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Enhancement of Thermal Storage Properties of Phase Change Material by Using Metallic Swarf

Abstract*- The phase change materials (PCM) is commonly used for storage heat as a latent heat, the main disadvantage of this method is slow response time during charging and discharging; this due to the PCM thermal properties. This work studied experimentally the enhancement of thermal properties of PCM by adding various metallic swarf such as copper, aluminum and iron swarf. Metallic swarf used as thermal conductivity promoter to produce modified paraffin wax samples. The addition of the previous enhancers was conducted with a weight fraction of (7.5%, 12.5% and 17.5%) to the whole weight of the mixture. The experimental results showed that adding of metallic swarf to the PCM decrease the charging time by (5.5 - 22.1%) for weight fractions from (7.5-17.5%) respectively. The addition of metallic swarf to PCM showed enhancement of discharging time by (27 - 77 %) compared with the case of pure wax for copper swarf weight fraction of (7.5 – 17.5%) respectively. Thermal conductivity of PW was enhanced by using aluminum, copper, and iron swarf, where it is found that the maximum enhancement about (53 times) due to the addition of (17.5%) of aluminum swarf. This method is considered a successful economic way due to the use of manufacturing waste.*

Keywords*- Thermal energy storage systems, Latent heat storage, Phase change materials, Heat transfer, Paraffin wax, Charging time, swarf.*

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1. Introduction

The latent heat storage technology such as PCM is widely used in many applications such as domestic solar applications, energy storage in building materials, electronic cooling, and containers for food and drinks. Thermal energy can be stored in three ways, thermo-chemical heat storage, latent heat, and sensible heat. There are many different types of PCMs available, organic, inorganic, metal and metal Alloy PCMs [1]. The PCMs have desirable properties such as high latent heat of fusion, high in density, high specific heat, it can be processed to improve its thermal conductivity, non-explosive, non-toxic and non-flammable, available with large quantities and cheap [2]. There are three popular methods to increase the effective thermal conductivity of PCM. The first one is the use of macroscale metallic inclusions such as fins, meshes or foams, the second way is the use of macroscale carbon inclusions, which utilizes the high intrinsic thermal conductivity of carbon based materials, and the third method is the use of nanoscale materials to create colloidal PCM suspensions [3]. Osama et al. [4] investigated numerically the enhancement of thermal conductivity of PCM storage, they used porous matrix with (PCM). The numerical model was solved the volume averaged, momentum, conservation equations for mass, and energy with phase change melting in the porous matrix, they found that the addition of the porous matrix had a great effect on heat transfer and melting rate of the PCM energy storage. Hisham et al. [5] investigated experimentally the heat transfer enhancement in energy storage of paraffin wax by metal beads addition, they performed experiments using spherical capsules filled with paraffin wax and metal beads, they found that the enhancement up to (15%) for the solidification and melting processes with increases the rates of heat transfer during melting and solidification caused decreasing of the melting or solidification times, they were also found that the enhancement rate increases with the increase of the diameter and number of the metal beads. Yajuan et al. [6] studied experimentally enhancement of heat transfer of paraffin wax by using graphite foam for thermal energy storage system TESS, they used four types of graphite foams GFs with different thermal properties and pore size to increase the thermal conductivity of PCM (paraffin wax), for latent heat thermal energy storage application, the result showed that the thermal diffusivity of the paraffin-GF was enhanced to (190, 270, 500, and 570) times as compared with pure paraffin wax. Hosseinizadeh et al. [7] investigated experimentally and numerically performance of PCM with internal fins have different configurations, they compared between heat sink with and without phase change material (PCM), they used various parameters include (number of fins, power levels, fin thickness and fin height), they found that increasing in fin height and number lead to increase in overall thermal performance. The result indicates that an increasing in the fin thickness gave a low improvement. Kireeti et al. [8] studied experimentally the storage capacity of energy, thermal performance, and effectiveness, they used three public different thermal conductivity enhancement methods tested and compared. The material included the used of aluminum foam with PCM (AF-PCM), graphite foam with PCM (GF- PCM), and PCM with (10 wt.%) graphite Nano-fibers (GNF-PCM), they found that the common of enhancement method had a significant effected on response of thermal system. The result showed that GNF-PCM mixture was less effective when compared to the aluminum or graphite foams. Rohit et al. [9] studied experimentally the thermo-physical performance of paraffin with Fe_3O_4 Nano-fluids addition, they found that there was an enhancement in thermal conductivity due to the addition of Nano-fluids complex and it increased with an increase of volume fraction of particle. Due to the importance and the effectiveness of porous media in enhancing heat transfer and to avoid the problems of others technique like particles, three types of metallic swarf shown in Figure 1 are used as an inclusion to enhance charging and discharging processes. Iron, copper and aluminum swarf are added for this purposes. Make an experimental investigation on the effect of metallic swarf on thermal conductivity and specific heat of paraffin. The container is heated with constant heat flux. The metallic swarf is produced by machining process with three different weight fraction. Two different Reynolds number are used for discharging process. This method is considered an economic way due to the use of manufacturing waste.

