performance and heat transfer during melting and solidification processes are functions of temperature and time and also are functions of the thermal resistance in the HTF and the PCM as were found by Peng *et al*. (2014). Therefore the thermal heat storage performance, during charging and discharging processes, is conducted experimentally using the axial temperature profiles as a function of time. Figure 3 shows the relation between the temperature isothermal line and the time variations for a specific period of (120 minutes). It shows the measuring temperatures at the mid of the plan view for depth = 7.0 cm and mass flow rate (ṁ = 5.2 kg/min) in the PCM domain as a time advance. The phase change process of PCM can be divided into three sub process with respect to temperature visualization, by: solid phase, phase transition and liquid phase. It is observed that the temperature profile is affected by the input flow conditions according to these classifications. As seen in the Fig. 3, the change in temperature profile is significant in the lower and upper zones (solid phase and liquid phase) while it is comparatively low in between (phase transition) with visible temperature gradient. Whilst the temperature gradient in the lower zone is so higher, the temperature gradient in the upper zone is lower and approximately linear. The lower zone temperature increases much faster with higher ascending temperature gradient compared with the upper zone. The temperature rise in solid and liquid phases is due to the high thermal conductivity of PCM container material, the enhancement of heat transfer by using fins with tube in the container and the sensible heat added by HTF. The results show that the sensible energy stored in the PCM causes the heat exchange effectiveness to be high at the beginning of the melting process. In the phase transition region (from 170 to 190°C), the melting of PCM is started at 170°C and completed at 190°C with a transitional appearance takes place over a varying temperature difference of 20°C. The dissipated heat is absorbed by the PCM as a sensible heat before 30 min and thereafter latent heat is absorbed upon reaching the melting point at 190°C after 70 min. The temperature gradient of the phase change interface region is smaller due to the large amount of energy dissipated as a form of latent heat of fusion and the heat needed to melt the PCM.

Figure 4 shows the time variations of temperature gradient of PCM at an elevation of 2.0 cm for mass flow (ṁ = 5.2 kg/min). The results show the temperature rise at the beginning of the melting process due to the high effectiveness of the sensible energy stored and the enhancement heat transfer using fin-tube as a heat transfer element between the heat transfer fluid and the PCM. This causes the heat exchange effectiveness to be high due to higher temperature difference, high specific heat and high thermal

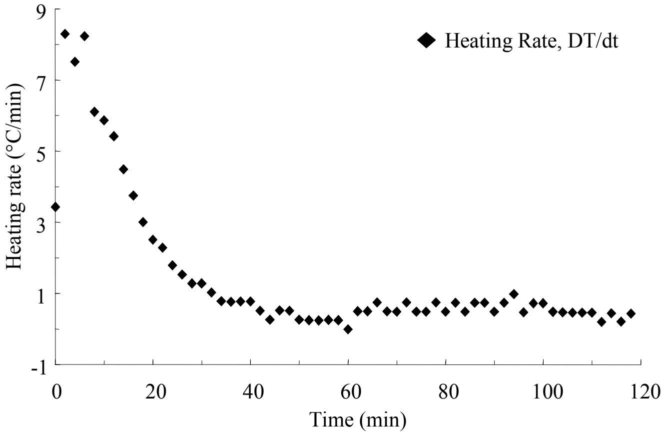

Fig. 4: Heating rate of PCM at depth = 7.0 cm for mass flow rate,$\dot{m} = 5.2\,\frac{\text{kg}}{\text{min}}$

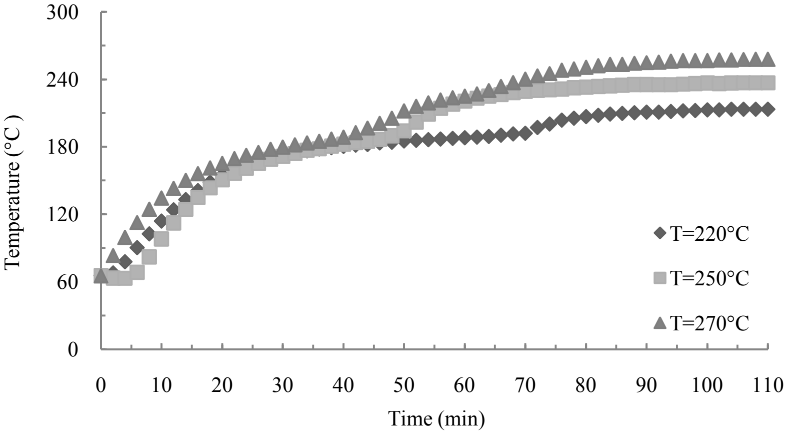

Fig. 5: The effect of heat transfer fluid HTF inlet temperatureon the thermal storage system peformance for $\dot{m} = 3.9$ kg/min

