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Research Article

Experimental Study of Phase Change Process of the Paraffin as a PCM with Copper Foam and Iron Wool

Mohammad Saleh Barghi Jahromi[a], Vali Kalantar[a*], Mohammad Sefid[a], Masoud Iranmanesh[b*], Hadi Samimi Akhijahani[c]

a Department of Mechanical Engineering, Faculty of Mechanical Engineering, Yazd University, Yazd, Iran.
b Department of Energy, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran.
c Department of BioSystems Engineering, Faculty of Agriculture, University of Kurdistan, Sanandaj, Iran.

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A B S T R A C T

Paraffin waxes are widely used as commercial organic heat storage phase changes (PCM) for many applications due to their suitable properties. Significant heat from fusion, nonpoisonous and stable properties, no phase separation, and the phase process result in a small volume change. Meanwhile, they are subject to low thermal conductivity. The thermal conductivity of PCMs can be increased by different techniques such as the use of dispersion of particles or nanomaterials with high conductivity in PCM and the use of metal foams. The use of nanoparticles has such disadvantages as high cost and particle deposition after various cycles. Hence, in this study, some experiments were carried out to investigate the effect of porous media like copper foam and iron wool as the filler instead of nanomaterials on improving the heat conductivity of PCM. The results show that the porous foam increases the heat transfer and during the charging operation, the temperature of the porous plate wall increases continuously at the same rate as the paraffin. At 2400 s, the temperature of pure PCM, iron wool, and copper foam reaches 67.3, 72.5, and 73.27℃, respectively. The optimal mode is the one in which the copper absorber plate is connected to the copper foam, thus reducing the charging time by 600 s compared to pure PCM and saving 75% of energy. Connecting the copper absorber plate to the iron wool has a good thermal performance and stores 70.83% of energy. Thus, iron wool has an acceptable performance and is suitable for storage systems.

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1. INTRODUCTION

Energy consumption has significantly increased in recent years because of the swift development of human civilization and the economy. Based on recent research and studies, energy consumption in the world doubles every 20 years. Because of this problem, less renewable energy is used than fossil fuels. However, in recent years, there has been a growth in the usage of renewable energy, particularly solar energy (Iranmanesh et al., 2020; Jahromi et al., 2022). Thermal Energy Storage (TES) systems are utilized in various climatic conditions as temporary thermal energy storage or store preservatives. For many engineering applications, thermal energy storage is essential (Zhao et al., 2010). The word "TES" is not a new term; it has been applied for centuries in numerous industrial and agricultural endeavors, including drying procedures and building heating. Energy storage helps power systems operate more efficiently by regulating supplies and boosting dependability (Matofali and Massawe, 2016). TES plays an essential role in thermal energy saving by reducing the degree of time or uncertainty between supply and demand. Thermal energy can be stored in a liquid or solid with sufficient thermal insulation by changing the internal energy of the material, such as sensible heat or latent heat, or a combination thereof (Ali et al., 2019). Sensible heat, latent heat, and chemical energy are the three primary subtypes of TES. Depending on the material's thermo-physical characteristics, applications may vary (Zhang et al., 2017). Sensible Heat Storage (SHS) uses the heat capacity of a solid or liquid to raise its temperature while changing the material temperature during charging and discharging to store heat energy. The environment, temperature swings, and the value of the heat storage material all affect how much heat is stored (brahim et al., 2017; Dincer and Rosen, 2021). When a material section transitions from a base state into another state, Latent Heat Storage (LHS) depends on the absorption or desorption of thermal energy during that transition (liquid to gas, solid to liquid, or vice versa) (Zhang et al., 2017; Barghi Jahromi et al., 2020). Given the latent heat in the PCM material, the heat storage process takes place at a temperature close to the melting point of the PCM, which increases the density of energy storage in two units of mass and volume in a cycle of approximately the same temperature (Zhao et al., 2010; Abhat, 1983). PCMs use chemical bonds to store and unleash heat. When the PCM materials regenerate from