2- Experimental Work

I. Experimental Setup

Experimental rig was consisted of the following parts and measuring devices, Figure 2 present the schematic diagram and photo; which includes (paraffin container, electrical heater, the duct, blower, voltage regulator, temperature controller, and instrumentation). The rectangular container of internal dimensions (30 cm × 10 cm × 10 cm) (length × width × height) has five surfaces made from plywood and covered with insulation Polyurethane foam board with a conductivity of about 0.017 W/m·◦C [10], while the sixth surface which is the bottom is made of copper plate with embedded electric heater which is used as a heat source during charge mode. During discharge mode another container is used with the same characteristics and dimensions. The only difference is that the copper plate has no heater coil embedded. The second copper plate without heater coil of 3 mm thickness is essential during discharging thermal calculation to avoid the unknown thermal properties of the heater coil and the insulation foils around it. Duct is made of plywood with length of 149 cm and cross section area of (2 cm height and 10 cm width). It is insulated by Polystyrene foam boards. It has an opening at the upper surface where the container is placed during discharge mode. Air flow inside the duct is promoted by an electric blower placed at duct entrance. Two thermocouples type k where used to measure inlet and outlet air temperature during discharging. Automatic voltage regulator or (stabilizer) was used to regulate output voltage on 220 v connected to voltage changers or (variac transformer). Heater and blower are connected to the voltage changer in order to control the supplied power to the heater and also the velocity of the blower as required. The instruments are used to measure temperature, air flow, current and voltage. To get the best result, variation of temperature should be recorded at a short interval, for this purpose, the experimental setup was equipped with a 12 channels thermometer recorder. Thermocouple type k was used to measure the temperatures. It was connecting to the thermometer recorder to display and record temperatures. Five of these thermocouples were placed in PCM charging container at mid plain with positions given in Table 1 and shown in Figure 3. The discharging container was fitted with six thermocouples, the first three positions are similar to position (T_2, T_3, T_4) as for charging container, and the other three (T_6, T_7, T_8) are implanted in a copper base plate and fixed by high thermal conductivity. Figure 4 show the distribution of measuring point for copper plate. Two thermocouples type k were used to measure the inlet and outlet air temperature during discharging mode. Power meter socket energy/electricity meter is used to measure the electric power. A hot wire anemometer was used to measure the air velocity. It was placed a distance about eight centimeters upstream outlet of duct to measure the air flow rate. Differential scanning calorimeter is used to determine melting temperatures and heats of fusion. It was found that the melting point of paraffin wax is 62.7 °C and the heat of fusion per unit mass is 105.52 J/g.

II. Experimental Procedures

1. Charging Process

a. PW was heated in an external container.
b. The molten of 2 kg PW was poured into the container of the test rig and then waiting for one day to solidify and cool the whole PW. 10% from the whole container volume is considered as a reserve to account for volume change of PW. The change in volume occurred because of the difference in density between the solid and liquid of PW.
c. After connecting the electric heater of container with the power meter socket and thermometer recorder with thermocouples, the sample was heated by operating the electric heater while the readings of thermocouples were observed and recorded.
d. The heating process was carried out for temperature range of (35 to 100) ° C to study the heating rates with time.
e. These tests were conducted for PW without and with the addition of swarf of copper, aluminum, and iron in three weight fraction (7.5%, 12.5%, and 17.5%) to the whole weight of mixture.
f. The processes were repeated at three heat fluxes (6.67, 10, and 13.33 kW/m^2) for each test.

2. Discharging Process

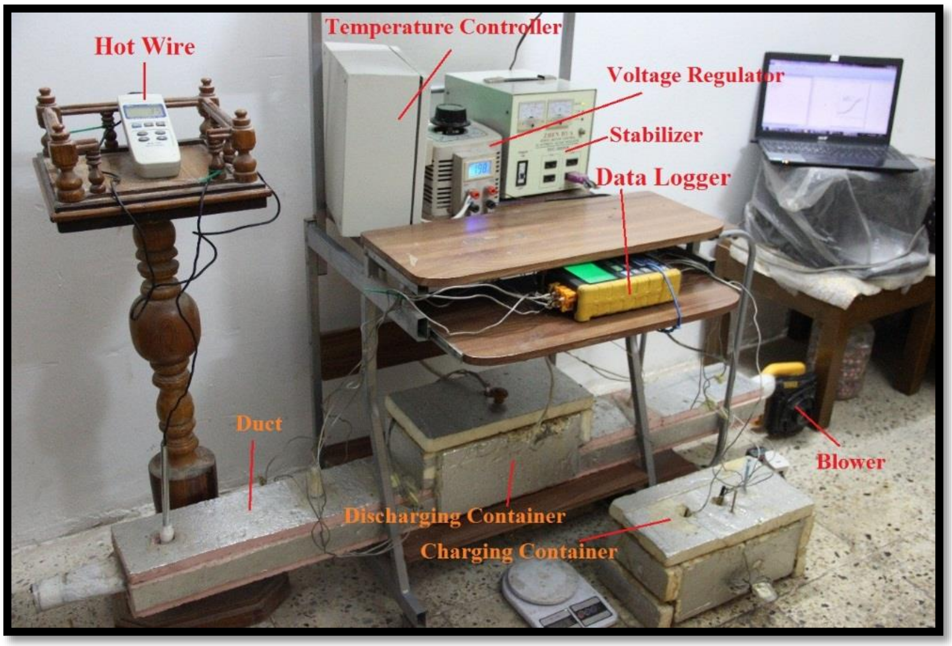
a. The discharging process started when the whole PW reached a 100 °C, the blower turned on with a specific velocity and thermometer started to record the readings of thermocouples with time.
b. Two different Reynolds number (9000 and 14000) were considered and three different weight fraction (7.5%, 12.5%, and 17.5%) of copper swarf were used.
c. The discharging process was carried out for temperature range of (100 to 50 ° C) to study the heating rates with time. Discharging process was done at room temperature T=18 °C.

