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Experimental Study on the Effect of Insertion of Copper Lessing Rings in Phase Change Material (PCM) on the Performance of Thermal Energy Storage Unit

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Abstract

One of the most suitable materials to be used in latent heat thermal energy storage system (LHTES) are Phase change materials, but a problem of slow melting and solidification processes made many researchers focusing on how to improve their thermal properties. This experimental work concerned with the enhancing of thermal conductivity of phase change material. The enhancing method was by the addition of copper Lessing rings in phase change material (paraffin wax). The effect of diameter for the used rings was studied by using two different diameters (0.5 cm and 1cm). Also, three volumetric percentages of rings addition (3%, 6% and 10%) were tested for each diameter. The discharging process was done with four velocities for each case. The obtained results indicated that the maximum volumetric percentage gave a diminished time for melting and maximized the heat transfer in both PCM and air sides as compare with the case of no rings, but the effect of these rings had lower effect on the solidification time. In case of 1 cm rings diameter minimum time for melting was obtained for both 3% and 6% volumetric percentages as compared with the same percentages in case of 0.5 cm diameter rings, while the latter with 10% volumetric percentage overcomes the 1 cm diameter rings for the same previous percentage. Also it can be seen that the minimum velocity (v=1m/s) gave the utmost outlet temperature and with the maximum one (v=3m/s), the minimum solidification time achieved.

Keyword: *Thermal energy storage systems, Latent heat storage, Phase change materials, Heat transfer enhancement.*

1. Introduction

The increase of fuel cost and impurities in environment due to conventional fuel consumption, increase the importance of renewable energy and make alot of researchers seeking for its new sources, and the solar energy plays the big role of renewable energy. The mechanism of storing thermal energy is now having a lot of interest. The storage of thermal energy is done by the using of thermal energy storage systems (TESS).

Thermal energy storage stored as sensible heat, latent heat and thermochemical or combination of these [1]. At those days, most of studies are conducted on materials that making use of sensible and latent heat storage system which are as phase change materials. They are one of the most important applications of TESS. Studies conducted to compare phase change and sensible heat storages shown that a significant reduction in storage volume can be achieved using PCM compared to sensible heat storage [2].

There are three main types of PCM which are organic-PCM, inorganic-PCM and eutectic-PCM in which each type is classified in to other subgroups.

The PCM can be applied conveniently in many fields such as peak shift of electrical demands, solar energy utilization, waste heat recovery, intelligent air-conditioned buildings, temperature controlled greenhouses, electrical appliances with thermostatic regulators, energy storage kitchen utensils, insulation clothing and season storage these applications was viewed by Molefi [3].

Abhat [4] showed that the PCM to be used in the design of thermal-storage systems must have a thermodynamic, kinetics, chemical and economic criteria.

The material to be used as PCM must have high latent heat, high thermal conductivity, low cost, uniformly melt, non toxic, not corrosive and melt within a practical required range of operation. Due to the Presence of most of these properties in paraffin wax that is making it occupies a considerable attention.

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 [5]. Lamberg and Sir'en [6] discuss melting process in PCM, during the phase change, the solid–liquid interface moves away from the heat transfer surface. Thus, the surface heat flux decreases due to increasing thermal resistance of the growing layer of molten or solidified PCM. Due to this problem, different authors studied methods for improvement of thermal conductivity such as the addition of metallic particles [7], porous media [8], pins [9], powder [11], fins [10], nanofibres [12] and graphite matrix [13].

Velraj et al. [7] investigated three methods for improving of heat transfer rate of paraffin wax encapsulated in a cylindrical aluminum tube by the using of internal longitudinal aluminum fins, steel lessing rings and water bubbles. The results showed that the most effective enhancement method was by using of lessing rings (20% by volume) that decreased the freezing time by a factor of 9, and increase thermal conductivity to 10 times more than pure paraffin. Also the finned tube with a volume fraction of 7% makes a reduction in the solidification time to about 4 times of that of no fins. Zhao et al. [8] tested the melting and solidification processes of paraffin RT58 with metal foam (95% porosity, 10 pores per inch) embedded through it. The obtained results showed that the metal foam gave a significant effect on PCM especially during melting process and the small pore density and porosity gave the best results. The heat transfer rate increased up to 3-10 times and the solidification time reduced to half as compared with the case of pure PCM. Also, a numerical model with two dimensions had been carried out to represent heat transfer in PCM with metal foam. Suresh et al. [9] made an experimental method for the improvement of paraffin wax using different forms internal aluminum fins sinks (straight plate fins, rectangular pin fins and circular pin fins). The obtained results made an indication about the increased thermal performance by using of fins sinks. It can be seen that as the power input and fins numbers increased, the melting locations of PCM also increased and the best type was the circular one. Castell et al. [10] studied the effect of using longitudinal vertical fins inside a cylindrical water tank which contain cylindrical PCM modules. The experiments were done with different fins height. It was found that the heat transfer coefficient was increased up to 3 times as compared with the case of no fins. Also, these fins reduced the time required for solidification of PCM. Mettawee and Assassab [11] examined 80 μm aluminum powder mixed with PCM in a solar collector. It was found that the addition of 0.5 mass fraction of powder minimized the charging time up to 60% as compare with the case of pure paraffin. Sanusi et al. [12] studies experimentally the effect of using graphite nanofibers on the solidification time with different aspect ratios. The obtained data showed that the addition of these fibers decreased the maximum temperature in the thermal containment unit up to 48%. Also a reduction in the solidification time was occurred with these nanofibers up to 61% for the case of 1 aspect ratio. Fedden [13] explored the effect of the addition of three different types of graphitized carbon foam to PCM. It was found that a rapid transfer of heat through PCM had been occurred by the help of this addition. Also, a decreased in temperature rate of change obtained during melting and solidification processes and the less dense foam made a lower thermal conductivity.

In this work, thermal conductivity of paraffin wax is improved by the addition of copper lessing rings with different volumetric percentages and two different rings diameter for the purpose of enhancing melting and solidification processes.

