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Experimental Study of Thermal Conductivity Effect on the Performance of Thermal Energy Storage

Hassan Hadi Sadiq, Munther Abdullah Mussa*

Department of Mechanical Engineering, University of Baghdad, 10071 Baghdad, Iraq

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Abstract

Renewable energy is an attractive energy source which helped to improve the global energy problems. Solar energy products are vital and have been supported by thermal energy storage. In this study, a latent heat thermal energy storage system (LHTESS) of horizontal shell-and-tube has been constructed. Two cases of paraffin wax with different thermal conductivities (TC) have been used as a phase change material (PCM), case1 and case2 of thermal conductivity of 0.265 W/m.K and 0.311 W/m.K respectively. Water has been used as a heat transfer fluid (HTF). In the current experiment, efforts have been made to investigate the influence of thermal conductivity on the thermal performance of thermal energy during the solidification process for both cases, case1 and case2. The investigation shows that case1 has got fully solid during 143 mins, while case2 has got full solidification during 116 mins. Also, the efficiency of the case2 is higher than case1. As a result, case2 is more efficient than case1.

Keywords: thermal performance, thermal conductivity effect, solidification, shell and tube.

Abbreviation

LHTESS	Latent heat thermal energy storage system
TES	Thermal energy storage
PCM	Phase change of material
TC	Thermal conductivity

Nomenclature

C_p	Specific heat (J/kg·K)
k	Thermal conductivity (W/m·K)
L	Latent heat (J/kg)
q	Instantaneous energy
Q	Accumulative energy
$\dot{m}$	Mass flow rate (kg/s)
T_{in}	Inlet temperature (K)
T_{out}	Outlet temperature (K)
Δt	Time (s)
$M_{H.E}$	Mass of heat exchanger (kg)
T_{end}	Temperature of the end process (K)
T_{ini}	Initial temperature of the process (K)
$Q_{H.E}$	Energy of heat exchanger
Q_{pcm}	Energy of phase change material
M_{pcm}	Mass of the PCM
$T_{solidus}$	Solidus temperature (K)
$T_{liquidus}$	Liquidus temperature (K)
Q_{max}	Maximum energy
D_{in}	Inner diameter of the shell
d_{in}	Inner diameter of the tube

Greek letter

ρ	Density (kg/m^3)
μ	Dynamic viscosity (kg/m·s)
η	Efficiency

Dimensionless

Re	Reynolds number

Subscript

in	Inlet
out	Outlet
ch&dis	Charge and discharge
H.E	Heat exchanger
end	End
ini	Initial
pcm	Phase change material
max	Maximum
in	Inner

1. Introduction

Over the last decade, demands for energy have increased, and that caused an energy crisis. Also, gas emissions (green-house effect), and fossil fuel depletion made the scientists look for other resources of energy. Renewable energy, such as solar, wind, and geothermal resources are promising. Solar energy is convenient for countries that have sunny weather as Iraq. The intermittency in solar energy products made researchers turn to search for solutions, as thermal energy storage systems showed the possibility to cover the discrepancy between energy demand and product. Thermal energy is divided into three types, sensible, latent, and chemical[1]. In this study, latent heat has been chosen. LHTESS is based on the phase transition of material solid-liquid,

* Corresponding author e-mail: munther@coeng.uobaghdad.edu.iq.