Table 1: Thermocouple positions in paraffin container

Thermocouples	x-Axial position , mm	y-Axial position, mm
T1	75	40
T2	150	25
T3	150	40
T4	150	55
T5	225	40

(a) (b) (c)

Figure 1: Photograph of metallic Swarf; (a) Aluminum swarf (b) Copper swarf (c) Iron swarf



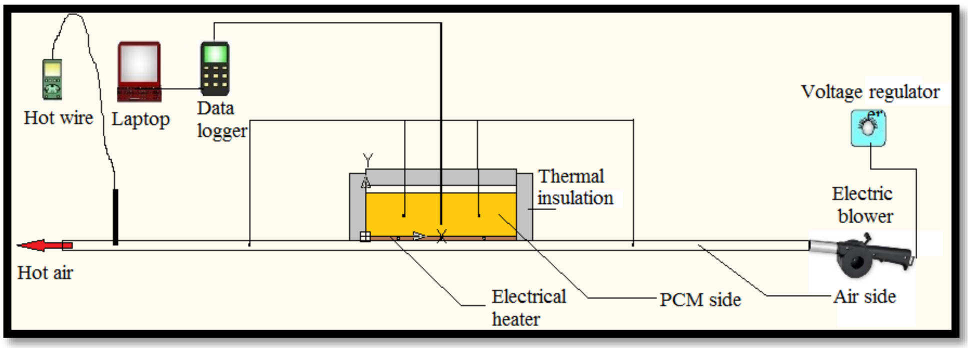


Figure 2: Schematic diagram and photograph of experimental rig

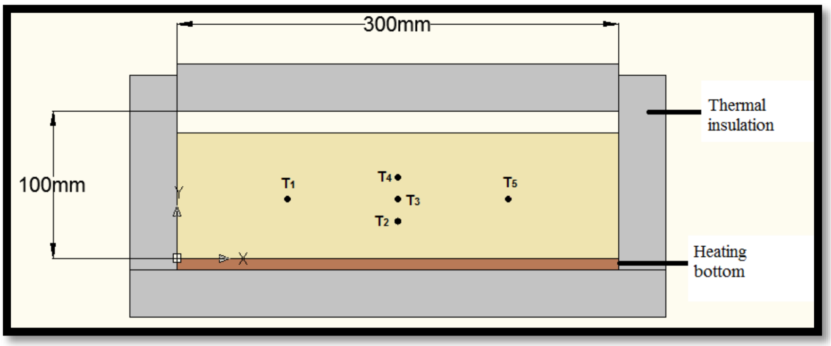


Figure 3: Distribution of measuring points for charging container

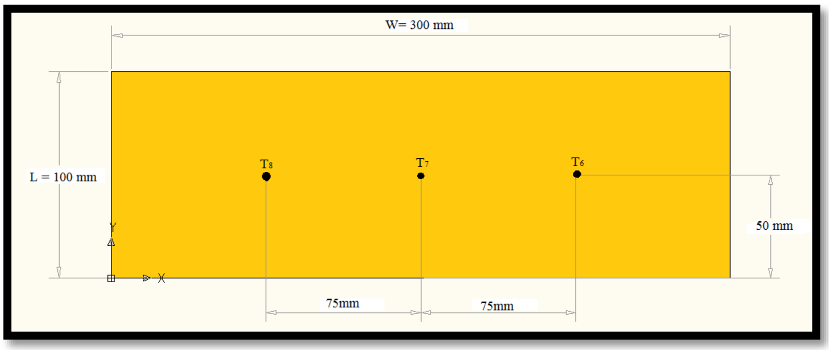


Figure 4: Distribution of measuring point for copper plate.