*Corresponding Author's Email: vkalantar@yazd.ac.ir (V. Kalantar)& m.iranmanesh@kgut.ac.ir (M. Iranmanesh)
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solid to liquid or liquid to solid, the chemical connections are disrupted and heat transmission occurs (Kumar and Gupta, 2021). Therefore, storing thermal energy in the latent heat of PCM is an exclusive benefit of increasing the value of thermal energy in the system. PCM materials fall into three main categories: organic, inorganic, and eutectic. The required temperature range is 0-150℃, which is very suitable for solar applications (Ali et al., 2019; Usman et al., 2018). For many applications, the PCM needs higher latent heat, higher thermal conductivity, and lower volume expansion (brahim et al., 2017). The thermal conductivity of PCMs, which ranges from 0.1 to 0.3$^{W}/_{m \cdot k}$, is relatively low, but has a significant latent heat value. If the thermal conductivity is low, the heat transfer coefficient when releasing the stored heat will decrease.

With a variety of methods, many researchers have tried to increase heat transport in PCMs. Due to the low thermal conductivity coefficient of PCM and increasing heat transfer, surfaces or containers with a higher thermal conductivity coefficient such as spiral copper tubes (Iranmanesh et al., 2020; Ebrahimi et al., 2021), aluminum containers (Shalaby and Bek, 2015; Bhardwaj et al., 2021), fins (Ali and Arshad, 2017; Arshad et al., 2018; Arshad et al., 2017), honeycomb structures (Xie et al., 2015; Wang et al., 2015), microencapsulation (Agyenim et al., 2010), and nanoparticle additives (brahim et al., 2017) can be used. To speed up heat transfer in PCMs, porous materials or porous metal plates are utilized. Highly conductive foams like copper, aluminum, iron, nickel, and others can be employed. To improve heat transfer, PCM is incorporated into a porous material. Foam exists in pores and different densities, affecting the heat transfer rate. In the applications of energy storage and increasing heat transfer, the porous copper plate should be used because it has a high thermal conductivity coefficient and a higher volume than the volume of the material filled in the porous plate. Research has been done on the melting variation of the phase change material in copper and iron foams. Zhang et al (Zhang et al., 2017), investigated the phase transition properties of a composite material comprised of metal porous plate and paraffin. The findings demonstrate that the unbalanced thermal effect on the heat transmission between the paraffin and the porous copper plate caused a significant temperature difference between the copper ligaments and the paraffin porous plate. The use of the two-temperature energy method correctly answers the characteristics related to heat transfer because in the research of most researchers, the experimental and simulation results have a low percentage of error. In order to store thermal energy, Nie et al (Nie et al., 2021), investigated the effect of geometry adjustment on the thermal response of metal porous plate/phase change composite materials. The findings demonstrate that compared to the cylinder system, the conical shell system boosts natural convection. The frustum tube arrangement, however, boosts convection as well as conduction. The performance of the composite metal/PCM porous plate in terms of heat transfer is largely unaffected by variations in geometry. For pure PCM and composite metal/PCM porous plates, the change in geometry reduces the full melting time by at least 9.2% and 5.6%, respectively. Zhao et al (Zhao et al., 2010), investigated the use of porous metal plates embedded in phase transition materials to enhance heat transfer to store thermal energy (PCM). Depending on the structure and composition of the porous plate metal, the porous metal plate was able to boost the overall heat transfer rate by 3 to 10 times in the melting process (two-phase zone) and the pure liquid region compared to PCM. Baby and Balaji (Baby and Balaji, 2013), performed experimental studies on the increase in thermal performance and the effect of orientation on a PCM-based heat sink filled with a porous plate. The working time of a PCM with a porous metal plate filled with PCM is compared to a PCM without a porous metal plate but filled with PCM 7.5 at 10 watts to determine the enhancement ratio and to determine the maximum PCM increase ratio. The PCM-based heatsink operation ratio is full of the porous metal plate to metal porous plate heatsink, but without PCM 3 at 7 watts for the set point temperature of 52℃. In addition, the results of heat sinks based on PCM with the aluminum metal porous plate were also very similar to the previous case. Cui (Cui, 2012), conducted an experimental investigation of the thermal charging procedure using a paraffin-filled high-porosity copper porous plate. The findings demonstrate that a metal porous plate can, therefore, be used to decrease the charging time and speed up the melting process by 36%. A myristyl alcohol/metal porous plate was used by Huang et al (Huang et al., 2017), to study the thermal characteristics and improved thermal conductivity of composite phase change materials for solar thermal storage. The latent heat when using PCM metal porous plate composite is reduced by 3-29% in the melting process compared to the latent heat of Myristyl pure alcohol. Jin et al (Jin et al., 2017), examined a visualized pore-scale study of the heat transfer of a molten paraffin wax saturated in a porous copper plate and the effects of pore size. The results showed that at a wall superheat of 20℃, 30 PPI and 50 PPI copper porous plates result in approximately the same overall melting rate, which is much faster than the 15 PPI melting rate. In order to store energy for electronic thermal management, Ali et al (Ali et al., 2020), conducted experimental research on the thermal behavior of paraffin in open-cell copper and nickel-iron foams. The results showed that the heatsink based on a porous copper plate at 5 to 6 ℃ exhibited a lower base temperature than a nickel-iron porous plate. When examining the effect of porous plate porosity, porous copper plate with less porosity (95%) at the end of the charge cycle exhibited an 11% lower base temperature. Using experimental and numerical methods, Marri and Balaji (Marri and Balaji, 2021), investigated the impact of metal foams' porosity and PPI gradients on the thermal efficiency of a composite phase change heat sink. The findings indicate that the porosity performs better than heatsink settings with uniform porosity and PPI density in terms of time to reach the set point temperature by 28 and 45%, respectively. It is clear from the numerical simulations that the convection velocity cells are dramatically altered by the PCM melt percentage, which impacts the PCM melting dynamics. Babapour and Karimi (Babapoor and Karimi, 2015), investigated the thermal storage optimization of paraffin composites with different nanoparticles. The results showed that Al2O3 nanoparticles had the ability to promote the thermal storage properties of paraffin. Bahari et al (Bahari et al., 2020), investigated the effect of paraffin nanocomposite with AL2O3 in an indirect solar dryer. The results showed that the addition of AL2O3 nanofluid to paraffin reduced the drying time of the product. A summary of experimental studies on the PCM material melting process in porous plates is presented in Table 1.