solid-solid, or liquid-gas. This method utilizes phase change of materials like paraffin wax and fatty acid. The main drawback of these materials is low thermal conductivity[2]. Hence, scientists investigate many methods to enhance thermal conductivity by adding material, such as nano-particles or increasing heat transfer surface area by adding fins. Agyenim et al. [3] studied the impact of integrating circular and longitudinal fins to shell and tubestorage unit on heat transfer rate. Erythritol has been selected as PCM which has a melting point of 117.7 ˚C and water as HTF. They demonstrated that the thermal energy storage(TES) with longitudinal fins performed the best result. Also, it improved the thermal response during charging and less in subcooling at melt during discharging. Ghozatloo et al. [4] established higher heat transmission via convection performance through a heat exchanger unit by utilizing graphene nanofluids. They concluded that mixing 0.075% of graphene withpure fluid will improve TC to 31.83%, in addition, the coefficient of convective heat transfer of graphene nanofluids at 38℃ improved by 35.6% at a concentration of 0.1%. Rathod & Banerjee [5] analyzed the average heat transfer done through the melting and solidification process in shell and tube heat exchanger. Longitudinal fins have been welded on the tube. The analysis has been done at different values of inlet temperatures and flow rates. They concluded that the time needed for the melting process decreased by about 12.5% and 24.52% for a fluid inlet temperature of 80˚C and 85˚C respectively. Furthermore, the time taken for solidification reduces up to 43.6%. Al-Abidi et al. [6] inspected heat transfer improvement by using a triplex tube heat exchanger as TES. At each tube, four longitudinal fins have been welded to improve thermal performance. In addition, the impact of natural convection on the charging process has been inspected. They concluded that there is an enhancement in the temperature of charging reduced by 86 % with fins, and the efficiency for TES was 71.8%. Gasia et al. [7] inspected the impact of installing fins and the use of two different HTFs water and a commercial silicone; Paraffin wax RT58 as PCM, in addition to shell and tube LHTES unit, have been used. Their result showed that the fins design enhanced heat transfer by about 40% for commercial silicone, and 44% for water HTF. Yazici et al. [8] investigated the performance of melting heat transfer and energy storage efficiency of PCM (paraffin)/graphite matrix in a shell and tube for LHTES. Also, the influence of the inlet temperature of HTF on melting time was analyzed. They concluded that the effective TC increases 35 times heat transfer rate higher than pure paraffin. The overall melting time decreases by about 92%. Furthermore, total melting time was decreased by about 31% with the rise in HTF inlet temperature for the PCM/graphite matrix.Venkitaraj et al [9]studied the impact of injecting alumina (Al_2O_3) nanoparticles into pentaerythritol at 0.5 and 1.0 wt.% fractions. Their experiments were performed during the charging and discharging process in a shell and tube storage unit. Therminol-55 had been used as HTF with different flow rates of 2, 4, and 6 l/min. Their results showed that the charging / discharging efficiency reached maximum levels of 86.8% and 75.0 %, respectively, at 6 l/mins, according to their data. The overall energy efficiency of the thermal energy storage system improved from 38.3 % for pentaerythritol to 50.5 % and 58.5 % for pentaerythritol mixed with 0.5 wt. % and 1.0 wt. % of Al2O3 nanoparticles, respectively. Hassan et al [10] studied thermal performance during the charging process for latent heat unit using different fins geometry. Their experimental analysis had been performed out on a shell and three geometries of tubes, non-finned, longitudinal finned and circular finned tubes. All tubes have an inner diameter of 20 mm and thickness of 1.3 mm and length of 560 mm and were manufactured from steel. The shell with an internal diameter of 70 mm, 50 mm and a length of 50 mm thickness was made from Plexiglass. Commercial grade paraffin wax and water had been used as a PCM and HTF respectively. Their results showed that the overall charging time reduces to 69% and 55% using circular finned and longitudinal finned respectively. In addition, they determined that the most cumulative stored enery enhancement was achieved by employing circular finned of about 52% as compared with longitudinal finned. Yadav & Sahoo [11]investigated the impact of energy and exergy analysis on the lauric acid and paraffin wax PCMs-based on 0.1% vol. fraction of Al_2O_3 and CuO nano-additives TES system. The TES system is installed into the exhaust gas side of the four-stroke diesel engine. They showed that 0.1% vol. fraction of Al_2O_3 in lauric acid nano-enhanced 16.13%, 8.06%, 38.71%, 25.81%, and 32.26% less charging period than pure lauric acid, CuO–lauric acid, paraffin wax, Al_2O_3- paraffin wax, and CuO–paraffin wax, respectively. Jidhesh et al.[12] examined the enhancement of the charging and discharging rate of PCM. Paraffin had been used as the PCM. The steatite powder had been used as the additive material added with different weight fractions to enhance the thermal property of the PCM. The performance of the Paraffin/steatite composite had been investigated using a horizontal latent heat energy storage system. Their result showed that the solidification rate of the PCM was higher than the melting rate with an additive of steatite powder which increased in the paraffin accordingly. They concluded that the effect of increasing rate is mainly due to the property of the steatite material as it has a large latent heat retention rate. They observed that the solidification rate was improved by about 25%, 37% and 40% than the melting time by adding steatite powder to the paraffin with weight fractions of 10%, 20%, and 30% respectively. Mayil Velnathan & Valan [13] conducted an investigation on the thermal performance of a shell and helical tube LHTESS. Commercial grade erythritol having a melting temperature of 120 °C was employed as the PCM. The effect of the addition of graphene nanoparticles on the performance of the storage system such as heat flow rate, overall heat transfer coefficient, charging and discharging efficiency and effectiveness were evaluated and compared with the storage system with only base erythritol during both energy storage and retrieval processes. The efficiency of the new composite increased to 16.29% during the storage period and 28.48 % during the retrieval period compared to the base PCM system. Furthermore, they observed that the effectiveness was about 14% greater at the beginning of the melting process and about 12% greater at beginning of the solidification process for graphene-erythritol. Al-Maghalseh [14] studied the effect of natural convection of melting of PCM filled around horizontal pipe within a rectangular thermal storage unit. Four different configurations on the test model were carried out. Paraffin wax with meltin temperature 60°C and water have been used as a PCM and HTF respectivily. They demonstrated that as compared to case 1, the overall melting time was roughly decreased by 16.57 % with case 2, 31.83 % with case 3, and 41.3 % with case 4. Furthermore, while the conduction heat transfer was kept constant in all cases by applying the same operation and boundary conditions to the pipe and HTF, the rate of heat transfer enhancement is noticeably more obvious in natural convection in molten PCM.AL-Migdady et al. [15]investigated the cooling performance heat sinks filled with PCM. Two types of PCMs (RT35HC and RT44HC) have been used and metal foam integrated with different porosity (100%, 97% and 90%) as enhancement material. In addition, three different values of convective heat transfer coefficient between the heat sink boundaries and the surroundings. Their result showd that the better cooling was obtained in the heat sink filled with RT35HC compared to RT44HC. Moreover, using metal foam has better enhancement in decreasing the temperature in the case of porosity (97%, 90%) by 6°C and 5°C of RT35HC compared to the no-metal foam case. Whereas in case of RT44HC, the decrease in the temperature was (5 and 4)°C for the porosity(97% and 90%) compared to the no-metal foam case.Also, they found that the increase in the convective heat transfer coefficient reduced the melting rate of the PCM. In current study, the impact of TC of the PCM on TES will be investigated experimentally in shell and tube LHTES. Furthermore, thermal performance will be calculated through the discharge process.

