Experimental Study on the Effect of Using Metallic Brushes on the Charging and Discharging Time of Thermal Energy Storage Unit

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ABSTRACT

Phase change materials are known to be good in use in latent heat thermal energy storage (LHTES) systems, but one of their drawbacks is the slow melting and solidification processes. So that, in this work, enhancing heat transfer of phase change material is studied experimentally for in charging and discharging processes by the addition of high thermal conductive material such as copper in the form of brushes, which were added in both PCM and air sides. The additions of brushes have been carried out with different void fractions (97%, 94% and 90%) and the effect of four different air velocities was tested. The results indicate that the minimum brush void fraction gave the maximum heat transfer in PCM and reduced the time for melting for (ϵ=90%) up to 4.49 times as compare with the case of no brush. It can be seen that the addition of brushes in air side helped to reduce the solidification time and increase the convection heat transfer coefficient as the brush void fraction decreased. Also the minimum velocity (v = 1 m/s) gave maximum outlet temperature.

Keywords: Thermal storage, Phase change materials, Latent heat thermal energy storage and heat transfer enhancement.

دراسة عملية على تأثير استخدام فرش معدنية على المادة المتغيرة الطور الخازنة للطاقة

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الخلاصة

المواد المتغيرة الطور تعد من المواد الجيدة المستخدمة في منظومات خزن الطاقة الحرارية الكامنة, ولكن احد عيوبها هو الانصهاروالانجماد ببطء. في العمل الحالي تم دراسة تحسين انتقال الحرارة للمواد المتغيرة الطور خلال عملية الشحن والتفريغ عملياً وذلك بأضافة مادة لها موصلية حرارية عالية مثل النحاس والذي سوف يكون بشكل فرش, وهذه الفرش سوف تضاف في جانب المادة المتغيرة الطور وجانب الهواء. تمت اضافة الفرش بنسب فراغ (97%, 94% و 90%) مع اختبار تأثير اربع سرع مختلفة. وقد بينت النتائج ان اقل نسبة فراغ للفرشاة اعطى اكبر زيادة في نسبة انتقال الحرارة في المادة المتغيرة الطور بحيث قل الزمن اللازم للانصهار لحالة (ϵ = %90) الى 4.49 مرة بالمقارنة مع حالة عدم وجود الفرشاة. وقد لوحظ ايضاً ان اضافة الفرش في جزء الهواء ساعد في تقليل الزمن اللازم للانجماد وكذلك زادت من معامل انتقال الحرارة بواسطة الحمل بنقصان النسبة الفراغية للفرشاة. وكذلك وجد ان اقل سرعة مستخدمة اعطت اكبر حرارة للهواء الخارج.

الكلمات الرئيسية: الخزن الحراري, مواد متغيرة الطور, خزن الطاقة الحرارية الكامنة و تحسين انتقال الحرارة.

1. INTRODUCTION

Solar energy is one of the most important types of renewable energy because it is one of the cleanest energy and has no impurities into the environment, also it is infinite. Thermal energy storage systems (TESS) are one type of renewable energy systems in which they were developed to use the solar energy in night or in case of dust or clouds. TESS is of critical importance in many engineering applications. The demand for CO_2 reduction to curb global warming considerably increases the interest in utilizing renewable energy sources, especially solar energy **Zhao, et al., 2010**. TESS is one of the most important applications of phase change materials (PCMs). They can be applied conveniently in many fields such as peak shift of electrical demands, solar energy utilization, waste heat recovery, intelligent air-conditioned buildings, and temperature controlled greenhouses, electrical appliances with thermostatic regulators, energy storage kitchen utensils, insulation clothing and season storage **Molefi, 2008.** They can be classified into three main categories according to different storage mechanisms: sensible heat storage, latent heat storage and chemical heat storage. To date most of the studies conducted on storage materials have concentrated on sensible and latent heat storage systems. Studies conducted to compare phase change and sensible heat storages have shown that a significant reduction in storage volume can be achieved using PCM compared to sensible heat storage **Tian**, **2012.**

There are mainly three types of PCMs existing in the solid-liquid category: organic-PCM, inorganic-PCM and eutectic-PCM. In order to be utilized for real applications, PCMs need to meet the thermal, physical, kinetic, chemical and economical requirements **Sunliang, 2010.** Materials to be used for phase change thermal energy storage must have high latent heat of fusion and high thermal conductivity. They should also have a melting temperature lying in a practical range of operation, melt uniformly, chemically inert, low cost, non toxic and non corrosive. As paraffin wax possesses most of these properties it attracts considerable attention as a PCM. However, paraffin waxes have inherently low thermal conductivity and so it takes considerable time to melt and solidify, which reduces the overall power of the thermal storage device and thereby restrict their application **Vadwala, 2011.**

Most PCMs have low thermal conductivity, which led to slow melting and solidification. Different studies have been done to enhance heat transfer in PCMs which include, for example, the addition of water bubbles **Velraj, et al., 1999**, carbon fiber brushes **Fukai, et al., 2002**, longitudinal fins **Castell, et al. , 2006**, metallic powder **Bellah,** and **Ghazy**, **2007,** graphite **Zhang, et al., 2011,** metal foam **Vadwala, 2011**, nanofibers **Sanusi, et al., 2011**and metallic particles **Hasan, 2013**.