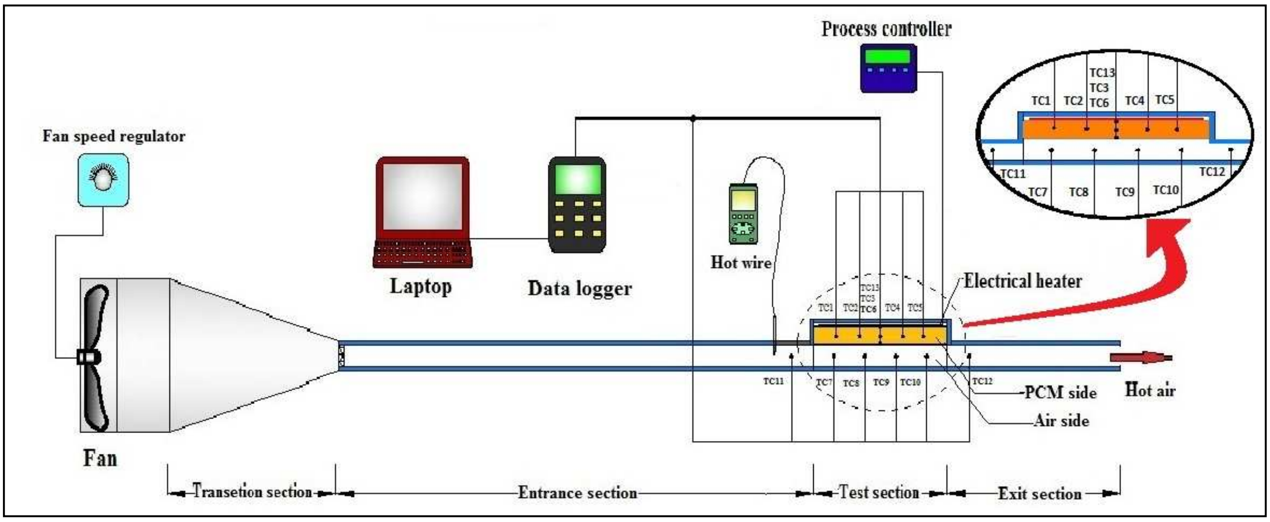


Fig. 1. Schematic sketch of the experimental model.

2. Experimental Work

2.1 Experimental Setup

A small model of thermal energy storage system is employed. The experimental model consists of three main parts, entrance, test and exit region. The length of these sections is about 1070 mm, 300 mm, and 390 mm respectively, as shown in Figure (1). A transition galvanized section (380 mm length) is used to connect the fan duct with the entrance region. A Perspex sheet (9 mm thick) is used to manufacture each region. The test section has a dimension of 300 mm × 90 mm × 86 mm (L × W × H). This region is divided horizontally into two sides which are PCM and air sides. The height of each side is 32 mm and 42 mm, respectively. Paraffin wax grade B (T_{melt} = 63.7°C) is used as a heat storage material. A copper plate (2.5 mm thick) is used to separate between PCM and air side in which it is fixed inside two opposite slots by the help of high temperature resistance silicon. Another copper plate with the same thickness is placed in another opposite slots in the upper portion of PCM side. The last plate is used to separate between PCM and the heat source which is an electrical heater (150 W) and has dimensions of 280 mm × 65 mm. a process controller (model: ESM-9950, EMKO company, working with maximum input module of 5 ampere and ± 0.25% accuracy) is connected in to the electrical heater to keep it at constant temperature (T = 100 °C) using an input thermocouple (TC13) connected into the controller. Its probe fixed on the middle of the upper copper plate. Five thermocouples are distributed uniformly along the axial center line of PCM side in which one of them is in the center and the other four thermocouples are beside the mid one with constant distance between each other. Also one thermocouple is fixed in the midpoint of the lower copper plate. For air side, four thermocouples are also fixed along the axial center line of this side with constant distance between each. While the entrance and exit of the test region are also have a thermocouple in each. All thermocouples are type K with probe diameter of 0.5 mm and ±2.2 error. They connected into a temperature recorder (model: BTM-4208SD, Lutron electronic enterprise company, 0.1 ℃ resolution, ± (0.4 % + 0.5 ℃) accuracy and 1 to 3600 sec sampling time range) to record temperature data from thermocouples with time interval of 1 min. the whole test region is insulated by fiberglass insulation with aluminum outer surface and 12.5 mm thick. Different velocities produced by a fan (0.27 A, 61 W, 60 Hz and 3100 rpm.) in which it is controlled by a fan speed regulator by changing the entered voltage into the fan to get the required velocities. a hot wire anemometer (model: YK-2005AH, Lutron electronic enterprise company, working range from 0.2 to 20.0 m/s, accuracy of ± (1% + o.1 m/s) and 0.1 m/s resolution) is fixed in the entrance of the test region to sense the entrance velocity.

2.2 Experimental Procedure

The experimental tests are done with several cases. Before the beginning of the test, the molten paraffin wax is poured into the PCM side of the test rig. Care should be taken to leave an air gap approximately 10% from the whole PCM side volume to be safe with volume change of wax. The change in volume is occurred due to differences in densities between the liquid and solid wax. After the cooling of the whole wax, the melting test will be started by turning on the electrical heater until the lower copper plate reach a temperature of 63.7°C (melting wax temperature). Then after that solidification process will begin immediately after the end of the melting process by turning the heater off and then turn the fan on. So that, solidification test will be end after the solidification of the whole wax and reaching approximately 30°C. So that, after the charging process ended, the discharging process started. The first test is done with pure paraffin and then with the addition of lessing rings of 0.5 cm diameter and then with lessing rings of 1 cm diameter. For each ring type, different volume percents should be studied (3%, 6% and 10%) and also four different velocities (1, 2, 2.5 and 3) m/s will be tested for each case. In all previous cases, data logger will record the whole thermocouples data for each minute. Table (1) shows thermal and physical properties of used wax and air.

Table 1
Physical and thermal properties of paraffin wax and air.

Material / Property	Paraffin	Air
Density (kg/m^3)	ρ_s=970 ρ_l=833	1.225
Specific heat (J/Kg.°C)	2871	1006.43
thermal conductivity (W/m.°C)	0.24	0.0242
Viscosity (Kg/m.sec)	0.0127	1.78×10^{-5}
Latent heat (J/Kg)	273760	-
Solid temperature (°C)	62	-
liquid temperature (°C)	68	-

2.3 Lessing Rings Manufacturing

A copper rings with tap at the center of them had been manufactured manually. Two types of it are used in which one of them with 0.5 cm and another with 1cm diameter. Each type was made from 0.15 mm copper sheet thick. The copper material selected rather than other materials types due to its high thermal conductivity. The purpose of this central tap is to increase the volume of each ring and make more contact surface area with PCM. These rings were made by the help of a cylindrical mold to get its required shape. Figure (2) shows rings inside rig and Figure (3) shows these rings.