The examined literature indicates that the melting of PCM material in two copper and iron foams (iron wool) connected to the copper absorber plate has not been studied. Due to the low thermal conductivity of paraffin as a phase change material, copper and iron foams (iron wool) were used, and the charging and discharging processes of PCM and the effect of the implementation of the copper absorber plate on the charging and discharging processes of PCM materials were investigated and the results were compared to each other. This new study can be widely used for solar storage applications, especially solar panels, types of solar collectors (FPSC, ETSC, and PTSC), solar air heaters (SAH), solar desalination systems, and solar dryers that are capable of using porous foams. The obtained results were achieved using the solar simulation device, which would significantly help scientists in the field of renewable energy in future research.

Table1. Several experimental research papers on the charging and discharging of PCMs in copper and iron foams.

Ref.	Type of PCM / melting temperature	Type of porous foam	Important results
(Zhang et al., 2017)	Paraffin / 54.43-64.11	copper foam	-Due to its high latent heat, paraffin warmed up slowly during the melting process, but porous copper plate warmed up more quickly. - The paraffin/ copper porous plate composite performed better in heat transmission than pure paraffin due to the solid thermal conductivity of the copper foam. Compared to paraffin, which is pure paraffin, the temperature distribution of the paraffin/foam copper composite was more even.
(Chen et al., 2016)	Paraffin / 54-56	copper foam	-To improve heat transfer, the FSPCMs (form-stable phase change materials) can infuse into the porous metal plate. -To improve heat transfer, the FSPCMs can impregnate porous metal plates.
(Li et al., 2012)	Paraffin / 46.48-60.39	copper foam	-The foam-PCM composite's ultimate overall thermal resistance was lower than that of PCM. - By either reducing the pore density to speed up natural convection or reducing the porosity to improve the effective thermal conductivity, the temperature distribution within the foam-PCM composite becomes more uniform.
(Li et al., 2017)	Sodium acetate trihydrate / 56.75	copper foam	-Copper porous plate /SAT has a thermal conductivity rate 11 times greater than pure SAT. -Copper porous plate /SAT composite PCM has an energy storage density up to 467MJ/m^3.
(Mancin et al., 2015)	Paraffin wax / 52-60	copper foam	-The function of PCM heat transmission is significantly improved by copper foams. -Using a copper foam structure allows for the elimination of severe freezing issues associated with asymmetric heating.
(Zhu et al., 2020)	lauric acid / 41-45	Iron foam	-The latent heat and melting point of the composites are 177.88 kJ/kg and 44.36℃. -Composites are made of lauric acid and porous iron plate that contain graphene offer good thermal stability and dependability.
(Ali et al., 2020)	Paraffin wax / 34-36	Iron-Nickel foam	- By examining the heat transfer, it can be concluded that foam with less porosity will perform better during charging and discharging. - Minimal melting point PCMs work well with light heating loads.
Present study	Paraffin wax / 57-60	Copper Foam and Iron wool	- The copper absorber plate attached to the copper foam accelerated the melting rate to a pure PCM of 600s. - Energy saving in the case of using the copper absorber plate connected to the copper foam had the highest value of 75%.