conductivity of PCM container material once the PCM is in the solid phase. The amount of energy transfer to the PCM raises the initial temperature to higher levels, resulting in the outlet temperature gradient being higher compared with the gradient at the phase change region. The temperature gradient profile then gradually decreases until the start of phase change has been reached then it becomes steady over the phase change period. The average temperature gradient (heating rate) over the phase change process remains constant at (0.75°C/min) at a flow rate of (5.2 kg/min). The figure clarifies that the steeper the slope, the higher the heat transfer rate and faster the charging process. The temperature difference is so small and the sensible energy is being negligible comparing with the latent energy which is significant. Therefore the outlet fluid temperature during the phase change process is a function of the thermal resistance between the HTF and the PCM in the system and limited by the phase change temperature and the maximum heat transfer is achieved when the outlet temperature is near the phase change temperature as found by Peng *et al*. (2014).

Figure 5 illustrates the effect of flow conditions of HTF on the melting mode of the PCM. It shows the effect of HTF inlet temperature on the time variations of PCM temperature profiles at a certain depth within the container. It shows the transient temperature profile of the PCM at depth 5.0 cm for different inlet temperatures (T_{inlet} = 220, 250 and 270°C) at constant mass flow rate, $\dot{m}$ = 3.9 kg/min. As shown in Fig. 5, decreasing the inlet temperature leads to increase the time needed to melt the PCM and shift the melting point to relatively lowered value. Moreover decreasing the inlet temperature gives less enthalpy flow from the HTF into the PCM. The figure indicates an increase in the HTF inlet temperature occurs at a higher temperature gradient near the HTF tube and this gradient dimensions with increasing melting time. It encourages the solid-liquid phase transition to start earlier and to end faster. As a result, it affects the transition period to become shorter. Two explanations are suggested for this. Firstly: At lower HTF inlet temperature (T_{inlet} = 220°C), the surface temperature of the horizontal tube of HTF is comparatively closer to

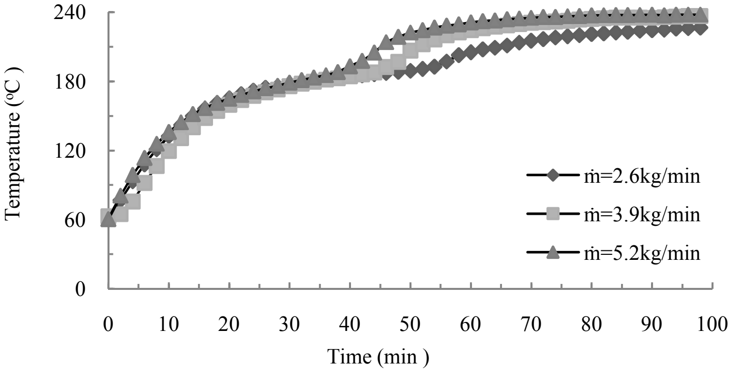

Fig. 6: Effect of the inlet mass flow rate of the HTF on the transient temperature of the PCM during melting mode for inlet temperature 250°C and at depth 5.0 cm

the saturated temperature of the PCM solution (from 170 to 190°C) with a small temperature difference (30°C). At this lower temperature difference, the heat transfer from the HTF surface to the PCM occurs by conduction as a dominant mode of heat transfer. Because the thermal conductivity of the solid phase is much greater than that of the liquid phase, the lower HTF inlet temperature resulted in an extremely high thermal conductivity and good phase change performance. As the inlet HTF temperature is increased, conduction heat transfer is decreased and convection through the PCM becomes more significant. As a result, the effective heat transfer decreases with further increasing in HTF inlet temperatures related to the phase change temperature. Secondly: During the phase change process, heat is exchanged between the HTF and the phase change interface within the PCM, at the phase change temperature. This heat transfer is a function of the thermal resistance in the HTF and in the PCM proportion which has already changed phase. Therefore the outlet fluid temperatures determined by the thermal resistance in the system and limited by the phase change temperature. Maximum heat transfer is achieved when the outlet temperature is equal to the phase change temperature as explained by Amin *et al.* (2012). For different inlet temperatures, (T_{inlet} = 220, 250 and 270°C), observations from the temperature profiles, at constant mass flow rate, indicate that the lower zone (solid phase) gets heated up in the first period of charging and a high temperature gradient was coexist. In the other zones, as charging go further, temperature profiles with time variations start to change with mostly linear forms. The highest input temperatures (T_{inlet} = 270°C) indicates a relatively lower decrease in temperature profiles compared with the other input temperatures. It is due to the greatest transformation of enthalpy added to the system, which is determined by the thermal resistance to heat transfer. It is also due to the relatively high thermal performance of the system because of the additional heat exchange and higher temperature difference between the oil and the PCM.