Velraj, et al., 1999, investigated three methods of enhancing the heat transfer rate of paraffin wax encapsulated in a cylindrical aluminum tube using internal longitudinal aluminum fins, steel Lessing rings and water bubbles. It found that the best enhancement method was by using of Lessing rings (20% by volume) in which they decrease the freezing time by a factor of 9, and increase thermal conductivity about 10 times than pure paraffin. Also the finned tube with a volume fraction of 7% decrease the solidification time to about 4 times of that of no fins. **Fukai, et al., 2002**, improved the heat transfer rate during the charge and discharge processes by making use carbon fiber brushes combined with n-octadecane. Carbon fiber improves the thermal conductivities of phase-change materials packed around heat transfer tubes. The thermal conductivity increased as the volume fraction and diameter of fibers increased. It was found that the use of brushes improved the charging and discharging rate to about 20% and 30%, respectively, higher than that using no fibers. **Castell, et al., 2006**, study the effect of using longitudinal vertical fins inside a cylindrical water tank which contain cylindrical PCM modules. The experiments were done with three different cases, without fins, with fins of 20mm height and with fins of 40 mm height. It was found that the use of these fins should increase the heat transfer coefficient up to 3 times larger than the ones without fins. Also, they reduced the time which was required for solidification of PCM to about 23.53% and 58.82% for the cases of 20 mm and 40 mm height respectively. **Bellah,** and **Ghazy**, **2007**, made use of 80 μm aluminum powder with PCM in a solar collector. It was found that the addition of 0.5 mass fraction of powder decrease the charging time up to 60% as compare with the case of pure paraffin. **Zhang, et al., 2011**, tried to improve the thermal conductivity of paraffin by using expanded graphite with 7% mass fraction. The results show that the graphite/paraffin composite PCM made 44% reduction in heat storage duration and 69% reduction in the retrieval duration, respectively, as compared with the pure paraffin. **Vadwala, 2011**, placed copper foam (85% porosity) in a rectangular TESS for both PCM (paraffin wax) and air sides. The results show that the thermal conductivity of PCM was increased to about 18 times that of pure paraffin. The time required to melt the same quantity of wax was reduced to 36% of that without foam. Also it was found that the addition of metal foam in the air side decreases solidification time. **Sanusi, et al., 2011,** study experimentally the effect of graphite nanofibers on thermal storage and the solidification time with different aspect ratios. It was found that the addition of these fibers reduce the maximum temperature in the thermal containment unit up to 48%. Also the results showed a reduction in the solidification time up to 61% for the case of 1 aspect ratio. **Hasan, 2013**, made a Comparison between Different Composite PCMs encapsulated for TESS. The thermal conductivity of paraffin had been enhanced by using four different additives which were graphite powder, copper particles, aluminum oxide particles and copper network. The mass ratios of the additives were 3%, 6% and 9%. It was found that copper network with 6% mass ratio gave best enhancement which reduce the time for charging and discharging by 26.4% and 30.3% respectively as compared with pure paraffin. Also thermal conductivity of PCM enhanced by2.57 times than pure paraffin.

The objective of this work is to study experimentally the enhancement of charging and discharging processes by using copper brushes embedded in both PCM and air sides with different void fractions. The effect of air velocity was also observed.

2. EXPERIMENTAL TEST

2.1 Experimental Setup

A small scale thermal energy storage device is fabricated, both with and without copper brush. A paraffin wax grade B (melting temperature equal to 63.7˚C, k= o.214 W/m.˚C) was employed as heat storage media. The experimental setup is shown schematically in **Fig. 1**. It consists of entry section, test section, exit section and transition section. The length of each section is about 1070 mm, 300 mm, 390 mm and 380 mm, respectively. A transition section connects between the entry section and a fan with specification of (0.27 A, 61 W, 3100 rpm). The dimension of the test section was 300 mm × 90 mm × 86 mm (L × W × H). The height of the air side and PCM side were 42 mm and 32 mm, respectively. A Perspex sheet with 9 mm thickness was used to form the test section. A copper plate (2.5 mm thick) is used to separate each side & was placed in two slots (3 mm thick) opposing each other. Other opposing slots of the same thickness of the former ones were in the upper part of the PCM side and another copper plate was placed inside it. In the upper side of this plate, a tape heater (150 W, 260 V) with dimensions of 280 mm× 65 mm, was fixed over it. To ensure good contact between the heater and the copper plate, a heat-conductive paste was used. For each copper plate, a thermocouple type K had been fixed in the middle of them. Other five thermocouples type K were distributed approximately in the center of PCM side with 10 mm distance between adjacent thermocouple. The top thermocouple should be connected to the process controller which works to control the heater to give a constant temperature of 100°c for the upper plate, so that it should be an input to it.

Six thermocouples type K had been distributed in the air passage, one in the entrance, one in the exit and the others are distributed along the centre plane of the air side with equal spaces between them (70 mm spaces). A data logger device (model: BTM-4208SD, Lutron electronic enterprise company) is used to record the data. Fiberglass insulation (12.7 mm thick) with an aluminized outer surface had been used to insulate the test section. The air velocity of 1, 2, 2.5 and 3 m/s is produced by a fan which was controlled by a fan controller by changing the voltages entering to it. These velocities had been measured by a hot wire anemometer (model: YK-2005AH, Lutron electronic enterprise company) fixed in the entrance of the test section.

Two copper brushes had been placed in PCM side which had a diameter equal to the height of the PCM container. So that, each wall was in contact with brushes copper wires. Other two brushes were placed in the air side, and also they had a diameter equal to the air side height. The length of all brushes is equal to the test section length. In each side the tests should be done with three different void fraction 97%, 94% and 90%. The void fraction of each brush had been calculated using standard test method (ASTM C 127). The brushes are weighted with gram unit in air and then in water to get there densities in air and water and then calculate void fraction (ϵ) using Eq. (3). The following equations are using for that purpose:

$$\rho_a = \frac{m_a}{V_b}$$

$$\rho_w = \frac{m_a}{m_a - m_w}$$

$$\epsilon = \frac{\rho_w - \rho_a}{\rho_w}$$

Where;

m_a = mass of weighted material in air, (g).
m_w = mass of weighted material in water, (g).
V_b = bulk volume of used material, (cm^3).
ρ_b = bulk material density, (g/cm^3).
ρ_w = density of material in water, (g/cm^3).
ϵ = void fraction, (%).