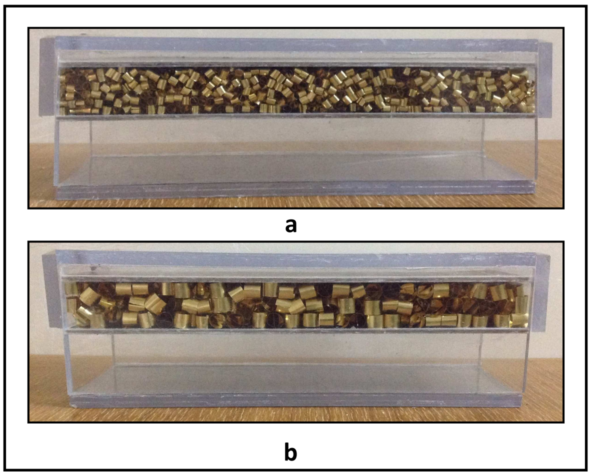
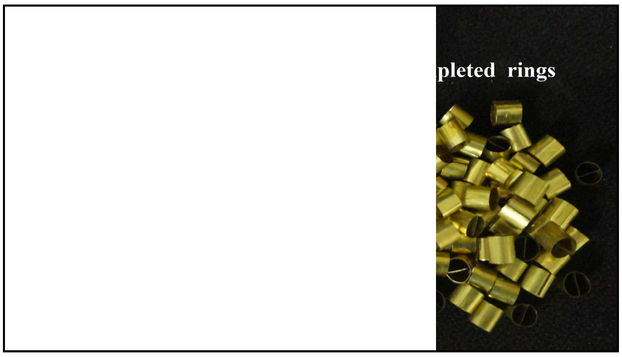
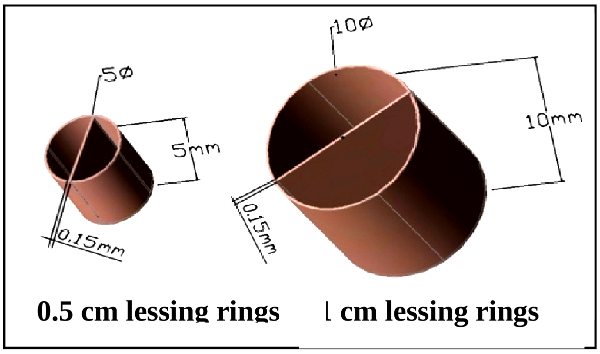


Fig. 2. a. Lessing rings D=0.5 cm inside test rig, b. Lessing rings d=1cm inside test rig.



(a)



(b)

Fig. 3. a. Rings manufacturing procedure. b. 3D drawing of two types lessing rings.

2.4. Thermal Conductivity Measurements

Due to the importance of this property in this field of study, thermal conductivity had been measured by making use of hot disk thermal constants analyzer (model TPS 500) which shown in Figure (4). This device is make measurement rapidly and accurately for different materials types. It make use of a mica disk sensor (diameter = 3.189 mm) to measure thermal conductivity of a coupled identical samples at constant temperature in which this sensor should be sandwich between them. The obtained data will be analyzed by special software to show thermal conductivity. The measurements are done for pure wax and also for wax with rings of two types and different volumetric percentages. The obtained results are plotted in Figure (5).

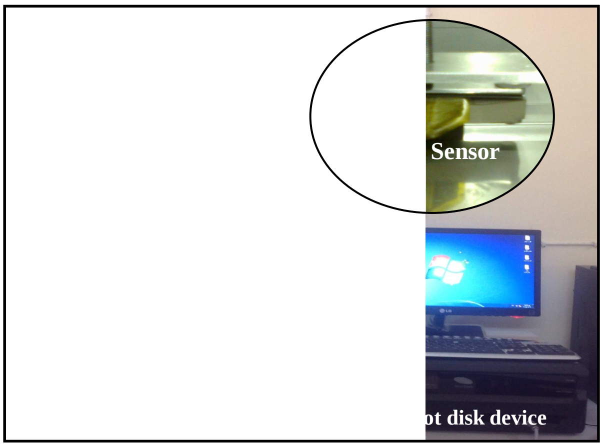


Fig. 4. Hot Disk device with its sensor.

3. Experimental Equations

a. Phase Change Material Side

Heat Storage: The form of storing heat in PCM side mainly as a latent heat. The storage capacity can be calculated from:

$$Q=\int_{T_1}^{T_m} m\,.Cp_s\,.\,dT+ m\,.\,a_m\,.\,\Delta h_m + \int_{T_m}^{T_2} m\,.\,Cp_l\,.\,dT$$
$$= m[Cp_s\,\underbrace{(T_m - T_1)}_{\text{Sensible heat}}+\underbrace{a_m\,.\,\Delta h_m}_{\text{Latent heat}}+\underbrace{Cp_l\,(T_2 - T_m)}_{\text{Sensible heat}} \quad \ldots(1)$$

The second term of equation (1) represents the amount of heat that phase change occurs during it, which means the required heat for transformation from solid to liquid and vice versa.

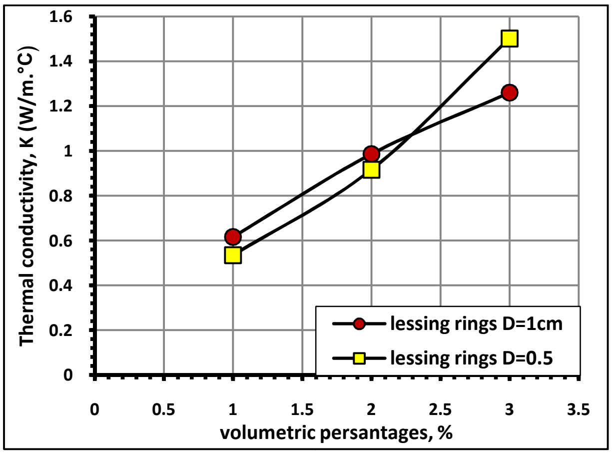


Fig. 5. Measured thermal conductivity vs. volume%.