3-Experimental Equations

I. Electric Power

The generated electric power is calculated from power equation: [11]

$$P = V \cdot I \quad (1)$$

II.Total Heat Storage (THS)

THS for system with a PCM medium is given by: [1]

$$Q_{THS} = \int_{T_i}^{T_m} m\, C_p dT + m\, a_m\, \Delta h_m + \int_{T_m}^{T_f} m\, C_p dT \quad (2)$$

$$Q_{THS} = m\, [C_{sp}\, (T_m - T_i) + a_m\, \Delta\, h_m + C_{lp}\, (T_f - T_m)] \quad (3)$$

For heat storage of mixture paraffin/swarf replacing (m, C_p) by (m_{mix}, C_{mix}), where:

$$C_{mix} = (m_p \times C_p + m_{sw} \times C_{sw})/m_{mix} \quad (4)$$

III.Conduction Heat Transfer

There is transfer of heat between PCM particles due to conduction. Conduction heat transfer (CHT) is expressed as Fourier's law.

$$Q_{cond} = K_{mix}\, A\, \frac{\Delta T}{\Delta Y} \quad (5)$$

$$K_{mix} = (v_p \times K_p + v_{sw} \times K_{sw})/v_{mix}, \text{[11]} \quad (6)$$

IV.Convection Heat Transfer

The convection heat from PCM across the lower copper surface of the container during discharging period is conducting to duct air flow. It is calculating from Newton's law of cooling as: **[10]**

$$Q_{conv} = h_a \times A_s\, (T_w - T_b) \quad (7)$$

$$T_b = (T_{inlet} + T_{outlet})/2 \quad (8)$$

$$h_a \times A_s\, (T_w - T_b) = \dot{m} \times C_a\, (T_{outlet} - T_{inlet}) \quad (9)$$

The mass flow rate can be calculated from:

$$\dot{m} = \rho\, u\, A_c \quad (10)$$

$$ha = \frac{\dot{m} \times C_a\, (T_{outlet} - T_{inlet})}{A_s\, (T_w - T_b)} \quad (11)$$

Reynold number can be calculated from:

$$Re = \frac{\rho_a \times u_a \times D_H}{\mu_a} \quad (12)$$

$$D_H = \frac{4(W \times H)}{2(W+H)} \quad (13)$$

Nusselt number calculated from the following equation:

$$Nu = \frac{h_a \times D_H}{k_a} \quad (14)$$

$$D_H = \frac{4(W \times H)}{2(W+H)} \quad (15)$$

4- Results and Discussion

This chapter displayed the results of experimental tests for paraffin with and without addition of metallic swarf enhancement. The obtained experimental results are discussed.

I. Charging Mode

From Figure 5, one can notice the general trend of pure PW charging process. It is obviously that the time required to charge completely (2000 g) of pure PW and to reach 100 °C is (82.2 min) when the heat flux is 6.67 kW/m^2, (54.5 min) when the heat flux is 10 kW/m^2 and (39.9 min) when the heat flux is 13.33 kW/m^2. It is clear that the time required to complete the melting process is power input dependent.The long time needed for melting is a defect in using pure PW as PCMs. This is attributed to the low thermal conductivity. Figure 6 manifests the variation of PCM average temperature with charging time in case of (6.67 kW/m^2) constant heat flux. The improvement is due to the addition of (copper, aluminum, and iron swarf) respectively with three weight fractions (7.5%-12.5%-17.5%) to the whole weight of mixture. It shows that the charging time is decreasing with an increasing in weight fraction of metallic swarf. Figures 7 illustrates the variation of PCM average temperature with charging time. It is shows a reduction in charging time in paraffin wax due to the addition of various metallic swarf, namely copper, aluminum, and iron swarf for different weight fractions in case of (10 kW/m^2) constant heat flux. Thermal conductivity enhancement appears clearly at charging time, as shown in Figure 8 that shows the variation of PCM average temperature with charging time. An increasing in weight fractions of metallic swarf of (Cu, Al, and Fe) enhanced thermal conductivity as well as reduced the charging time. Melting process of paraffin wax used in experiments, occurs during a range of temperatures and doesn't occur at a single temperature, because the paraffin used contains different hydrocarbons and it is not a pure Alkane.From the obtained results, it was found that an increasing in weight fraction of swarf decreases the charging time, as compared with the case of pure PCM. The charging is considered to reach a PCM temperature of (100 °C).

II. Test Conditions at discharging mode

The test conditions were not as ideal as laboratory conditions, since the surrounding temperature in discharging mode was not fixed at all. The experiments continued during the months of year, and there is a difference in the temperature of the surrounding temperatures, which influence on the performance of the experiments, as well as the temperature difference between day and night, has the same affected on the experiments readings.

III. Discharging Mode

Discharging process was done with the addition of copper swarf of high thermal conductivity only because of the large number of experiments and the long period of time taken by the heat discharging process for each test. Also the test with one material gives an impression of the behavior of the other metallic swarf. Figures 9 and 10, it can be seen that the addition of copper swarf in different weight fractions reduce the discharging time. It is obvious that the addition of metallic swarf of high conductivity will certainly increase PCM mixture thermal conductivity and enhance heat conduction and heat transfer from or to surrounding. Actually the convection heat transfer coefficient, which is Reynold number depended, is the predominate factor for the discharging time and reducing discharging time. Figure 11 shows that the discharging time at (Re = 14000) is faster that at (Re = 9000). It is noticed from Figure 13 that an increasing in weight fraction of swarf reduces the heat capacity of mixture, because the heat capacity of additives is less than the heat capacity of pure paraffin leads to a decreasing in quantity of heat stored. Figure 13 Shows that an increasing in weight fraction of copper swarf at Re = 14000 caused to an increasing in Nusselt number while there is no effect on Nusselt number at Re = 9000.