2. Experimental work

In the current survey, Paraffin wax has been used as the PCM, and water as HTF. The choice of PCM
for shell and tube LHTES is based on thermal conductivity . Two types of wax have been used, Iraqi commercial paraffin with (k = 0.265 W/m.K), and commercial paraffin with (k = 0.311 W/m.K) and represented as case1 and case2 as shown in Figure 1 and Figure 2. The thermophysical properties of PCM have been depicted in Table 1.

2.1. Differential scanning calorimeter (DSC)analysis

Latent heat and specific heat of paraffin have been measured by DSC-60 Shimadzuand used as a PCM,Figure 3 represented the DSC measurement. A sample of size 5mg of paraffin in an aluminium pan has been used. The analysis has been conducted in the temperature range of 35-100˚Cat a rate of 12 ˚C/min with a nitrogen flow rate of 50 ml/min. The parameters have been determined by numerical integration of the area under the peak as illustrated in Figure 4.

Figure 1. Iraqi Paraffin

Figure 2. Commercial Paraffin

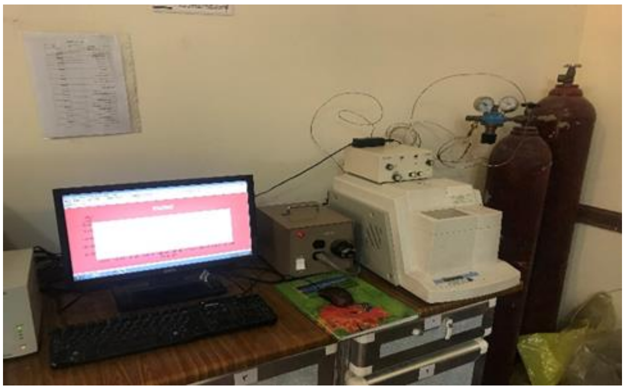

Figure 3. DSC instrument

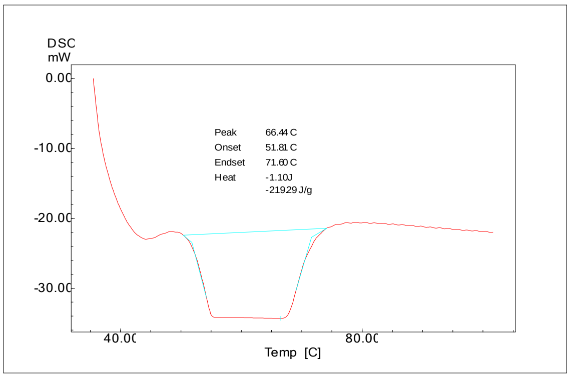

Figure 4. DSC analysis curve

Table 1. thermo-physical properties of PCM

Material	Properties						
	ρ_{solid}(kg/m^3)	ρ_{liquid}(kg/m^3)	C_p (J/kg·K)	k (W/m·K)	L (J/kg)	Melting temp. (K)	μ (kg/m·s)
Iraqi paraffin	852.14	766.11	2900	0.265	270715	334	0.0188
Commercial paraffin	813.795	733.33	2104	0.311	219290	331	0.0236
Water	-	998.2	4182	0.6	-	-	0.001003