Several experiments of melting and solidification moderate conducted to investigate the influence of flow parameters on the characteristics and performance of the PCM in order to achieve energy efficient storage. The experiments were arranged to study the impact of mass flow rate of the HTF on the melting and solidification time and thermal behavior of the PCM when operating as a thermal storage system. It depends on the effective heat change that is developed in the PCM during the solidification of the PCM and heat absorbed during discharging process as explained by Amin *et al.* (2012). The value of mass flow rates (2.6, 3.9 and 5.2 kg/min) are used to investigate the melting mode while the values of mass flow rates (2.6, 1.9 and 1.3 kg/min) are used during solidification mode. Figure 6 displays the effect of the mass flow rate of the HTF on the transient temperature profiles of the PCM during melting process. The results show the effect of flow conditions, mass flow rates in the HTF, on the melting mode of the phase change material PCM. It shows the time variations of PCM temperature profiles at a certain depth within the container. The results shows the transient temperature profiles of the PCM at depths (1.0, 4.0 and 8.0 cm) for different mass flow rates$\dot{m}$ =2.6, 3.9 and 5.2 kg/min at the same inlet temperature, (T_{inlet} = 250°C). As seen in the results the effect of HTF mass flow rates outside the phase change zone, were the PCM is not undergoing a phase change, is significant while the effect inside the zone is insignificant.As shown in Fig. 6, increasing the HTF mass flow rates leads to decrease the time needed to melt the PCM and influence the melting point to become at relatively lowered value. It encourages the solid-liquid phase transition to start earlier ands to end faster. As a result, it affects the transition period to become shorter. It is due to the increase in effective heat transfer between the HTF and the PCM. At higher HTF mass flow rate ($\dot{m}$ = 5.2 kg/min), the effective heat transfer and enthalpy flow are so high since the hot oil heat capacity rates is relatively higher and the variation in the energy storage effectiveness is due to the change in phase change effectiveness. Moreover the

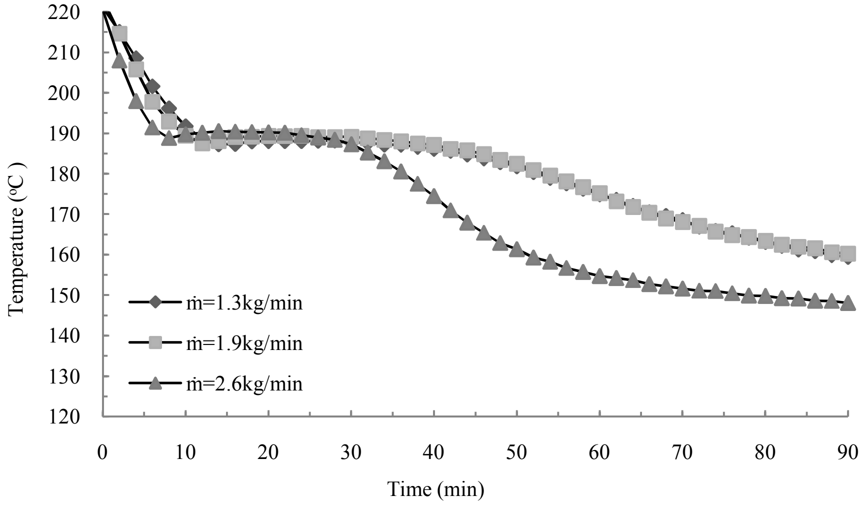

Fig. 7: Effect of the inlet mass flow rate of the HTF on the transient temperatureof the PCM during solidification mode at depth 5.0 cm