Thermal Conductivity Enhancement

Metallic swarf has a high thermal conductivity. And, it provides a large solid to fluid surface area, which leads to high thermal conduction from swarf to pure PW. The enhancement in thermal conductivity leads to increase in the value of thermal diffusivity. Equation 6 was applied to calculate the thermal conductivity of mixture, the obtained results are presented in Figure 14 that show the thermal conductivity enhancement. Thermal conductivity of PW was enhanced with adding three types of metallic swarf, but this enhancement differs from each one of metallic swarf to other. It is clear that the aluminum swarf gave the higher values of thermal conductivity enhancement. The reduction in charging and discharging time doesn't only depend on thermal conductivity (conduction heat transfer), but also on surface area of additives that cause to increase convection heat transfer according to Newton's law of cooling.

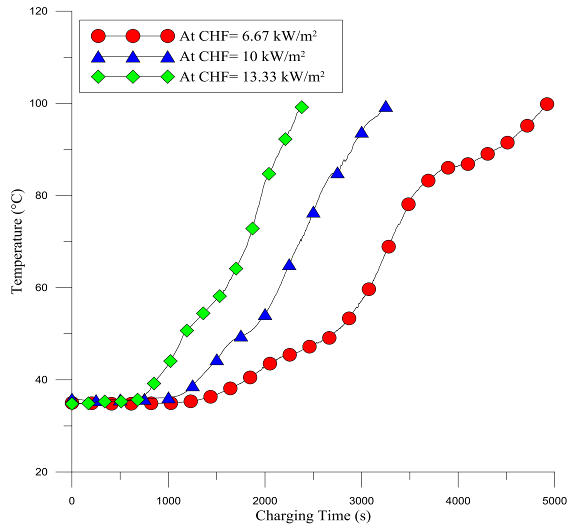
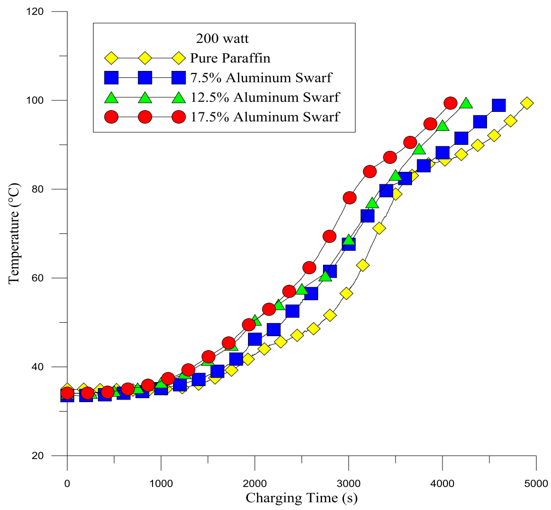
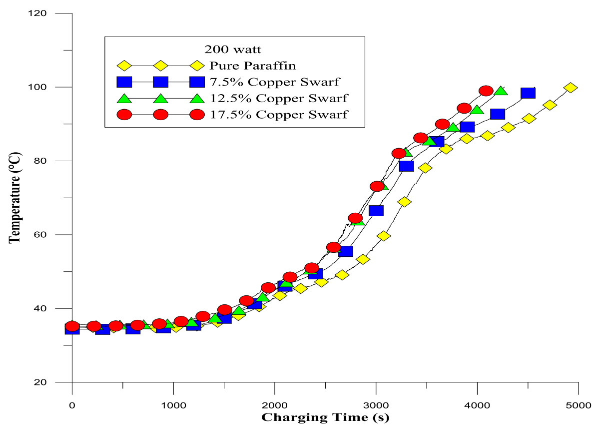


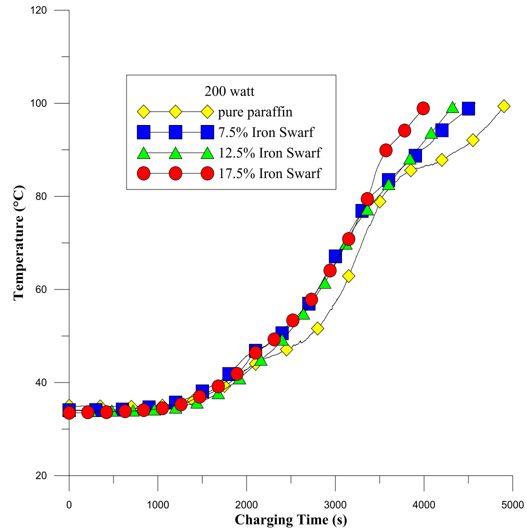
Figure 5: Average Temperature with Charging Time for Different Charging Powers Using Pure Paraffin