Because of the high thermal conductivity of the copper wires (k= 385 W/m.°C), the PCM brushes work to enhance thermal conductivity and reduce the time for paraffin wax melting. Also the addition of brushes in air side work to decrease the time of solidification.

2.2 Experimental Procedure

Several experimental tests were done with different cases. First of all, the molten paraffin wax was poured into the test rig. After its solidification, a gap of air would be appear in the upper part of the test section because of the decrease in volume of PCM due to differences in solid and liquid densities. After the fixation of the whole TESS, the melting and solidification tests (without brush) should be done for different velocities. A process controller was setup to control the heater to provide constant temperature (100°C) to the top copper plate. The melting time starts from the time the heater turned on, till the lower copper plate reaches a temperature of 63.7°c. after the heater turned off, the fan turned on and the solidification process starts. The fan was controlled via a fan controller to get the required velocities. This process ended until the whole wax reached its starts temperature. So that, as the charging time is over, the discharging time begins.

The previous processes should be repeated but with the addition of copper brushes in both air and wax sides. Also, the tests should be done with different void fractions (97%, 94% and 90%) to show the effect of the void fraction in charging and discharging processes. **Fig.2** shows these brushes and their position.

3. EXPERIMENTAL DATA REDUCTION

3.1 PCM Side

3.1.1 Latent heat storage

The heat storage in PCM side is in the form of latent heat. The storage capacity can be found from:

$$Q = \int_{T_1}^{T_m} m \,.\, Cp_s \,.dT + m \,.\, a_m \,.\, \Delta h_m + \int_{T_m}^{T_2} m \,.\, Cp_l \,.\, Dt$$

$$= m\,[\,Cp_s\,(T_m - T_1) + a_m \,.\, \Delta h_m + Cp_l\,(T_2 - T_m)] \tag{1}$$

Where;

T_m = melting temperature of the storage material, ˚C.
T_1 = initial temperature of the storage material, ˚C.
T_2 = final temperature of the storage material, ˚C.
m = mass, kg.
Cp_l = average specific heat between T_m and T_2, J/kg.˚C.
Cp_s = average specific heat between T_1 and T_m, J/kg.˚C.
a_m = the fraction melted**.**
Δh_m = heat of fusion, J/kg.

It can be seen that the second term represents the period in which phase change occurs during it, which means that it is the period for transformation from solid to liquid and vice versa. Conduction heat transfer: The heat transfer inside the PCM occurs due to conduction between its particles. The conduction occurs from the upper surface of PCM to the lower surface of PCM. The following equation represents Fourier's law for heat conduction:

$$Q = k\,A\,\Delta T/\Delta x \tag{2}$$

Where;

Q = power extracted, W.
A = area, m^2.
ΔT = temperature difference between the upper and lower point of PCM, ˚C.
Δx = distance between the upper and the lower point of PCM, m.

3.2 Air Side

The following procedure was used to calculate mass flow rate, Nusselt number, Reynold number, convection heat transfer coefficient and power extracted. The experimental data includes the measured velocities and thermocouples readings. The air thermo physical properties were taken at bulk mean air temperature;

$$T_b = \frac{Ti+To}{2} \tag{3}$$

Where;

T_b = bulk temperature of air, ˚C.
T_i = inlet air temperature, ˚C.
T_o = outlet air temperature, ˚C.

3.2.1 Mass flow rate

Mass flow rate can be calculated using the following relation;

$$m = \rho \ v \ A_c \tag{4}$$

Where;

v = velocity, m/s.
A_c = crosses sectional area, m^2.

3.2.2 Rate of heat transfer

Value of heat transfer between the hot surface and the moving air can be calculated experimentally from;

$$Q = m \ Cp \ (T_o\text{-}T_i) \tag{5}$$

3.2.3 Convection heat transfer coefficient measurement

Convection occurs between the hot copper plate and the air flow beneath it. It was considered to be constant along the duct length. So that it is given by;

$$h = \frac{Q}{As(\boldsymbol{T_s}-\boldsymbol{T_b})} \tag{6}$$

Where;

T_s = surface temperature, ˚C.
A_s = surface area, m^2.

3.2.4 Reynolds number

It is calculated from;

$$Re = \frac{\rho v \boldsymbol{D_H}}{\mu} \tag{7}$$

Where;

Re = Reynolds number.
μ = dynamic viscosity, kg/m.s.

In which D_H is the hydraulic diameter and can be calculated from;

$$D_H = \frac{2WH}{4(W+H)} \tag{8}$$

Where;

W = width, mm.
H = height, mm.

3.2.5 Nusselt number

It can be calculated using the following equation;

$$Nu = \frac{hD_H}{k} \tag{9}$$

4. RESULTS AND DISCUSSION

This work investigates the effect of copper brush on the melting and solidification time of an organic PCM (paraffin wax grade B). **Fig. 3** shows the lower copper plate temperature variation with time for four cases, without brush, with brush (ϵ=97%), with brush (ϵ=94%) and with brush (ϵ=90%). The time for melting was decreased up to 2.67, 3.71, 4.49 times, respectively, as compare with the pure paraffin case, which means that the heat transfer was enhanced.

Fig. 4 shows the behavior of middle point temperature of PCM in melting and solidification process. It can be seen that the melting and solidification time was decrease in the addition of metal brush as compared with pure paraffin, where the lower void fraction, the lower time for melting and solidification. The copper brushes reduced the solidification time of paraffin up to 1.47, 1.55 and 1.64 when they add in both sides with 3%, 6% and 10% volume percent, respectively, as compared with pure paraffin case.