2. EXPERIMENTAL

An experimental system including a solar simulator, data logger and K-type thermocouple, pyranometer, and Teflon insulation was set up to place samples. Tests were performed at the "Institution of Science and High Technology and Environmental Sciences, Kerman." Figure 1 shows the experimental settings used. Test boxes made out of Teflon insulation with dimensions of $5 \times 5 \times 2\ cm$ and the samples were placed inside the cubic hole in the middle compartment of Teflon with dimensions of $4 \times 4\ cm$. Copper foam and iron wool were both $3 \times 3\ cm$ in size and $1\ cm$ in thickness. The thermo-physical properties of copper foam and iron wool and PCM material (paraffin RT57-60) are given in Table 2.

The porosity effect was considered for copper foam with a constant PPI density of 10. The solar simulator provided the heat required for melting PCM in terms of LUX. Therefore, a pyranometer was placed in the solar simulator to measure irradiation intensity and heat flux. In all experiments, the heat flux was 3.824$^{kw}/_{m^2}$. The features of the solar simulator are given in Table 3.

As shown in Figure 2a, the sample preparation steps include: (1) calculating the weight of PCM material and porous foams, (2) melting PCM material with an electric heater, (3) filling copper and porous iron plates with PCM material, and (4) placing samples in Teflon insulted box. The next step, shown in Figure 2b, is to place the copper plate using solder on copper and iron foams and, then, to fill it with PCM. The melting temperature fluctuations of PCM material were investigated using pre-calibrating K-type thermocouples. K-type thermocouples were affixed to the paraffin-filled inside of the foam, and a 16-channel data logger was employed to capture temperature data (Model: 32M96, Hioki, Japan, precision 0.1). Pyranometer (KIPP ZONEN, CMP6, precision 4W/m2) was used to gauge the radiation output of the solar simulator. Therefore, by analyzing the collected data, it is possible to determine the melting rate of PCM materials and their heat storage capability. A sample of pure paraffin core (without any porous metal plate) was examined for comparison to investigate the increase in heat transmission caused by copper and iron foams. Moreover, the impact of the structure (porosity) of porous foams on the transfer of heat from solid to liquid was examined. DSC analysis was also carried out to obtain the thermo-physical attributes of paraffin, as shown in Figure 3.

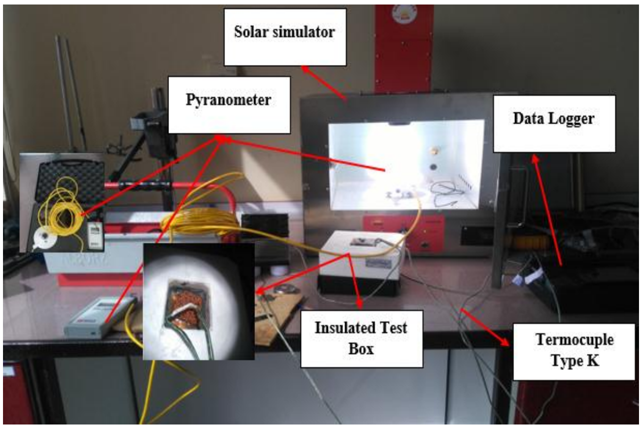

Figure 1. Image of test setup and measuring instruments.