Conduction Heat Transfer: The transfer of heat inside the PCM occurs due to conduction between its particles, in which it is occurring from the upper surface of PCM to the lower surface of PCM. The Fourier's law for heat conduction is expressed as:

$$Q = k_{PCM} A \frac{\Delta T}{\Delta x} \qquad \ldots(2)$$

3.2. Air Side

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

$$T_b = \frac{T_i + T_o}{2} \qquad \ldots(3)$$

Mass flow rate: the mass flow rate can be calculated as follow:

$$m_a = \rho_a v_a A_c \qquad \ldots(4)$$

Extracted power: the heat transfer from the hot surface to the moving air can be calculated experimentally from:

$$Q = m_a Cp_a (T_o - T_i) \qquad \ldots(5)$$

Convection heat transfer coefficient: convection process is occurred between the hot copper plate and the air flowing beneath it. It was considered to be constant along the duct length, which can be calculated from:

$$h = \frac{Q}{As(T_s - T_b)} \qquad \ldots(6)$$

Reynold number: it can be calculated from:

$$Re = \frac{\rho_a v_a D_H}{\mu_a} \qquad \ldots(7)$$

Where; D_H can be calculated from

$$D_H = \frac{4 (W * H)}{2(W+H)} \qquad \ldots(8)$$

Nusselt number: the following equation used to calculate it:

$$Nu = \frac{h D_H}{K_a} \qquad \ldots(9)$$

4. Results and Discussion

In this work, a study was done to investigate the effect of using copper lessing rings mixed with an organic PCM (paraffin wax grade B), in which the melting and solidification time was changed.

Figure (6) illustrate the storage region (pink area) and releasing region (white area) of paraffin wax (grade B). These data was recorded for the midpoint of wax. From this figure, the transition from solid zone to mushy zone (phase change) and then to liquid zone was represented. At beginning, the heat is store in wax as sensible heat in which the increasing in temperature molecules cause an increase in its oscillation and that lead to increment its kinetic energy. This is occurs during solid zone. But then when the temperature of wax reaching the melting or phase changes temperature, the stored heat was as latent heat for this period. Commonly, the phase change temperature (melting process) is not as a single point, but it is occurring during ranges of temperature. This is because PCM consist of more than one component (not pure material) and that make it have a range of melting temperature. This range depending on the components' melting temperatures that PCM contain. For this paraffin grade, the phase change occurred during a range of (62-68) °C. After the complete melting, the storing of heat was being as a sensible heat again. But the question is why the latent heat storage period has little or no change in temperature in spite of the applied heat source? The answer for this is that during sensible heat period the increase in temperature makes an increasing in molecule kinetic energy which causes an increase in temperature until reaching the melting point or range. Then through melting range period, there will be no or little increase in temperature because the coming heat for molecules will be as a potential energy. The same previous processes would be repeated inversely through solidification process (heat releasing period).

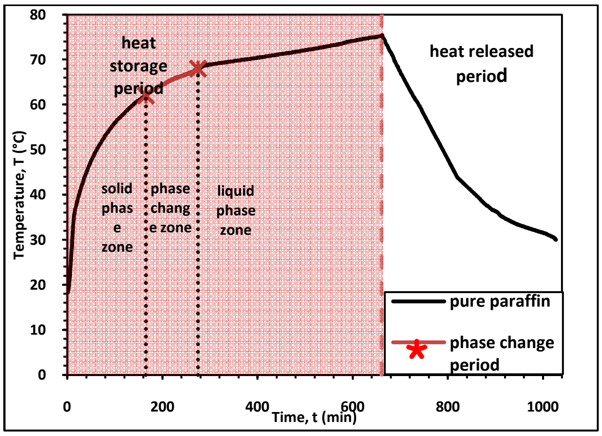


Fig. 6. Heat storage and released for paraffin wax midpoint. The heat storage occurred with constant heater temperature of 100°C. The heat released happened with 2.5 m/s air velocity.

It can be seen from Figure (7) and (8) that how did the lower copper plate temperature (TC6) shift up with time during melting process in cases of pure wax and wax with addition (lessing rings of 0.5, 1 cm diameter respectively). The heat applied from heater to PCM upper surface about 150 W and with constant temperature of 100°C. In each case three volumetric percentages of rings have been tested. It is clear that the time required for complete wax melting with 3%, 6% and 10% volumetric percentages compared with pure wax have been decreased up to 1.13, 2.61 and 5.47 times respectively for 0.5 cm rings. While for the case of 1 cm diameter rings the reduction was up to 3.13, 3.39 and 3.94 times respectively with the same previous percentages. That is the best enhancement method occurred with 0.5 cm diameter lessing rings with 10% volume percent; this is due to its perfect distribution through PCM in which maximum contact between wax and rings occurred. Also, the lower rings diameters increased wax areas in contact with copper rings walls and the maximum volume rings percent make better increase in the whole mixture thermal conductivity, while for the same rings diameter (0.5 cm) and lower volume percent, the enhancement process was the weaker and the 3% percent rings with 1 cm diameter gave better results than 0.5 cm diameter rings even if the latter had more volume percent (6%), because of the rings number with 3% and 6% percent was insufficient to fill the whole rig and has bad distribution through wax. This causes no direct contact between upper copper plate, rings and lower copper plate. Therefore; low conduction heat transfer occurred in these two cases. That made it need more time for storing heat.

In Figures (9) and (10), the behavior of paraffin middle point plotted during melting and solidification processes. The obtained data shows that the time required for melting and solidification, when rings inserted in wax, is minimized. It is obvious that the maximum reduction in solidification time was occurred with the case of 0.5 cm diameter rings with 10% volume percent. But it is clear that melting process is more affected by this addition than solidification process. This is due to no enhancement in heat transfer in air side which cause low heat transfer. So that, heat lost from the lower plate slowly, which make PCM lose heat slowly too. Also for higher rings percentages, lower time for charging and discharging processes are reported.

The measured temperatures changes with time during melting for five points through PCM axial center line and another one at the lower copper plate are shown in figures (11) and (12) for the cases of 0.5 and 1 cm diameter rings respectively, with 10% volume percentages for each. As clear in these two figures, the midpoint (TC3) is melt faster than other points. That was first because it was the furthest point from the PCM rig walls and that make it the furthest point from the surrounding in spite of the used insulation, so that more heat would be stored at this region. The lower PCM point (TC6) which is near the lower copper plate was melt slower than other points due to the largest distance between it and the heat source at the upper surface of PCM and that make it need more time to melt completely.