It can be seen from **Fig. 5** the temperature distribution of five points distributed along PCM in case of brushes with 90% void fraction during melting process. The middle point was melted faster than other points because it was the furthest point from the walls. Also the lower point takes longer time to melt due to its distance to the upper copper plate.

Fig. 6 presents that the lower void fraction of brush in air side gave the maximum outlet temperature. This was due to the increase in contact between the upper copper plate and the brush wires which cause an increase in heat transfer from copper plate and brush to the air flow over them. So that, the decrease in void fraction cause an increase in turbulent which helps to increase the heat exchange between them. The amount of increase in outlet temperature for (ϵ= 97%, 94% and 90%) as compared with the case of no brush were 8.75, 10.32 and 11.99 ˚C, respectively with 2.5 m/s air velocity, in which these values are taken as hourly temperature.

The outlet air temperature vs. time was shown in **Fig. 7** during solidification process with four different velocities in case of brushes (ϵ=90%) in both wax and air side. As compared with the case of no brushes in both sides, it can be seen that the maximum temperature difference reach up to (21.85˚C) occurred in case of minimum void fraction (90%) and minimum velocity (v=1 m/s). That is because at low velocity (v=1 m/s) air will has enough time to acquire heat and make heat exchange with the lower copper plate. While at maximum velocity (v=3 m/s) air will be pass beneath the lower plat quickly.

Also, the higher the velocity, the minimum the outlet temperature and the maximum the temperature gradient. The results show that the decrease in void fraction of brushes in air side cause an increase in Nusselt numbers due to a significant increase in outlet air temperature which resulted in higher Nusselt number for the three void fractions (97%, 94%90%). This increase, as shown in Fig. 8, was up to 2.83, 3.69 and 4.23 times, respectively, as compared with the case of no brush. Fig. 9, 10, shows the relation between velocities with power extracted and convection heat transfer coefficient with different brushes void fractions. As in Nusselt numbers, for lower void fraction, higher power and convection heat transfer coefficient are obtained. The amounts of increase in power for (ϵ=97%, 94%, 90%) were 2.24, 2.49 and 2.83 times, respectively, and 2.9, 3.79 and 4.34 times, respectively, for h as compared with the case of no brush. The results in **Figs. 8, 9** and **10** were taken as an average values for hourly temperature.

5. CONCLUSION

In this work, the thermal conductivity of wax and heat transfer coefficient of flowing air was enhanced by using copper brushes. The enhancement process done to reduce the time for melting and solidification by the addition of brushes in wax and air sides, the following conclusions can be extracted:

The addition of brushes in PCM side reduce the time for melting for (ϵ=90%) by 4.46 times as compare with the case of no brushes. It can be seen that, for lower void fraction, minimum melting time is obtained. The addition of brushes in air side worked to enhance the discharging process, and also reduce the time required for solidification. Lowest void fraction in air side decreases the solidification time and increases the outlet air temperature. The maximum temperature difference reached up to 21.85˚C which occurred in case of minimum void fraction and minimum velocity. The obtained results show that minimum velocity gave maximum outlet temperature. But maximum velocities increased the heat transfer rate especially in the initial period which resulted in minimum time required for freezing. Also, at minimum void fraction and maximum velocity, higher Nu, h and Q for air can be observed. This is because of increase in turbulence which causes an increment in heat transfer rate.

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NOMENCLATURE

a_m = the fraction melted.
A_c = crosses sectional area, m^2.
A_s = surface area, m^2.
Cp = specific heat of air, J/kg.˚C.
Cp_l = average specific heat between T_m and T_2, J/kg.˚C.
Cp_s = average specific heat between T_1 and T_m, J/kg.˚C.
D_H = hydraulic diameter, m.
h = convection heat transfer coefficient, W/m^2.˚C.
Δh_m = heat of fusion, J/kg.
H = height, mm.
K = thermal conductivity, W/m.˚C.
L = length, mm.
m = mass, kg.
m_a = mass of weighted material in air, (g).
m_w = mass of weighted material in water, (g).
Nu = Nusselt number, dimensionless.
Q = power extracted, W.
Re = Reynolds number.

t = time, minute.
T = temperature, ˚C.
ΔT = temperature difference between the upper and lower point of PCM, ˚C .
T_b = bulk temperature of air, ˚C.
TC = thermocouple.
T_i = inlet air temperature, ˚C.
T_m = melting temperature of the storage material, ˚C.
T_{mid} = middle temperature of the storage material, ˚C.
T_o = outlet air temperature, ˚C.
T_s = surface temperature, ˚C.
T_1 = initial temperature of the storage material, ˚C.
T_2 = final temperature of the storage material, ˚C.
v = velocity, m/s.
V_b = bulk volume of used material, (cm^3).
W = width, mm.
Δx = distance between the upper and the lower point of PCM, m.
Greek symbols.
ϵ = void fraction, %.
μ = dynamic viscosity, kg/m.s.
ρ = density, kg/m^3.
ρ_b = bulk material density, (g/cm^3).
ρ_w = density of material in water, (g/cm^3).