Table 2. Thermo-physical attributes of paraffin and selected foams

Feature	Copper Foam	Iron Wool	PCM (paraffin RT57-60)
Porosity (%)	85	95.2-98.3	-
Melting range (℃)	-	-	57-60
Thermal conductivity (W/m.K)	378	81	0.2
Latent heat (J/g)	-	-	169.51
Apparent density (kg/m3)	200	180	783

Table 3. Technical specifications of the tested solar simulator

Components	Details and Dimension
Chamber solar simulator	12 inches wide, 12 inches deep, and 8.5 inches high are the internal dimensions. External dimensions are 18 inch wide, 13.75 inches deep, and 26 inches high. Weight 31 pounds and output current 110 or 220 VAC with 6 amps. The external and internal materials of the body are stainless steel and aluminum alloy (highly reflective), respectively.
Lamp	A 300W Cermax Xenon light is used by the device. There is also a dimmer switch so that power output can be adjusted to meet AM 1.5 intensity.
Filter	A single 2-inch round filter is positioned at the chamber's top (in the filter holder).
Lense	Lenses with a diameter of 2" can fit the filter adaptor. This beam can modify the output intensity by expanding or contracting the beam.

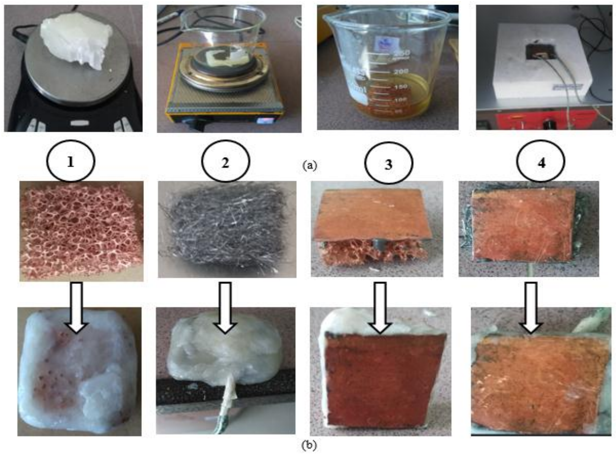

Figure 2. (a) Sample preparation steps; (b) Paraffin filling in cases with copper foam, iron wool, copper foam with copper absorber, and iron wool with copper absorber.

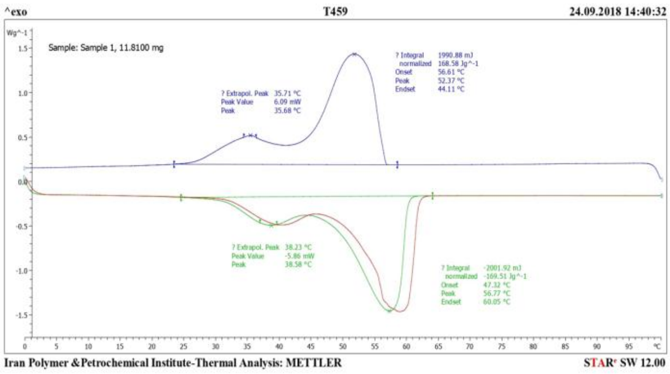

Figure 3. The melting curve of paraffin from DSC.

3. UNCERTAINTY ANALYSIS

The measurement error in the case of the input heat flux and temperature is responsible for the overall uncertainty. Test uncertainty in this research was conducted using Equation 1 (Zhao et al., 2010). With δT_{TC} being ±0.1ºC (±0.43 %) for thermocouples, the uncertainty of the solar simulator is ±0.5 %. Using Eq. (1), the test's overall degree of uncertainty was calculated as 1.41%.

$$U_T = \sqrt{\left(\frac{\delta T_{TC}}{T_{TC}}\right)^2 + \left(\frac{\delta q_{PM}}{q_{PM}}\right)^2} \times 100\% \quad (1)$$