The data got from the outlet air temperature for an hour during heat releasing for both rings diameter cases are shown in figures (13) and (14) with 2.5 m/s entrance air velocity after the heat storing from heater with 150 W. It can be seen that the higher volume percent, the higher outlet temperature. Also the upmost outlet temperature is got with the case of 0.5 cm diameter lessing rings with maximum volume percent due to increasing in PCM thermal conductivity by this addition. The curves show that T_{out} values increased to peak and then decreased gradually. That is because the lower copper plate temperature decreased with time during air flow beneath it.

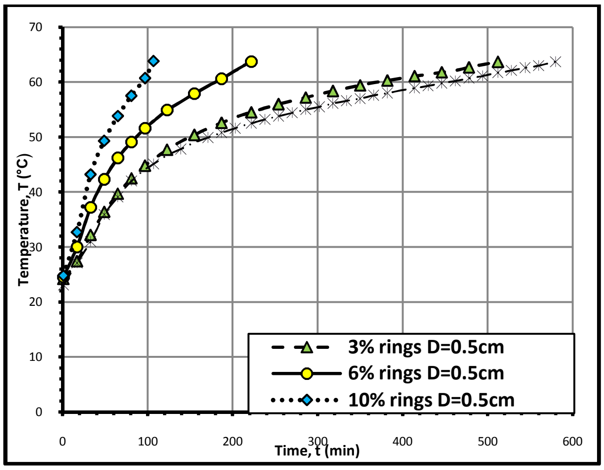


Fig. 7. Temperature of the lower point of paraffin wax variation vs. time during melting process for case of 0.5 cm diameter rings with different volume percent compared with the case of pure paraffin.

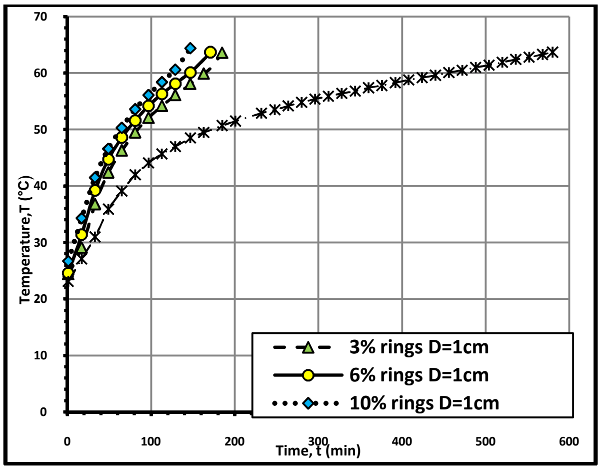


Fig. 8. Temperature of the lower point of paraffin wax variation vs. time during melting process for case of 1 cm diameter rings with different volume percent compared with the case of pure paraffin.

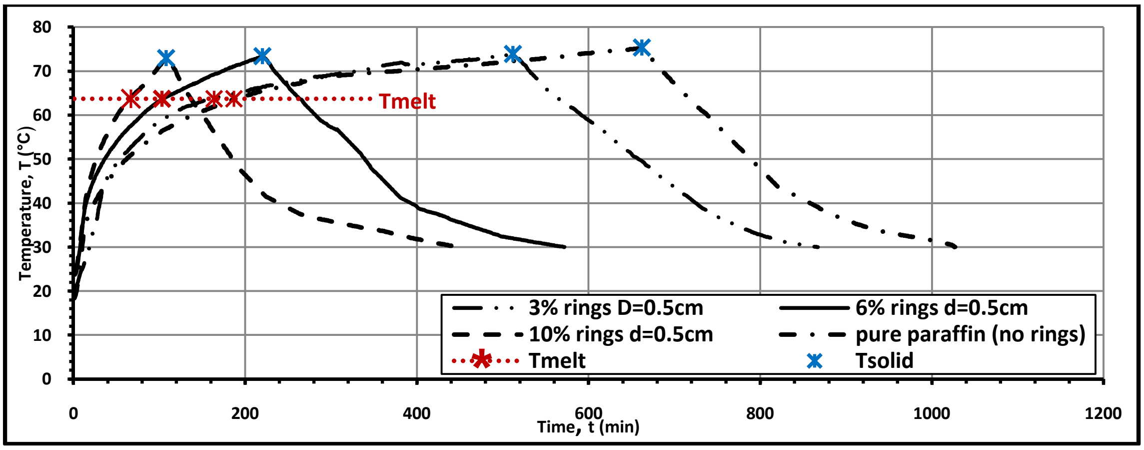


Fig. 9. Change in temperature of mid PCM point during melting and solidification with lessing rings of D=0.5cm compared with the case of pure wax. The solidification process was done at v = 2.5m/s.

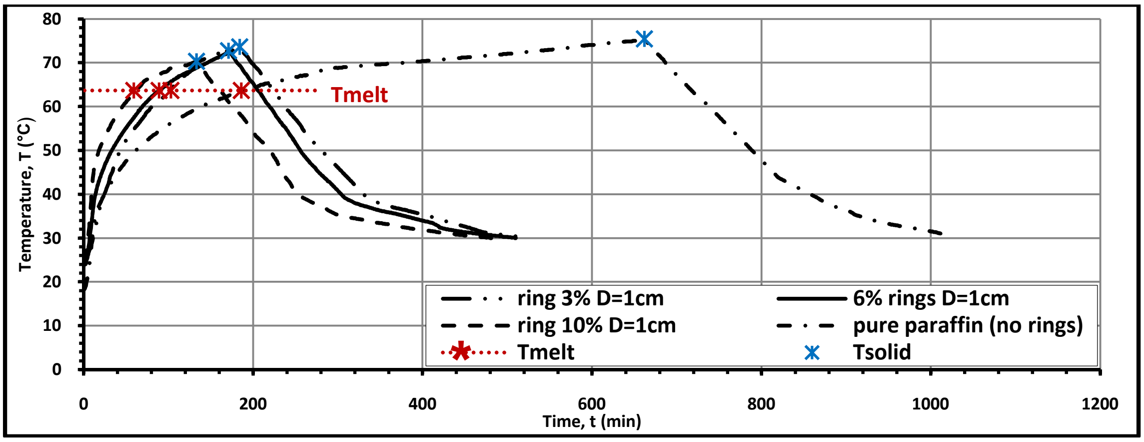


Fig. 10. Change in temperature of mid PCM point during melting and solidification with lessing rings of D=1cm compared with case of pure wax. The solidification process was done at v= 2.5 m/s.