2.2. Thermal conductivity measurement

In this study, Lee's Disc method has been utilized to measure the TC of organic paraffin. A steady-state is considered where the calculation can be made when the experimental test reaches equilibrium. Lee's method includes three-disc of brass; one of them prescribed as a heater with power input (1.5 Watt) as illustrated in Figure 5andFigure 6.The sample insert between disc2, and 3. T_1, $T_2$and T_3 are recorded after reaching the steady-state condition.

3. Mathematical Background

The instantaneous energy (q) and accumulative energy (Q) which are obtained or realized by water as HTF throughout the charging and discharging process described by as [16] :

$$\mathbf{q_{ch}} = \dot{\mathbf{m}}\mathbf{c_p}(\mathbf{T_{in}} - \mathbf{T_{out}}) \quad (1)$$

$$\mathbf{q_{dis}} = \dot{\mathbf{m}}\mathbf{c_p}(\mathbf{T_{out}} - \mathbf{T_{in}}) \quad (2)$$

$$\boldsymbol{Q_{ch\&dis}} = \sum \boldsymbol{q_{ch\&dis}}\,\Delta \boldsymbol{t} \quad (3)$$

Where(c_p), ($\dot{m}$), and (T_{in}& T_{out}) are the specific heat, mass flow rate, and inlet/outlet temperature of the HTF respectively.

In the transient process, the accumulative energy that is realized or acquired by water ($Q_{ch\ \&\ dis}$) and the PCM ($Q_{pcm,\ ch\ \&\ dis}$) are opposedto the steady-state process. This part of heat exchange can be expressed as below:

$$\boldsymbol{Q_{H.E,ch}} = \boldsymbol{M_{H.E}}\boldsymbol{C_{p,H.E}}(\boldsymbol{T_{end}} - \boldsymbol{T_{ini}}) \quad (4)$$

$$\boldsymbol{Q_{H.E,dis}} = \boldsymbol{M_{H.E}}\boldsymbol{C_{p,H.E}}(\boldsymbol{T_{ini}} - \boldsymbol{T_{end}}) \quad (5)$$

Where ($M_{H.E}$), and ($C_{p,H.E}$) are the mass and specific heat of the exchanger respectively, and (T_{ini}& T_{end}) are the start/end temperature of the PCM through the charge/ discharge process.

Furthermore, the accumulative energy exchangeable with PCM ($Q_{pcm,\ ch\&dis}$) can be written as follows:

$$\boldsymbol{Q_{pcm,ch\&dis}} = \boldsymbol{Q_{ch\&dis}} - \boldsymbol{Q_{H.E,ch\&dis}} \quad (6)$$

The thermal performance of LHTES can be described as follow:

$$\eta_{theory} = \frac{Q_{pcm,ch\&dis}}{Q_{max,ch\&dis}} \quad (7)$$

The maximum quantity of energy (Q_{max}) through the charging and discharging process which obtained from PCM can be written as:

$$\boldsymbol{Q_{max,ch}} = \boldsymbol{M_{pcm}}\left[\boldsymbol{C_{p,pcm}}(\boldsymbol{T_{ini}} - \boldsymbol{T_{solidus}}) + \boldsymbol{L} + \boldsymbol{C_{p,pcm}}\left(\boldsymbol{T_{end}} - \boldsymbol{T_{liquidus}}\right)\right] \quad (8)$$

$$\boldsymbol{Q_{max,disch}} = \boldsymbol{M_{pcm}}\left[\boldsymbol{C_{p,pcm}}\left(\boldsymbol{T_{ini}} - \boldsymbol{T_{liquidus}}\right) + \boldsymbol{L} + \boldsymbol{C_{p,pcm}}(\boldsymbol{T_{end}} - \boldsymbol{T_{solidus}})\right] \quad (9)$$

where (M_{PCM}), ($C_{p,PCM}$), (L), and ($T_{solidus}$& $T_{liquidus}$) are the mass, specific heat, latent heat, andsolidus/liquidustemperature respectively.