(a)Aluminum Swarf

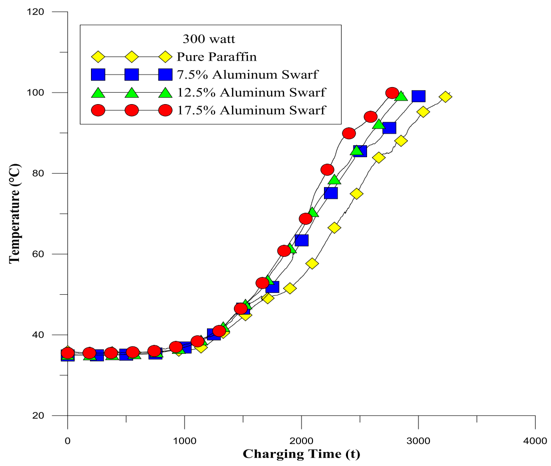


(b)Copper Swarf

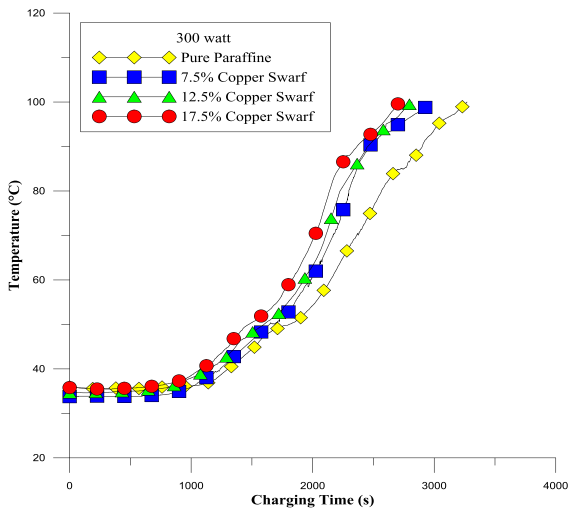


(c)Iron Swarf

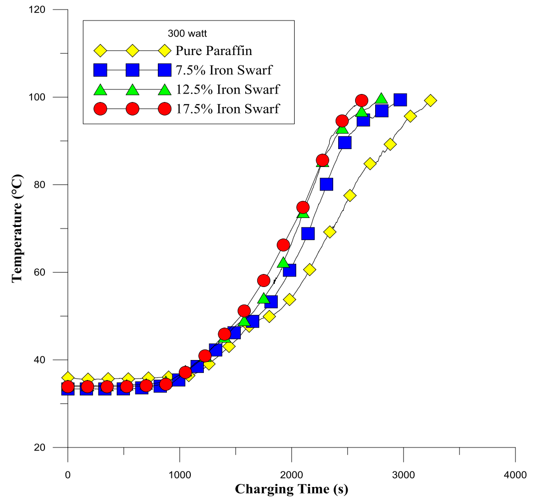
Figure 6: Average Temperature Variation of the PCM with Charging Time for 6.67 kW/m^2 CHF with the Addition of Metallic Swarf for Different Weight Fractions Compared with the Case of Pure Paraffin.



(a)Aluminum Swarf

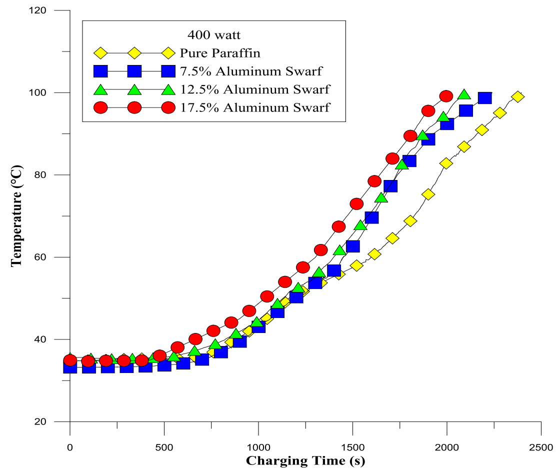


(b)Copper Swarf

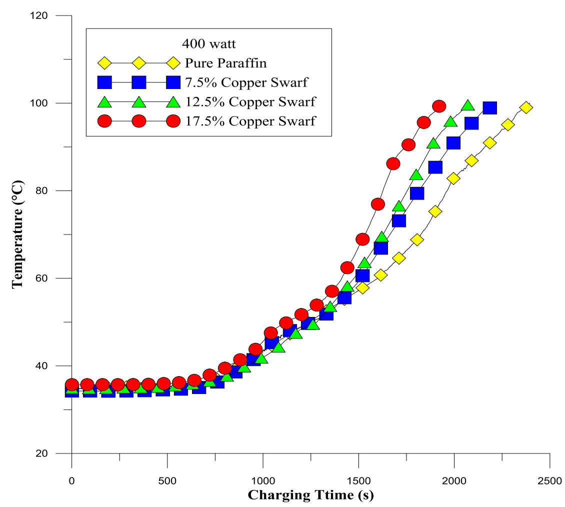


(c) Iron Swarf

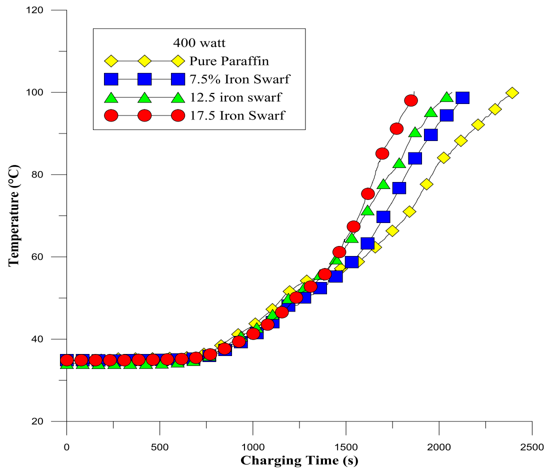
Figure 7: Average Temperature Variation of the PCM with Charging Time for 10 kW/m^2 CHF with the Addition of Metallic Swarf for Different Weight Fractions Compared with the Case of Pure Paraffin.