In Figures (15) and (16) the outlet air temperature vs. one hour time was plotted for four velocities and 10% volume percentages for both rings cases. It is clarified from these figures that the minimal used velocity (v = 1m/s) gave maximum outlet temperature and also that is occurred with the case of 0.5 cm lessing rings. That is because with lower velocity the flowing air would had more time to flow over the seperated plate and that made it able to have more heat exchange. Also, at 10% volume percent, the transfer of heat in PCM side is more (higher thermal conductivity) which make the released heat in PCM and heat exchange from the lower copper plate are faster. So that the maximum increase in outlet temperature was up to 2.2 °C compared with pure wax case.

The calculated Nusselt number for both addition types for an hour was plotted as an average values which represented in figures (17) and (18) as a relationship with Reynold number. The higher Nusselt number was occurred with the case of 0.5 cm rings, maximum volume percent and maximum used velocity; this was because of the significant increase in heat transfer rate for that case. Also the same previous case gave maximum extracted heat as in figs. (19) and (20) and maximum convection heat transfer coefficient as in figures (21) and (22). The extracted heat and convection heat transfer coefficient are plotted vs. the used velocities which show a rise in their values as the velocities augmented.

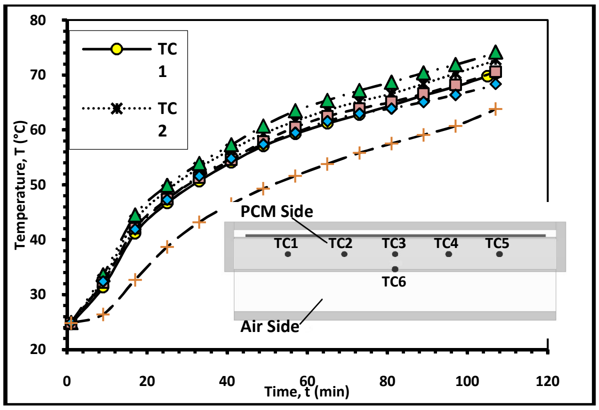


Fig. 11. Temperature distribution for different points through PCM with addition of 0.5 cm diameter lessing rings during charging process.

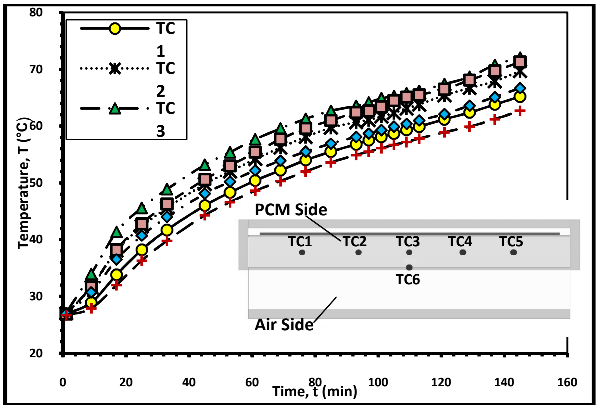


Fig. 12. Temperature distribution for different points through PCM with addition of 1 cm diameter lessing rings during charging process.

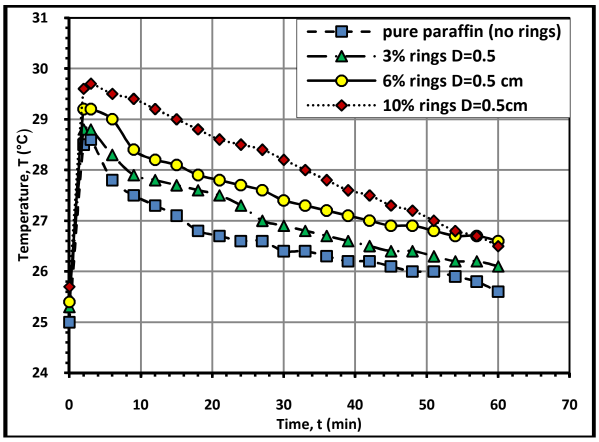


Fig. 13. Outlet air temperature for v=2.5 m/s in cases of lessing rings D=0.5 cm in PCM side compared with the case of pure paraffin.

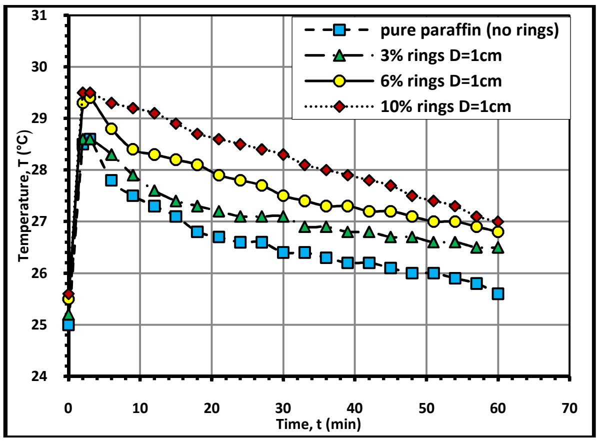


Fig. 14. Outlet air temperature for v=2.5 m/s in cases of lessing rings D=1 cm in PCM side compared with the case of pure paraffin.

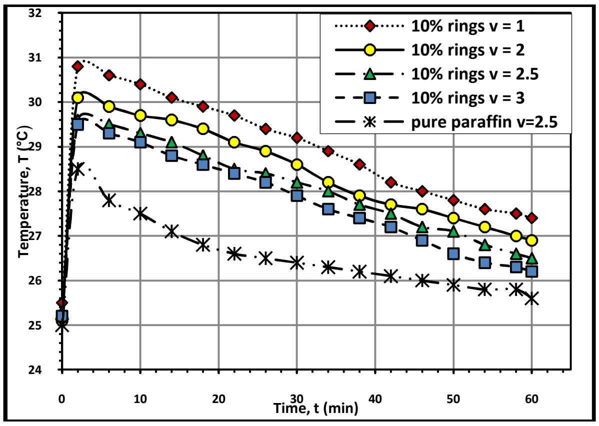


Fig. 15. Outlet temperature of air with different velocities for case of the addition of rings D=0.5 cm with 10% volume percent compared with pure paraffin case at 2.5 m/s velocity.