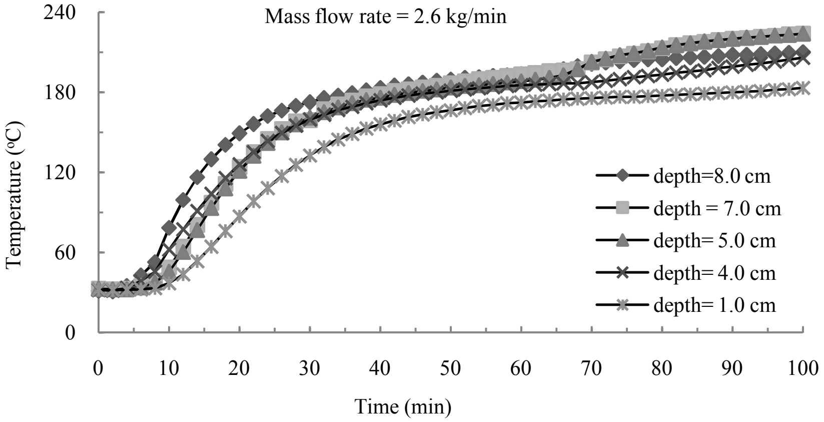

Fig. 8: The effect of the inlet mass flow rate of the HTF on the transient temperature of the PCM during melting mode at different depth

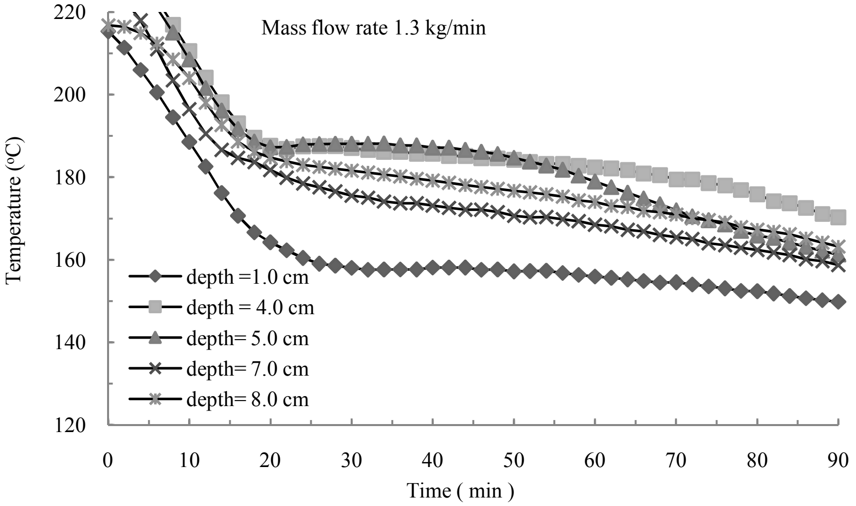

Fig. 9: Effect of the inlet mass flow rate of the HTF on the transient temperature

higher mass flow rates require higher pumping power which Leeds to the lower values for an energy efficient thermal energy storage process.

Figure 7 illustrates the effect of the mass flow rate of fluid flow on the transient temperature of PCM during discharging process. As shown in the figure, at the beginning of the experiment the PCM is in the liquid phase and as time passes abrupt change in temperature occurs clearly due to the temperature difference between the inlet temperature of the cold fluid and the temperature of the PCM then continue with small changes of temperature which decreases gradually until reaches solidification temperature of the PCM. The figure shows clearly, the solidification time decreases as the mass flow rate increases. The increasing mass flow rate leads to increase Reynolds number. Thus heat transfer coefficient will increase for the same value of PCM volume.

The following curves shown in Fig. 8 and 9 are focusing on the behavior of temperature profile as space and time variations during both melting and solidification modes of the PCM. The melting process is started by flowing the HTF through the cycle. The process is proceeded until all thermocouple-temperature readings within the container which distributed at different depth within the domain of PCM (depth = 1.0, 4.0, 5.0, 7.0, 8.0 cm) indicates higher value of the melting temperature of the PCM. The selection of suitable inlet temperature of HTF was investigated by Olimat *et al*. (2013). Since higher value more than 270°C of inlet temperature leads to overheating and unequal heat distribution in the domain. At constant inlet HTF temperature, 250°C, the solidification mode is carried out in the reverse direction of the melting mode by passing cold fluid. Figure 8 shows the time variations of temperature profiles of PCM during melting process at various depths. Thermal Variations take place in the PCM provide the same behavior of profiles with comparatively significant variations in the lower part of the PCM where (depth = 8.0 cm). On the other side, the variations in the PCM temperature profiles reveal different forms of profiles with comparatively significant variations in the middle and most upper part of the PCM where (depth = 1.0 cm). The forms of temperature profiles in the lower and upper zones are significantly different. The variations are due to the different modes of heat transfer inside both the lower and the upper zones. In the lower zone the PCM is in the solid phase where the main mode of heat transfer is conduction. In the upper zone the PCM is in the liquid phase and the major mode for heat transfer is convection which is drawn up by the buoyancy forces generated due to the temperature and density difference. The amount of energy stored and the effectiveness of the thermal storage is based on the required temperature difference and the design HTF flow rate.