(a)Aluminum Swarf



(b) Copper Swarf



(c)Iron Swarf

Figure 8: Average Temperature Variation of the PCM with Charging Time for 13.33 kW/m^2 CHF with the Addition of metallic Swarf for Different Weight Fractions Compared with the Case of Pure Paraffin.

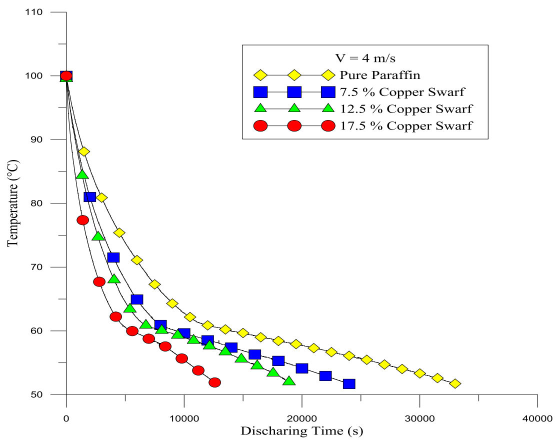


Figure 9: Average Temperature Variation of the PCM with Discharging Time with the Addition of Copper Swarf for Different Weight Fractions Compared with the Case of Pure Paraffin at Re = 9166

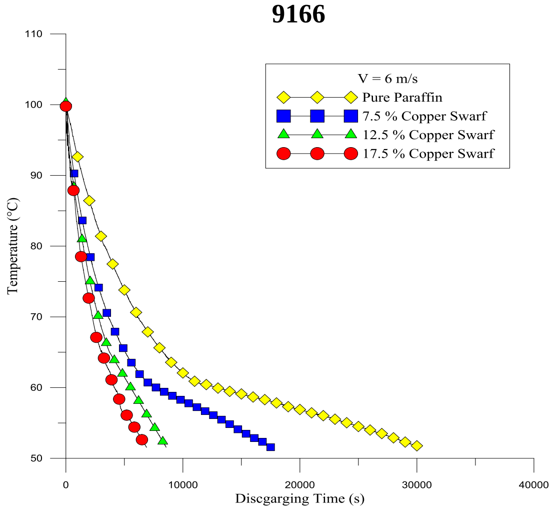


Figure 10: Average Temperature Variation of the PCM with Discharging Time with the Addition of Copper Swarf for Different Weight Fractions Compared with the Case of Pure Paraffin at Re =13750

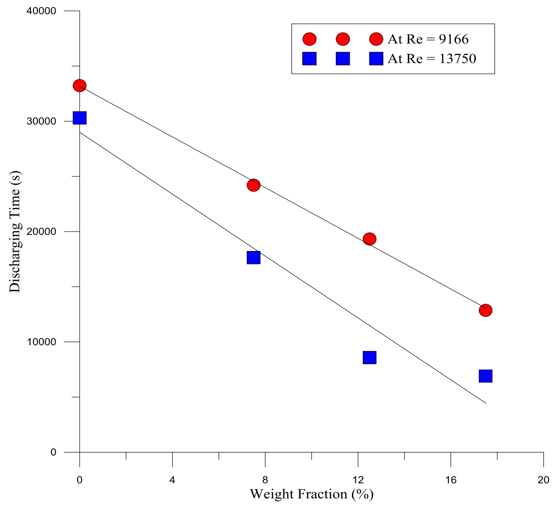


Figure 11: Discharging Time Variation for Different Copper Swarf Fraction at Two Reynolds Number

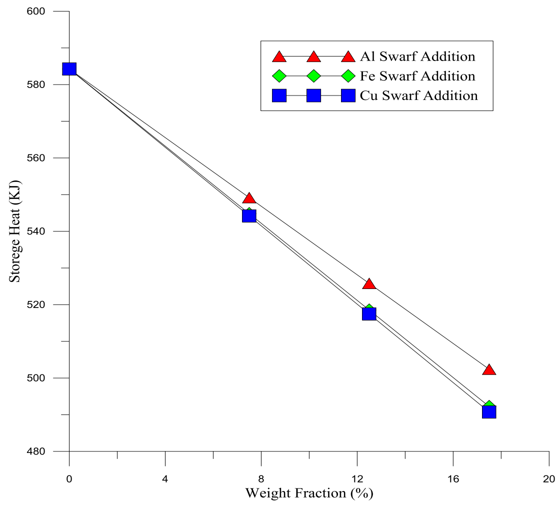


Figure 12: Heat Storage at 100 °C with the Addition of Different Weight Fractions of Metallic Swarf