4. RESULTS AND DISCUSSION OF EXPERIMENTS

Figure 4 depicts the PCM sample outcome when two pieces of foam made of copper and iron are involved. The wall temperature rises steadily at the same rate as paraffin throughout the charging process. The 2400s pure PCM reaches 67.3℃, i.e., above the melting point; copper foam and iron foam reach 73.27℃ and 72.5℃, respectively.The increase in heat transfer via copper foam is due to the excellent heat conduction of metal foam solid structures. The temperature line experiences a significant drop following the successful transition of the pure PCM from solid to liquid. The increase in heat transmission brought about by the inherent convection effect of the liquid phase can be the cause of it. Foam can make the temperature distribution more homogeneous in the discharging process. The heat from the PCM can be efficiently dissipated via a foam structure, resulting in a reduction process for copper and iron foams. Therefore, using metal foams significantly improves the PCM heat transfer efficiency, similar to the charging process.

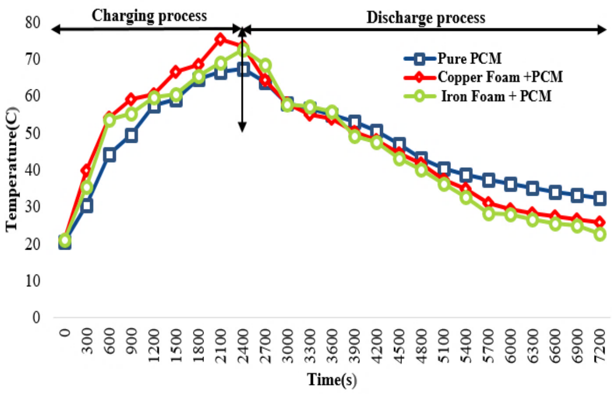

Figure 4. Comparison between three different modes of pure PCM: PCM with copper foam and PCM with iron foam in the charging and discharging processes.

In Figure 5, upon the addition of a copper absorber plate to copper and iron foams, the melting process of PCM material and the effect of heat transfer are investigated. As can be seen, by adding the absorber plate, the heat transfer increases and the maximum value is 77.41℃ for copper foam and 74.67℃ for iron foam. The reason for this can be the effect of conductive heat transfer between the copper absorber plate and the foam structure containing PCM. For copper and iron foams, a foam structure can quickly dissipate heat from the PCM and reduce discharging. However, when the copper absorber plate is added to copper and iron foams, the process does not decrease during discharge and the heat present in the copper absorber plate, which still transfers to the foam containing PCM, can explain the reason.

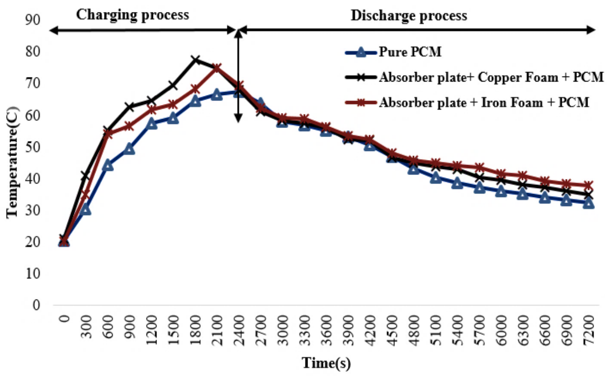

Figure 5. Comparison between pure PCM samples and copper and iron foam samples with copper absorber plate during the melting process

Figure 6 depicts a diagram showing the temperature of the absorber plate when mounted on copper and iron foams while they are melting PCM. The maximum temperature of the absorber plate reaches 104℃ in the 1800s. Moreover, at 3000s to 7200s, the temperature of the absorber plate slowly declines. Figures 4 and 5 show that the onset of phase change of PCM material from liquid to solid is in the 2400s. As shown in Figure 7, when copper and iron foam are used, the phase changes in the time of the PCM material are 2100 and 2390s, respectively. When the copper absorber plate is added to the copper and iron foam, the phase changes in the time of the PCM material are 1800 and 2100s, respectively. Therefore, the best case is when the copper absorber plate is connected to the copper foam containing PCM. However, when the copper absorber plate is connected to the iron foam, it can provide acceptable results.