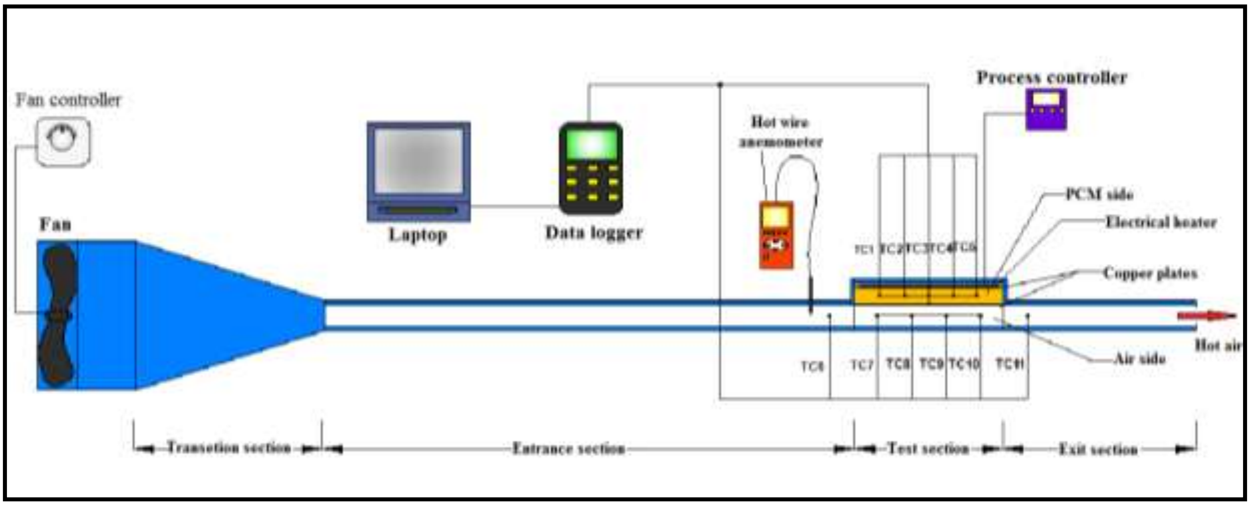

Figure1. Schematic diagram of experimental apparatus.

-a- -b-

Figure 2. a) PCM and air brushes, b) Test section with brushes.

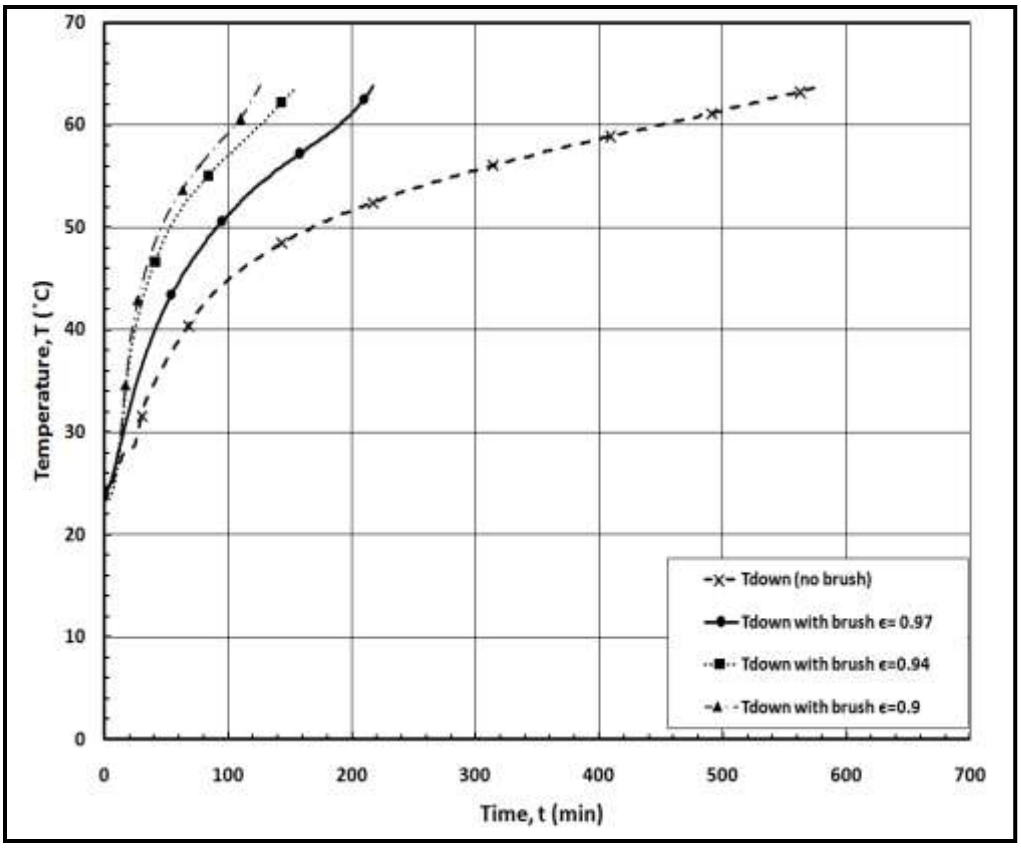

Figure3. Temperature variation of bottom point of paraffin wax vs. time during melting process for the cases of brushes with different void fractions.