4. Experimental apparatus and procedure

In the present research shell and tube, horizontal concentric LHTES unit have been constructed to investigate the effect of TC of PCM on the TES system. Figure 7 and Figure 8 illustrate the schematic diagram, and test rig of the experiment respectively.The test rig consists of the measurement system, flow system and test section. The shell length is (800mm) and is made from aluminium with an inner diameter D_{in} of (80mm) and a thickness of (10mm). A tube of(26mm) inner diameter and made from copper located at the center of the shell where HTF through the tube and exchange heat with PCM, Figure 10.The paraffin wax is located in between the shell and tube. The outer surface of the shell has been insulated with two layers of asbestos tape of (5mm) thickness and thermal conductivity of (0.16 W/m.K).The charging system consisted of an electrical heater of power (1500W) installed on the shell's exterior surface. Acquisition system of data comprised of twentythermocouples K-type with accuracy (±2.5)utilized to record thePCM temperatureand distributed in two sections each section of 10 thermocouples located in a radial place as illustrated in Figure 9.Furthermore,two thermocouples are located at the inlet and outlet tube of HTF to record water temperature.Also, two data loggerswere employed to record the temperatures during the dischargecondition. Two cases of organic material paraffin with different thermal conductivities have been used as a PCM, case1 and case2 of thermal conductivity of 0.265 W/m.K and 0.311 W/m.K respectively. For the cas1,the heat exchanger was filled with 3kg of Iraqi paraffin, then for the case2,filled with 2.8kg of commercial paraffin. The PCM was melted inside the heat storage system by the electrical heater until reacheda temperature of(340K), and then HTF was pumped through the tube at a flow rate of (2l/min) and a constant temperature of (296K). The flow assumed laminar according to Reynolds number [17] (Re < 2300).

$$Re = \frac{4\dot{m}}{\pi d_{in}\mu}$$

Where $\dot{m}$is the mass flow rate, μ is the viscosity of water, and d_{in} is the inner diameter of the tube.