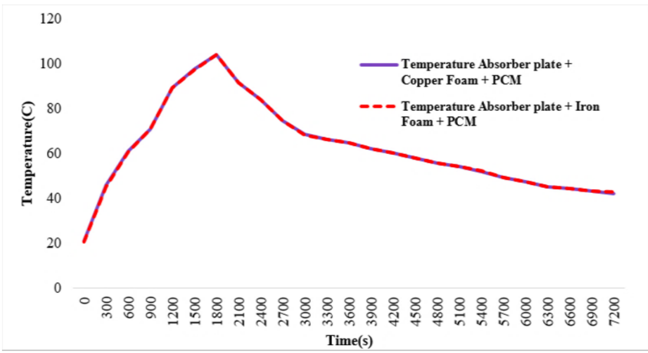

Figure 6. Temperature absorber plate used when melting PCM

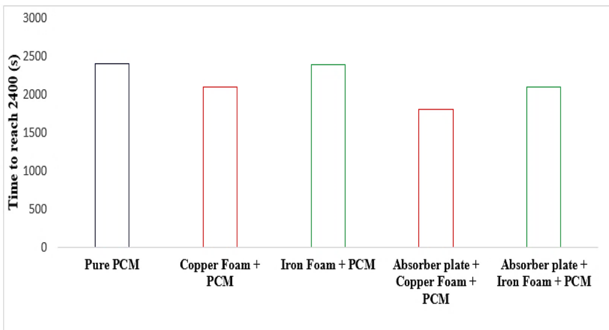

Figure 7. Comparison of paraffin melting time in different modes

To calculate the energy saving of PCM materials in different modes, the start time of the phase change process can be reduced from the total phase change time (7200s) and divided by 7200s. In Figure 8, when copper and iron foam are used, the stored energy reaches 70.83% and 66.8%, respectively.

However, when the copper absorber plate is used, it reaches 75% and 70.83%, respectively. The best case is when the copper absorber plate is attached to the copper foam.

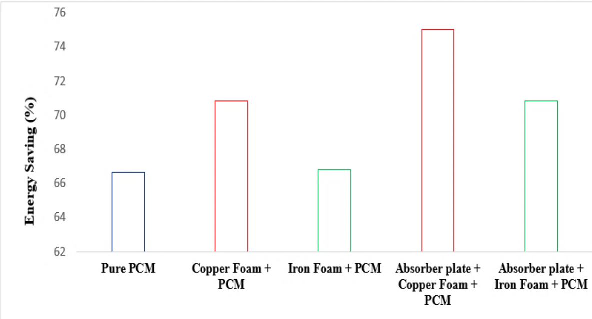

Figure 8. Comparison of melting paraffin energy saving in different modes

5. CONCLUSIONS

This study used pure paraffin filled with and without porous copper plate and iron wool, as well as pure paraffin with the addition of a copper absorber plate to the copper and iron wool, to melt PCM. The findings demonstrated that adding metal foams could significantly increase the effective thermal conductivity of the melting process. Given that it uses a porous copper plate and iron wool, the highest temperature of PCM reaches 73.27°C and 72.5°C, respectively. By adding copper absorber plates to copper porous plate and iron wool, the highest PCM temperature reached 77.41°C and 74.67°C, respectively. The heat transfer rate increased by 14% when the copper porous plate was combined with a copper absorber plate. Therefore, using metal foam with a copper absorber plate might hasten its melting and cut down on charging time. Natural convection can boost heat transfer efficiency and lower the temperature discrepancy between the wall and the PCM when the PCMs start to melt. The best case is when the copper absorber plate is connected to the porous copper plate, which reduces the charging time by 600 seconds compared to the pure PCM and saves 75% of the energy, while the pure PCM saves 66.66% of the energy. In addition, connecting the copper absorber plate to iron wool ensure viable thermal performance and stores 70.83% of the energy. The most important disadvantage of porous copper plates is their high cost, which makes them less popular for use in storage systems. Therefore, according to the results of this research, iron wool exhibits acceptable performance in terms of increasing heat transfer and speeding up the melting of PCM materials, and it can be used in storage systems.

6. ACKNOWLEDGEMENT

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Nomenclature

U_T	Uncertainty total (%)
ETSC	Evacuated tube solar collector
FPSC	Flat plate solar collector
LHS	Latent Heat Storage
PCM	Phase change material
SAH	Solar air heater
SHS	Sensible Heat Storage
TES	Thermal energy storage

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