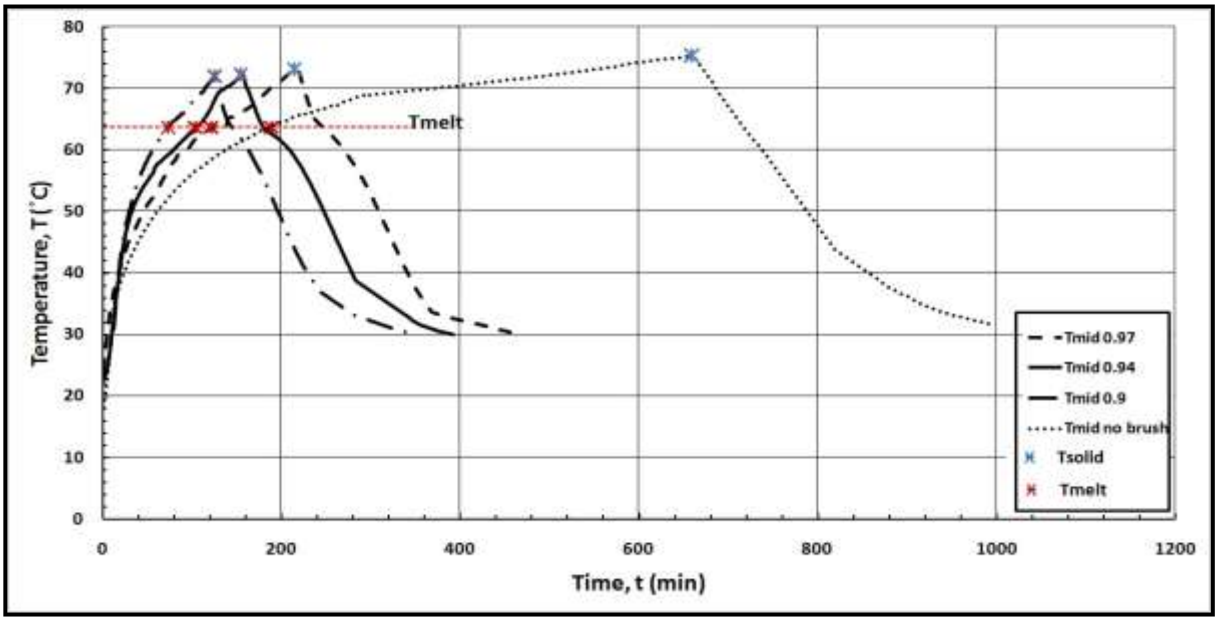

Figure 4. Temperature variation and the melting and solidification point of middle PCM point in charging and discharging processes with and without brushes for different void fractions. The discharging process is conducted for velocity of 2.5 m/s.

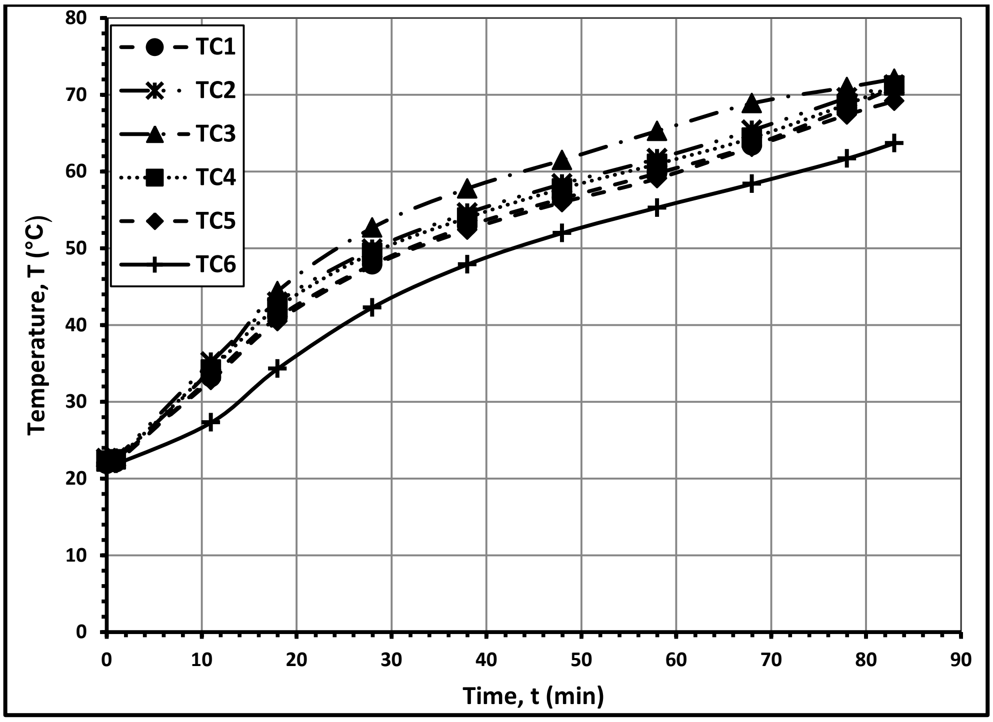

Figure 5. Temperature distribution for different points along the axial center line of PCM during melting process in case of brushes with 90% void fraction.

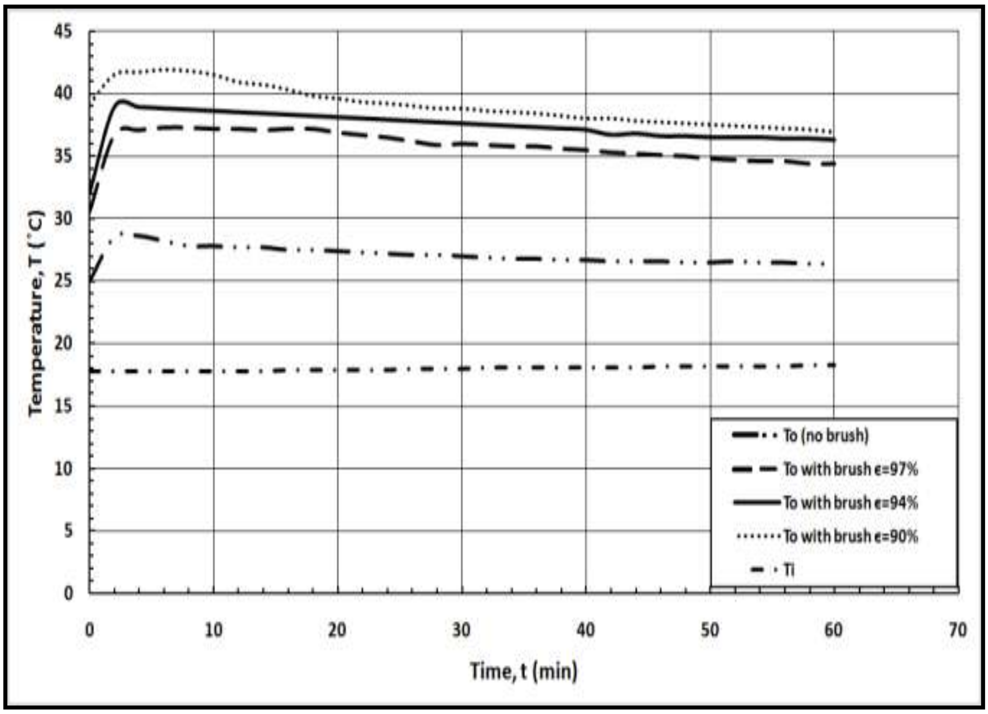

Figure 6. The change in outlet air temperature vs. time in cases of brushes in both wax and air side with three void fractions brushes compared with the case of no brush for an air velocity of 2.5 m/s for an hour.