The charging and discharging effectiveness is so important where the performance of the thermal storage system for any application is defined by the energy storage effectiveness and the design specifications as specified by Amin *et al*. (2012). Observations from the temperature profiles presented in Fig. 9 show that the transient temperature profiles at different depths within the PCM domain are approximately typical for mass flow rate = 1.3 kg/min and T_{inlet} = 250°C. At the beginning for a period of time 0 to 20 min, rapid changes in temperature profiles are occurred related to the confined depth. It followed by slow changes in temperature profiles over the phase change process for a period of time 20 to 60 minutes. The temperature profiles then gradually decreases over the remaining time and the PCM are to be discharged. The explanations estimated for these results are:

Firstly: At the beginning, the temperature difference between the fluid and the melted PCM is comparatively high then it decreases gradually over the first period of time 0 to 20 min. As a matter of fact, the heat exchanged between the heat transfer fluid HTF and the phase change interface within the PCM is a function of temperature difference, while the temperature difference between the inlet temperature and the phase change temperature is specified fixed 60^{o}C. The sensible energy is significant and the latent heat is to be negligible.

Secondly: When the temperature difference between the fluid and the melted PCM is decreases and the PCM temperature reaches its solidification value, a small change in temperature profiles is occurred. This small change is related to the sensible heat transfer who is assumed to be completed and the latent heat is to be significant.

The temperature profile is gradually reduces over the phase change process until the PCM is solidified, which is happened over a period of time 20 to 60 min.

Thirdly: The temperature profiles then gradually decreases over the remaining time. The results are related to the amount of sensible energy remained in the PCM. It causes the heat exchange to be low at the end of solidification process where the solidification (from 190 to 170°C) is practically completed. In this period of time, the heat is absorbed by the HTF as a sensible heat. While the temperature difference between the fluid and the melted PCM is relatively low and the amount of energy released from the latent heat of fusion during solidification process the temperature gradient of this period becomes smaller and the outlet temperature becomes lower.

CONCLUSION

An experimental study on a thermal energy storage system has been carried out in order to investigate the main parameters, inlet temperature and mass flow rate, of HTF which influences the performance of the system in particular time duration for melting and solidification process of Plusses H190 as phase change material. PlusICE H190 is a combination of nitrate, inorganic substance and sodium nitrate is charged in the constructed thermal energy storage system. In this study, five K-type thermocouples at different elevation are inserted in the domain of the PCM in order to measure the variations of temperature as the time advance.

The experiment performed on the storage system showed that the PlusICE H190 melting temperature range falls between 170 and 190°C which is compatible with the transition temperature, 190°C, from manufacture. This range of transition temperature has many application industries especially for generation steam. The results showed that the average temperature gradient (heating rate) over the phase change process remains relatively constant near 0.75°C/min at a flow rate of 5.2 kg/min. The result**s** indicated that the influence of inlet temperature of HTF during melting process is significant. As the inlet temperature decreases, the time needed to melt the PCM is increased and shifted the melting point to relatively lowered value.

At lower HTF inlet temperature (T_{inlet} = 220°C), the surface temperature of the horizontal tube of HTF is comparatively closer to the saturated temperature of the PCM mixture (170 to 190°C) with a small temperature difference (30°C). Also the results clarify that increasing the HTF mass flow rates leads to decrease the time needed to melt the PCM and influence the melting point to become at relatively lowered value. The results show clearly, the solidification time decreases as the mass flow rate increases. The behavior of curves at different depths during melting process shows that the lower and upper zone is significantly different due to the responsible mode of heat transfer inside the solid PCM, lower zone, is the conduction mechanize, while the convection regime is the major factor for the heat transfer in the upper zone, melting, which due the bouncy forces induced by the density gradients as a result of temperature difference.

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