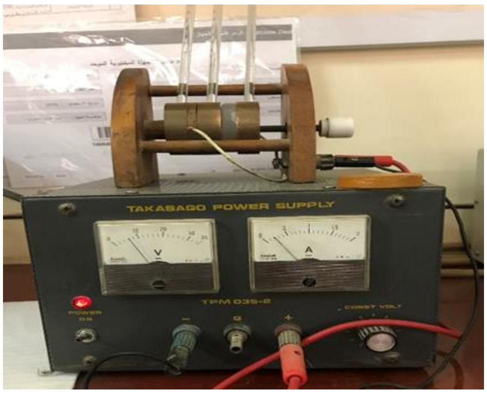

Figure 5. Disc Lee's instrument

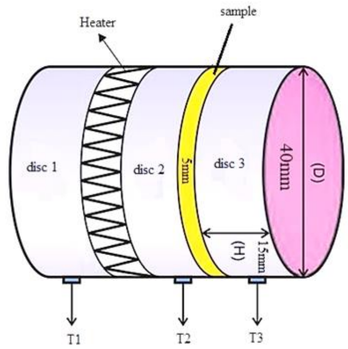

Figure 6. Schematic diagram of Disc Lee's

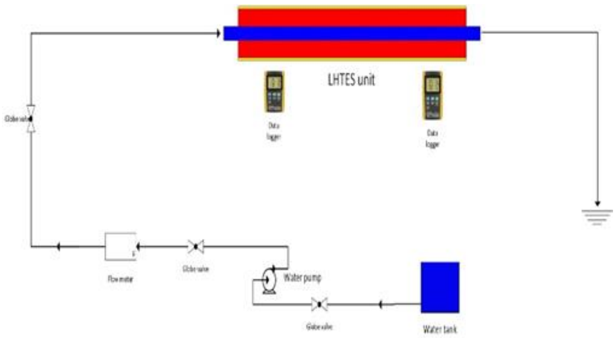

Figure 7. Schematic diagram of LHTES

Figure 8. Test Rig

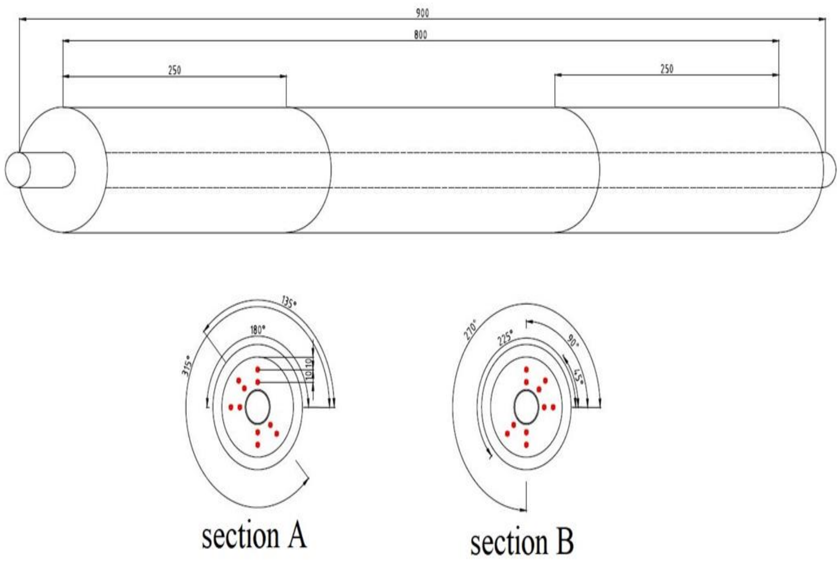

Figure 9. Thermocouple distribution

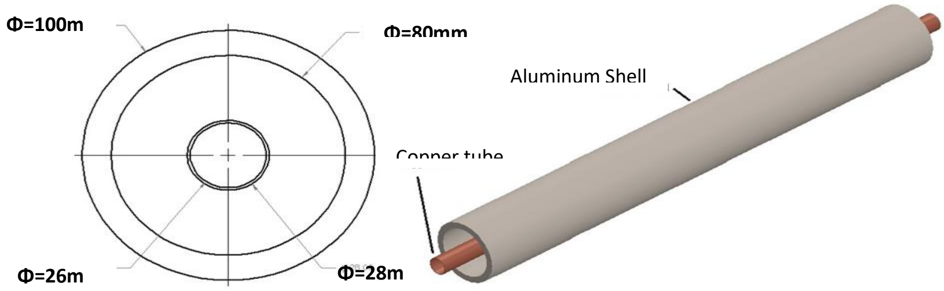

Figure 10. Shell and tube

5. Result and discussion

In the present research, the influence of TC of PCM on the performance of the energy storage experimentally has been studied. The experiment is conducted with two kinds of PCMs which are different in thermal conductivity, case 1=0.265 W/m.K and case 2=0.311 W/m.K. The mass flow and the temperature of the HTF at the inlet are considered constant with a value of 2 l/min and 296 K respectively. The variation of HTF temperature at the outlet of the storage unit during the discharge process at a constant inlet temperature and the constant flow rate has been illustrated in Figure 11. It can be shown that the drop in temperature for case2 is higher than that of the case1until 116 min. The temperature of case1 will be continue dropping until 145 min. More investigation has been performed on the heat gain as illustrated in Figure 12. It can be shown that the heat obtained by the HTF is faster and higher for case2 than case1. Furthermore, the maximum heat gain by HTF for case2 is after 60min whereas for case1 the maximum heat gain is after 90 min. The decrease in heat transfer is faster for PCM of high thermal conductivity. The mean temperature of the axial direction of sections A and B have been illustrated in Figure 13 and Figure 14, respectively. The temperature profiles for the same case of the PCM in the axial direction are remarkably similar. The difference in temperature was in between the two types of the PCMs when a comparison was made between the result of each. The calculations have been constructed from the average temperature reading of thermocouples. It is recognized that in the PCM for case2, the temperature decrease is faster than case1. For case1, the latest temperature of section A is 307.29K after 145min whereas it is 307.99K for case2 after 116min. In addition, for section B it is 308K for case1 after 145min and 308.9 for case2 after 116min. Figure 15 shows the evolution of the average temperature of the LHTES unit for the PCMs with different thermal conductivity. It could be noted that the duration of the decrease of the temperature will be decreased with increasing thermal conductivity. It is can be concluded that the rise in TC for PCM is shorter than the time needed to reach the final temperature of the solidification process. The increase in TC of the PCMs which is done by any method like using nanoparticles and material additives will affect on thermal properties of the material and one of them is latent heat. The discharge time of the PCM is influenced by the sensible and latent heat during solidification. Figure 16 illustrates the effect of the increase in TC of PCM on the latent heat. This enhancement in TC has a negative impact on the latent heat which causes reduction in it [18]. Hence, optimization should be considered to choosing the PCM in the application, a high TC mean reduces the dicharge time but reduction in the latent heat. The efficiency of LHTES for case1 is 66% after 145min whilst the efficiency for case2 is 76% after 116min. Its clear that in this study, case2 is highly efficient than case1. Figure 17 shows a statistical comparison of the variant in temperature at a specific time for both cases 1 and 2.