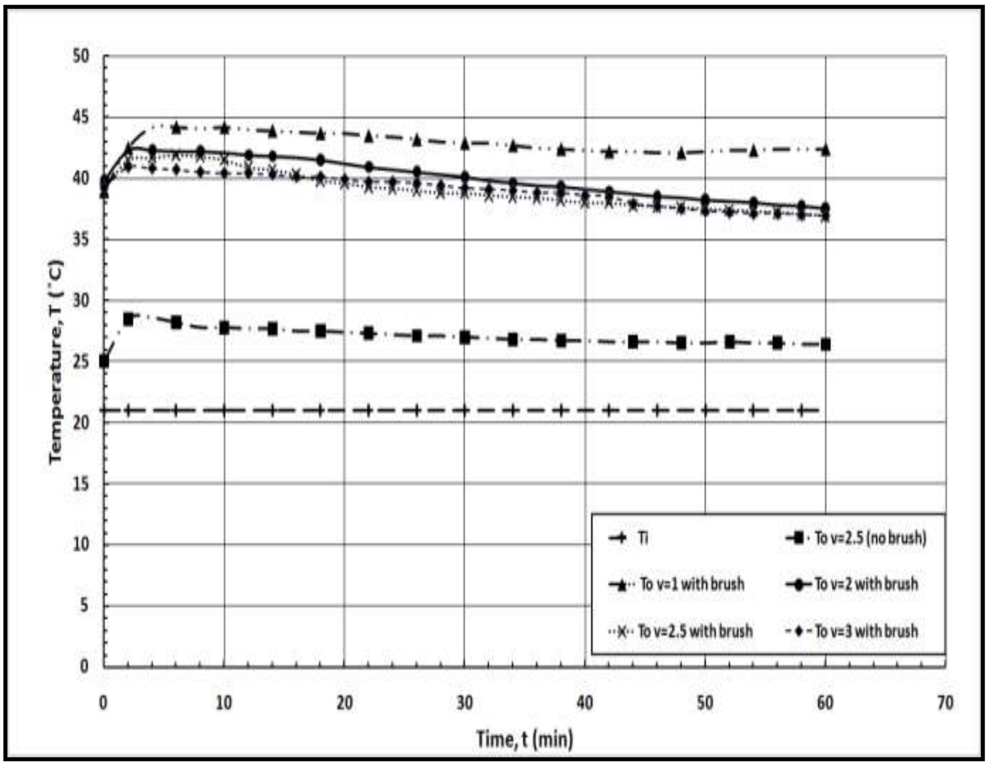

Figure 7. Change with time in outlet air temperature with brushes in both sides for different velocities compared with the case of no brushes for an air velocity of v=2.5 m/s for an hour.

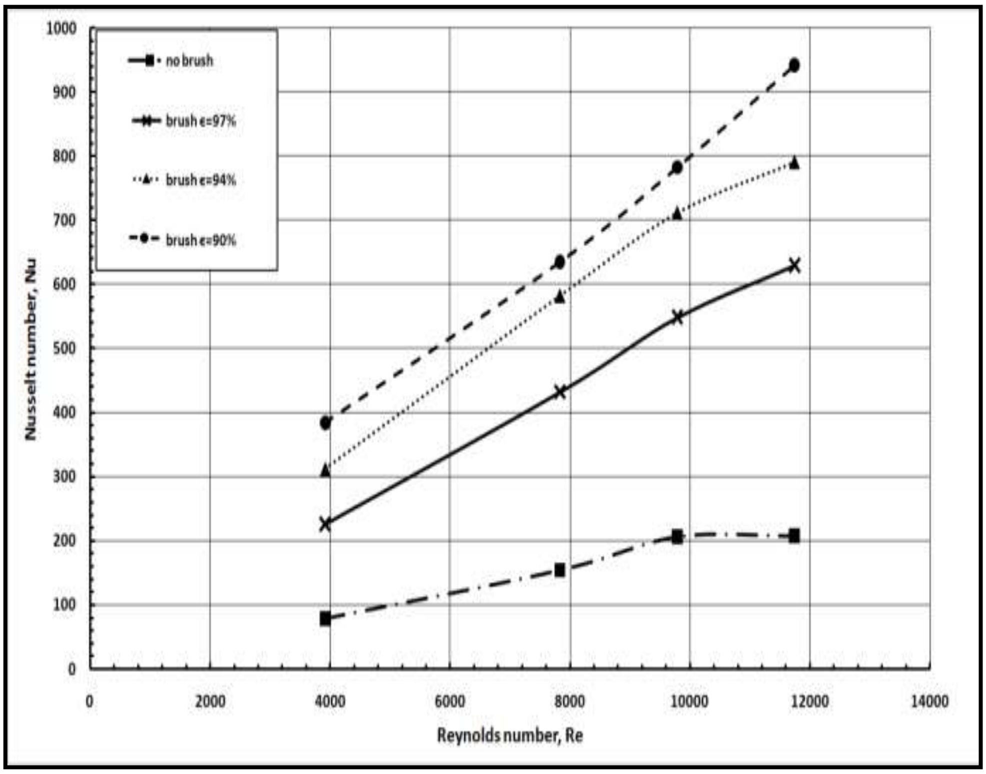

Figure 8. The computed Nusselt numbers with respect to Reynolds number for the cases of different void fractions brushes on both sides compared with the case of no brushes.