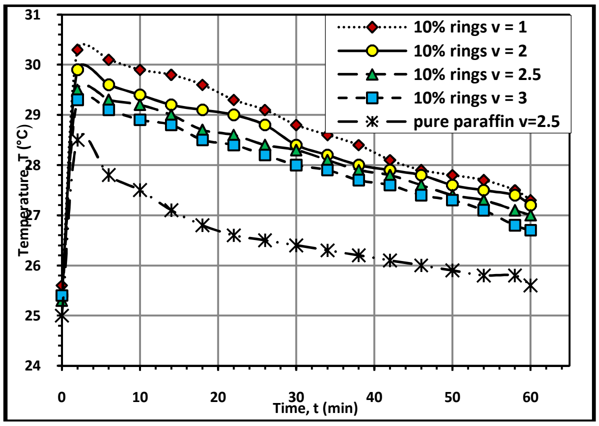


Fig. 16. Outlet temperature of air with different velocities for case of the addition of rings D=1 cm with 10% volume percent compared with pure paraffin case at 2.5 m/s velocity.

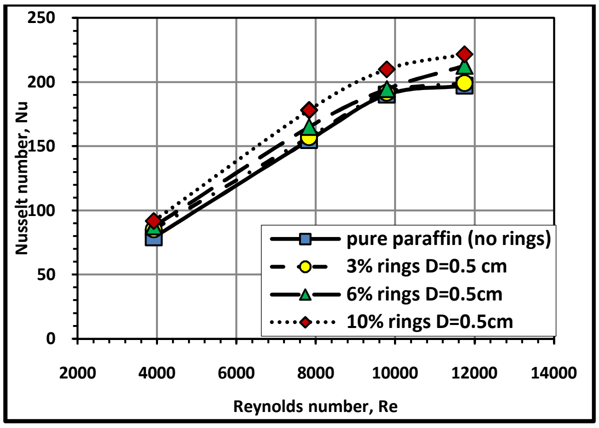


Fig. 17. Relation between Nusselt and Reynolds numbers for different volume percent of lessing rings D=0.5 cm compared with pure paraffin case.

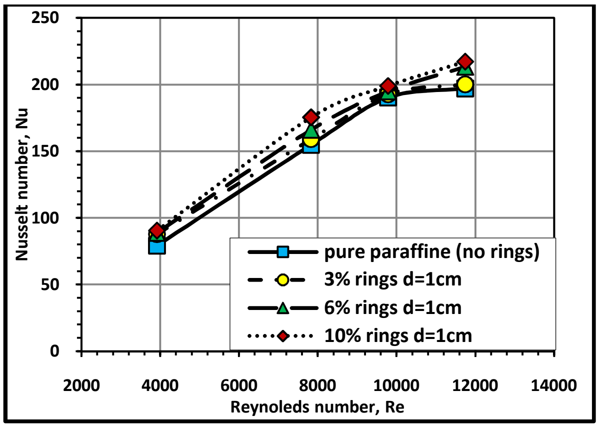


Fig. 18. Relation between Nusselt and Reynolds numbers for different volume percent of lessing rings D=1 cm compared with pure paraffin case.

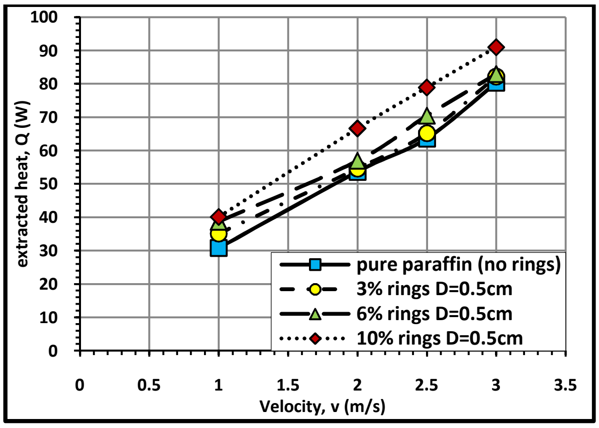


Fig. 19. Relation between extracted heat and velocities for lessing rings D=0.5 cm compared with pure wax.

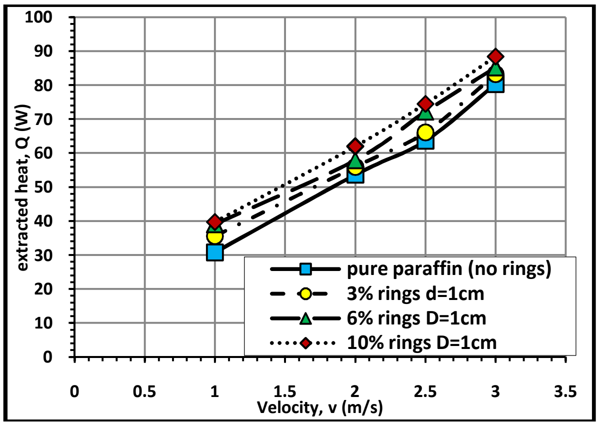


Fig. 20. Relation between extracted heat and velocities for lessing rings D=1 cm compared with pure wax.

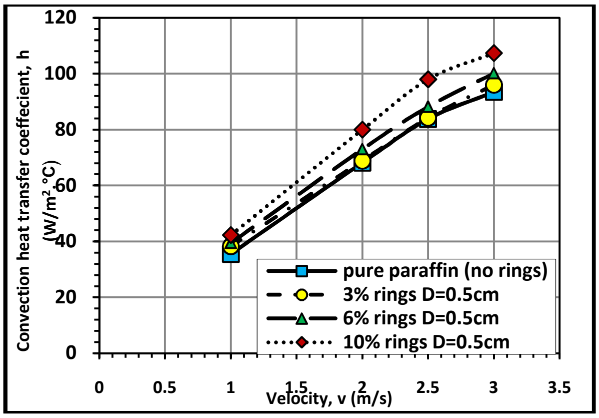


Fig. 21. Calculated convection heat transfer coefficient vs. velocities of air for lessing rings D=0.5 cm compared with pure wax case.