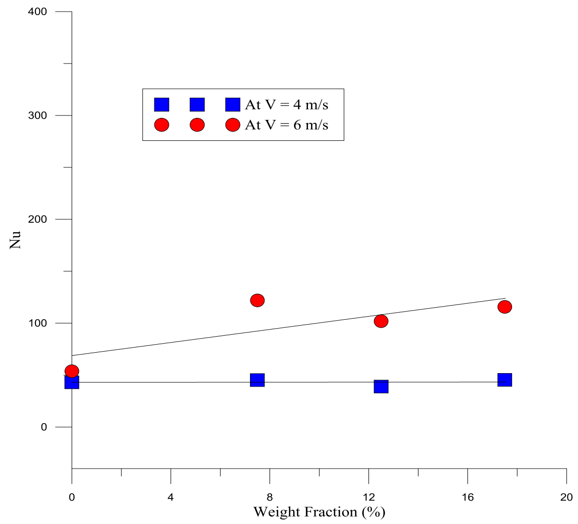


Figure 13: Nusselt Number Variation with Weight Fraction at Two Velocities During Discharging Mode

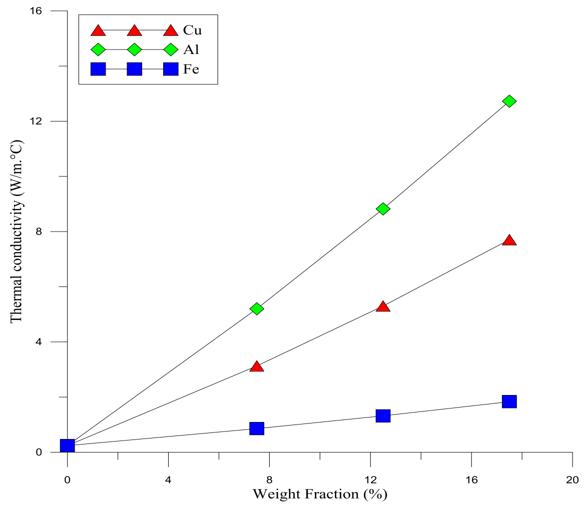


Figure 14: Enhancement in Thermal Conductivity Vs. Weight Fraction of the Metallic Swarf

5- Conclusions

The experimental study of swarf-enhanced phase change material exhibits the following conclusions and recommendations for future works.

- Adding of metallic swarf to the PCM decrease the charging time by (5.5 - 22.1%) for weight fraction from (7.5-17.5%) respectively
- The addition of metallic swarf to PCM showed enhancement of discharging time by (27 - 77 %) compared with the case of pure wax for copper swarf weight fraction of (7.5 – 17.5%) respectively.
- Time of charging is reduced gradually by increasing the weight fraction of added swarf.
- The melting in container is specified by three stages, the first stage is characterized by conduction heat transfer, the second stage is conduction-convection heat transfer with phase change process, and the third stage is a pure convection heat transfer characterized by high rate of temperature rises and more curvature during the melting.
- Thermal conductivity of PW is enhanced by using aluminum, copper, and iron swarf, where it is found that the maximum enhancement about (53 times) due to the addition of (17.5%) of aluminum swarf.
- An increase in metallic swarf reduces the specific heat and storage heat, where it is found that the maximum reduction in heat storage about 15.8 %due to the addition of 17.5% of iron swarf.
- The time required to complete the melting process is power input dependent, and the time required to complete the solidification process is depending on Reynold number.

Symbol	Description	Unit
a_m	Fraction melted	-
A	Area	m^2
Ac	Cross sectional area of duct.	m^2
C	Specific heat	J/kg. °C
C_{ap}	Average specific heat between T_i and T_f	(J/kg. K)
C_{sp}	Average specific heat between T_i and T_m in the solid phase	J/kg. °C
C_{lp}	Average specific heat between T_m and T_f in the liquid phase	J/kg. °C
D_H	Hydraulic diameter	m
e	Error associated with given instrument	-
h	Convection heat transfer coefficient	W/m^2. °C
H	Height	m
Δh_m	Heat of fusion that is required to change the phase from solid to liquid per unit mass.	J/kg
I	Current	A
k	Thermal conductivity	W/m. °C
L	Length	m
$\dot{m}$	Mass flow rate of air	kg/s
m	Mass	kg
Nu	Nusselt number	-
P	Electric power	W
Q	The amount of heat storage.	KJ
Q_{conv}	Convection heat transfer	w
Q_H	Total heat of heater	KJ
Q_{THS}	Quantity of total heat stored	J
Re	Reynolds number	-
t	Time	s
T	Temperature	°C
T_w	Temperature of surface wall of copper plate	°C
T_b	Bulk temperature of air.	°C
T_{inlet}	Temperature of the fluid at inlet of the duct	°C
T_{outlet}	Temperature of the fluid at outlet of the duct	°C
u	Mean velocity	m/s
V	Voltage	V
v	Volume	m^3
W	Width	m
x	Dimensional length of the x-axis	m
y	Dimensional length of the y-axis	m

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