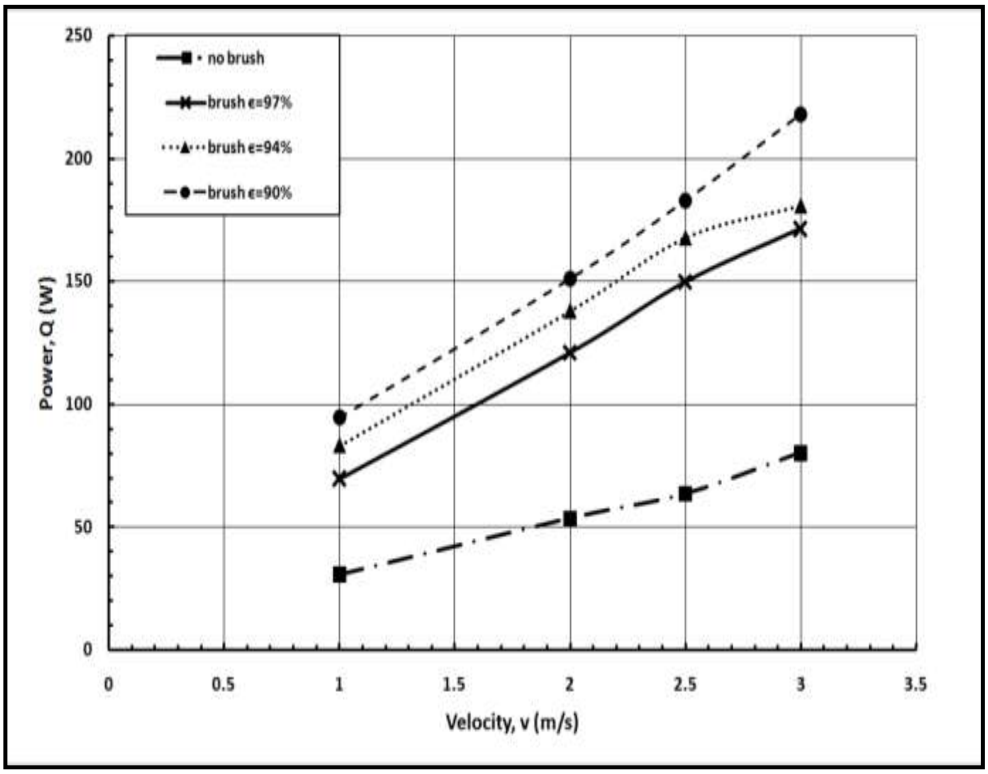

Figure 9. The calculated power extracted vs. velocities for the case of brushes in both sides with different void fractions compared with the case of no brushes.

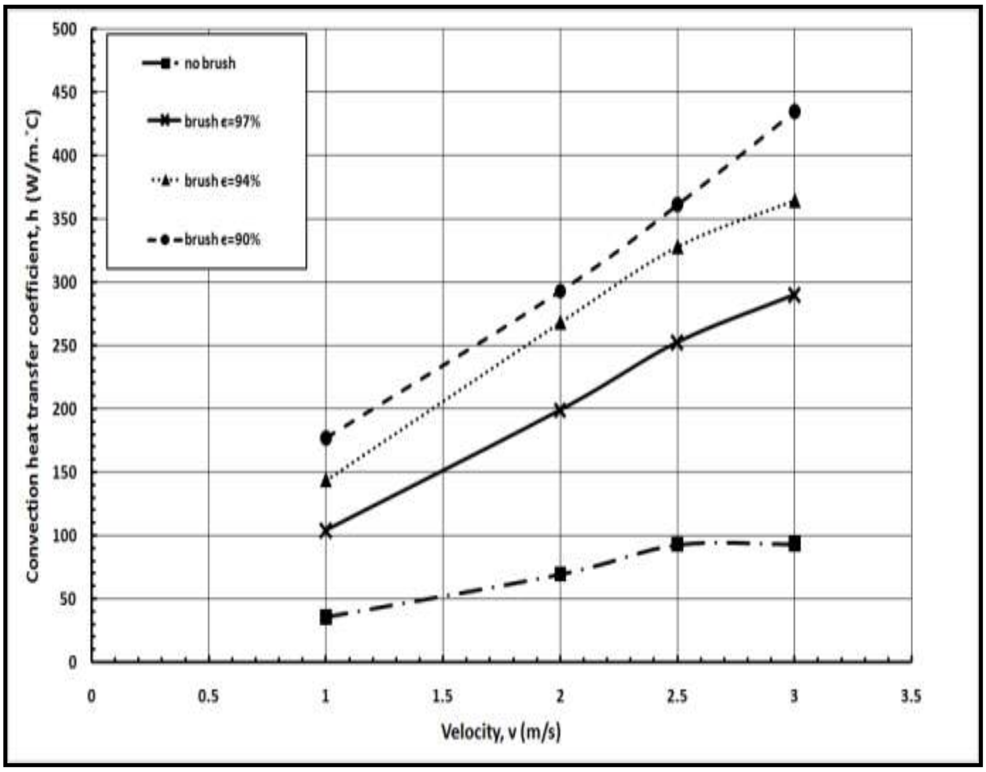

Figure 10. The computed convection heat transfer coefficients vs. velocities for the cases of brushes in both sides with different void fractions compared with the case of no brushes.