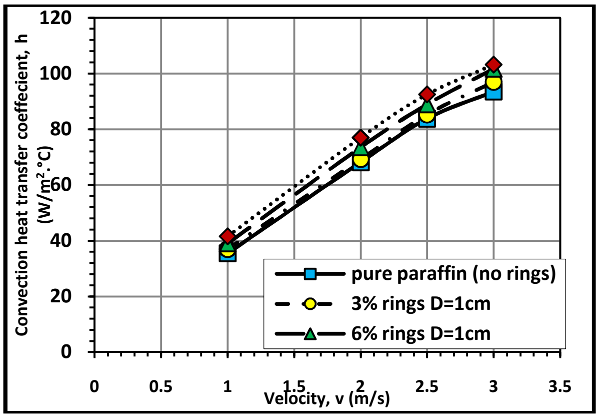


Fig. 22. Calculated convection heat transfer coefficient vs. velocities of air for lessing rings D=1 cm compared with pure wax case.

5. Conclusion

In this work, thermal conductivity and heat transfer for paraffin wax had been enhanced for the purpose of improving charging and discharging processes. The study of conductivity enhancement was conducted using two different lessing rings diameters with three volumetric percentages at four different air velocities studied. The following conclusions can be extracted from the discussion of the obtained results:

- The addition of high thermal conductive lessing rings reduced the time required for melting. Which cause an increase in whole thermal conductivity of paraffin/rings mixture. So that, the higher volume percent, the lower charging time.
- The rings with 1cm diameter gave better results in charging and discharging process than the rings with 0.5 cm diameter in cases of 3% and 6% volume percent. Because of the latter rings did not fill the whole wax rig with these percent and there was an amount of wax still had no rings among it especially at the upper portion of PCM. That is 3% rings of 1cm are more effective and economic than the 6% rings of 0.5cm.
- The minimum recorded time of melting and solidification processes was happened in case of 0.5 cm diameter rings with maximum volume percent (10%) in which the enhancement process reached up to 5.47 times as compared with case of pure paraffin through melting process. This was occurred due to good distribution of these
- rings type through PCM with this percent.
- The solidification time was enhanced but not like what occurred during melting when rings added. The minimum recorded time for wax solidification was occurred with the same case as in melting and with maximum used inlet air velocity (v = 3 m/s).
- The outlet air temperature did not increased a lot when rings added. The maximum increasing obtained for case of inserting 0.5 cm diameter rings, maximum volume percent and minimum entrance air velocity.
- at lower velocity, higher outlet temperature obtained. But with maximum velocities; a gain in heat transfer rate was acquired especially in the initial period of cooling which resulted in minimum time required for solidification.
- The calculated Nusselt number, power extracted and convection heat transfer coefficient were also improved by these additions. And all of them got maximum values with maximum velocity.
- Finally; this enhancement method can be considered as an economic method. Because the manufacturing process of these rings was so easy (manufactured by a manual mold). Also the added amount of enhancers is not very much (maximum 10%) which need low cost, while the enhancement magnitude was high.

Nomenclature

a_m	the fraction melted
A_c	crosses sectional area, m^2
A_s	surface area, m^2
Cp_a	specific heat of air, J/kg.˚C
Cp_l	average specific heat between T_m and T_2 for PCM, J/kg.˚C
Cp_s	average specific heat between T_1 and T_m for PCM, J/kg.˚C

D	lessing ring diameter, cm
D_H	hydraulic diameter, m
h	convection heat transfer coefficient of air, $W/m^2.^\circ C$
Δh_m	heat of fusion of PCM, J/kg
H	height, mm
K_a	thermal conductivity of air, W/m.˚C
K_{PCM}	thermal conductivity of PCM, W/m.˚C
L	length, mm
m	mass of PCM, kg
m_a	mass of air, kg
m_{PCM}	mass of PCM, kg
Nu	Nusselt number, dimensionless
Q	extracted heat, 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_a	velocity of air, m/s
W	width, mm
Δx	distance between the upper and the lower point of PCM, m

Greek symbols

μ_a	dynamic viscosity of air, kg/m.s.
ρ_a	density of air, kg/m^3.
ρ_l	density of liquid PCM, kg/m^3.
ρ_s	density of solid PCM, kg/m^3.

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دراسة عملية على تأثير ادخال حلقات ليسنغ النحاسية في مادة متغيرة الطور على اداء منظومة خزن حراري

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الخلاصة

تعد المواد المتغيرة الطور واحدة من اكثر المواد المناسبة للاستخدام في منظومات الخزن الحراري بوساطة الحرارة الكامنة، لكن مشكلة الانصهار والانجماد البطيئين لهذه المواد جعل تركيز العديد من الباحثين على كيفية تحسين الخواص الحرارية لهذه المواد. لهذا السبب فأن هذا البحث يدرس تحسين الموصلية الحرارية لمادة متغيرة الطور. عملية التحسين تمت بأضافة حلقات ليسنغ النحاسية للمادة المتغيرة الطور (شمع البارافين). تمت دراسة تأثير قطر الحلقات النحاسية بأستخدام قطرين (١ cm و ٠.٥ cm). كذلك لكل قطر تمت دراسة ثلاث نسب حجمية من الحلقات المضافة (٣%، ٦% و ١٠%). كما ان عملية التفريغ تمت مع اختبار اربع سرع لكل حالة. ان النتائج التي تم الحصول عليها بينت ان اكبر نسبة حجمية من الحلقات قللت زمن الانصهار وزادت من انتقال الحرارة في كل من جانب المادة المتغيرة الطور وجانب الهواء اذا ما تم مقارنته مع حالة عدم وجود اضافة حلقات للشمع، لكن هذه الحلقات كان لها تأثير اقل على زمن التصلب. لحالة الحلقات بقطر (1 cm) تم الوصول الى اقل زمن لازم للانصهار عندما كانت النسبة الحجمية لاضافة الحلقات (٣% و ٦%) مقارنة مع النسب نفسها من الاضافة لكن مع حلقات بقطر (0.5 cm). في حين ان الاخير اعطى اقل زمن للانصهار لحالة (١٠%) نسبة حجمية مقارنة مع الحلقات ذات القطر (1cm) و للنسبة السابقة نفسها. كذلك من الممكن ملاحظة ان اقل سرعة (v = 1 m/s) اعطت اعلى قيمة لدرجات حرارة الهواء الخارجة، بينما تحقق اقل زمن للانجماد عند اعلى سرعة (v= 3m/s).