6. Conclusion

In the current study, the experiment focused on the measurements during the solidification process. Also, the influence of the PCM's thermal conductivity on the performance of the TES was investigated in this work. LHTES of horizontal concentric double pipe shell and tube heat exchanger has been designed and manufactured. Investigation of two types of PCM has been used with different thermal conductivities. It is concluded that the PCM's efficiency of high thermal conductivity has increased by 13.15% compared to the PCM of low thermal conductivity. Moreover, the solidification process is reaching the final temperature faster for PCM of higher thermal conductivity. In addition, the effect of TC of PCM on latent heat was analyzed. The main conclusion is that the PCM with higher thermal conductivity will have an efficient heat transfer and high efficiency which in turn preferred in many applications such as space heating. To verify the result of the present study a comparison was made with previous research. The temperature distribution profiles in Figure 15 agreed with the result of refence [19]who they studied the charastrastic of paraffin wax during the melting/soldification process as can be seen in the Figure 18.

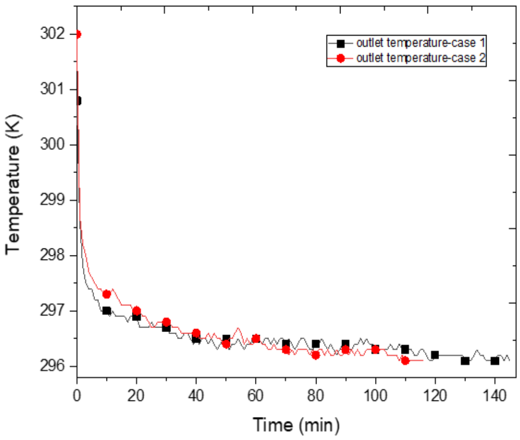

Figure 11. Outlet temperature of HTF

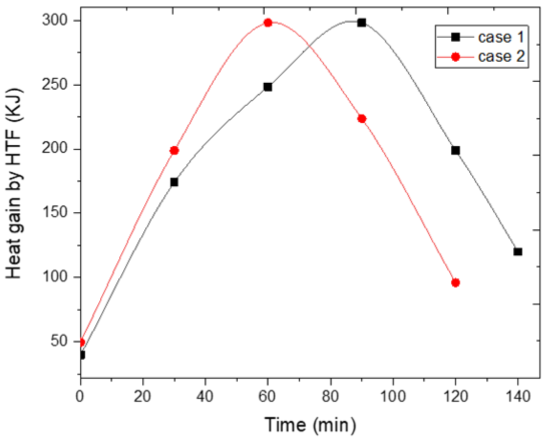

Figure 12. Heat gain by HTF

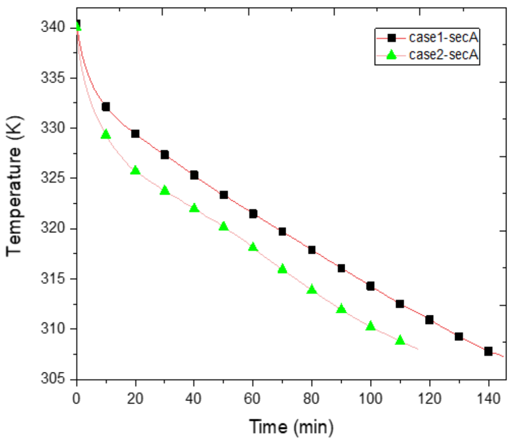

Figure 13. temperture variation of section A

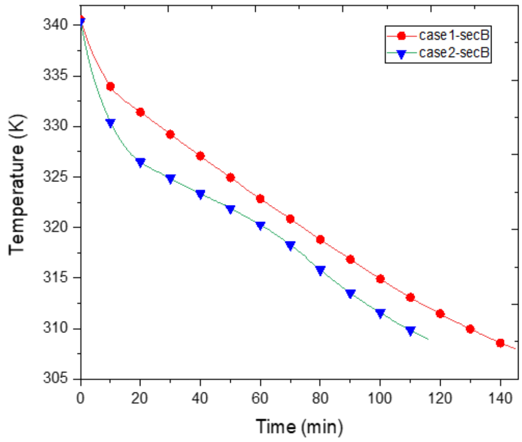

Figure 14. temperture variation of section B

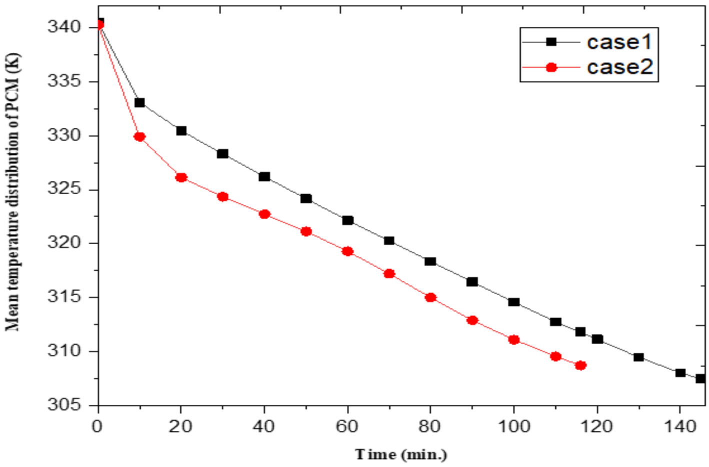

Figure 15. Average temperture variation in PCM

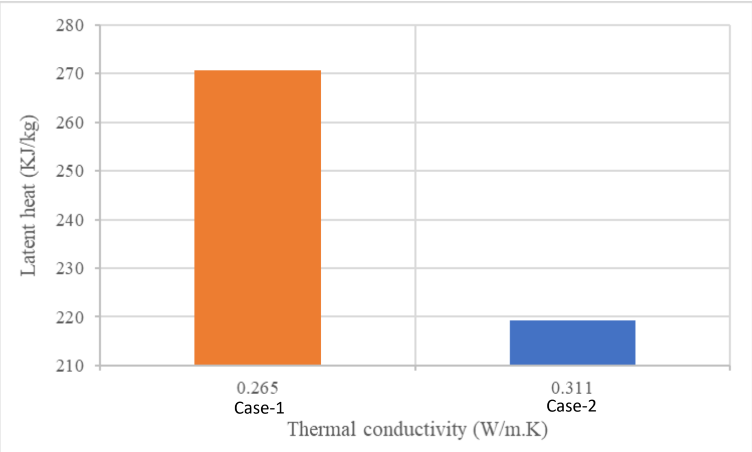

Figure 16. comparison Latent heat with Thermal conductivity

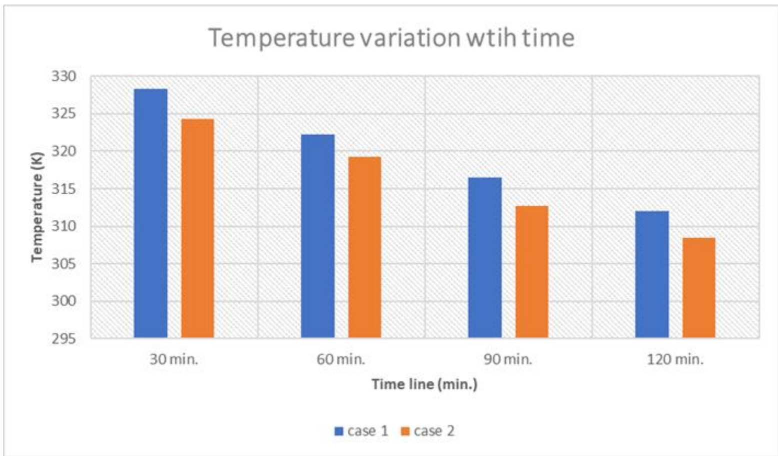

Figure 17. comparison of the variant in temperature at specific time

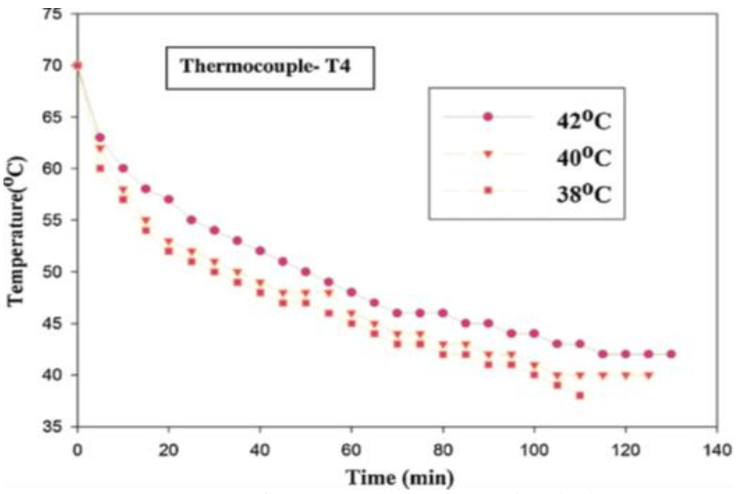

Figure 18. The result of temperature distribution profile of refrence [19]

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