ENHANCEMENT OF QUICK CHARGING AND DISCHARGING OF TERMO ENERGY STORAGE SYSTEM BY PCM MIXED WITH Al_2O_3 NANOPARTICLES FOR ELECTRIC VEHICLES

by

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Technology for storing heat energy with small amount of area has been proposed a challenge to the researchers over the past few decades. This would render highly useful for the thermal management system of electric vehicles. The PCM was used as an energy storage system in this work. It offers the chief advantage of higher storage density which is very much expected for both industrial and domestic needs, especially electric vehicles. In this work, the enhancement of specific heat capacity for the provided PCM was improved by embedding alumina nanoparticles into the storage medium. The addition of nanoparticles in the PCM resulted in the increase of heat absorption capacity, a 50% increase in charging time and a 25% reduction in discharging time of the PCM for the volume concentration of 0.833%. The increase of efficiency by 6% during charging and 4% during the discharging processes were observed as the effect of addition of alumina nanoparticle in the system.

Key-words: *Al_2O_3 nanoparticle, paraffin wax, exergy analysis, availability, energy storage*

Introduction

The field of energy studies is showing a great demand these days due to the depletion of non-renewable energy resources. The idea of reducing the amount of energy wasted while consuming the renewable energy resources is very much needed. The PCM has been playing a vital role in utilizing the renewable solar energy and converting the same into various useful forms. The energy storage capacity of the PCM is also very high for appreciable temperature changes. One such approach was being carried out in the present work by adding Al_2O_3 nanoparticle into the system of the paraffin wax used for heating and cooling applications. From the energy absorbed, the charging and discharging of heat inside electric vehicles (EV) were studied.

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Literature review

Venkitaraj *et al*. [1], studied about the addition of pentaerythritol PCM materials with Al_2O_3 to check the thermal and chemical stability. The Al_2O_3 nanoparticles in the weight ratio 0.1%, 0.5%, and 1% were tested in TGA, DSC, and FTIR. Based on the results obtained, the stability of the composition had been proved to improve under thermal and chemical equilibrium conditions. Al Ghossein *et al*. [2], tested the performance of silver nanoparticles infused within the chosen-based PCM. Samples with varying proportions of silver nanoparticles (0 wt.%, 1 wt.%, 2 wt.%, 3.5 wt.%, 5 wt.%, 6.5 wt.%, 8 wt.%, and 10 wt.%) were prepared and studied for stability. The PCM was tested during the solidification cycle carried out through different routes. The property of thermal conductivity and latent heat of fusion were also studied for the stability. These properties exhibited an inverse relationship with the amount of nanoparticles added to PCM. Ghasemi *et al*. [3] discussed about PCM with expanded graphite at different wt.% (0-90% of concentration). The test was conducted in controlled solar radiation understand the heating cycle of the system. Results revealed approximately seven times faster response rate to charging for 80% expanded graphite + 20% PCM composites, when compared with 10% expanded graphite + 90% PCM composite. Sheikholeslami [4] studied the performance improvement of PCM material with the addition of CuO nanoparticles to latent heat thermal energy storage system. Finite element method was used to simulate the unsteady process. The highest solidification was obtained at d_p = 40 nm.

Venkatesh and Vijayan [5] designed a multi-purpose solar collector and used CFD for understanding the fluid-flow and heat transfer characteristics. The result identified an optimum flow rate of 0.0176 m^3 per minute. During the summer season, the maximum average thermal efficiency was 73.06% and the same for the winter season was 67.15%. The deviation fall will be ±11.61% for summer season and ±10.64% for winter season. Sakthivel *et al.* [6] made an attempt to understand the heat transfer capacity and thermal efficiency. The observed results showed a decreasing trend in the thermal resistance of base fluid used in heat pipe applications by adding SiO_2 and TiO_2 nanofluid. The improvement in results was greatly influenced by the tilt angle, volume fraction of nanoparticle in the working fluid. Chinnarasu *et al.* [7] examined the cross-flow arrangement of radiators with fins made up of aluminum and copper alloy. Box, sharp type, and round type fins were fabricated and tested as additional fins caused for a higher cooling capacity of radiators. The SiC nanofluids were used as coolant. Simulation results obtained from ANSYS 13.0 were in good agreement with the experimental results.

Pradeep *et al.* [8] studied spiral heat exchanger having concentric coiled sheet with equal distance between them. Flow pattern and heat transfer were analyzed using counter flow model geometry to increase the efficiency of heat exchangers by optimizing the flow rate. Ahmed *et al.* [9] tested organic thermal energy storage materials like paraffin wax with Al_2O_3, SiO_2, CNT, graphene*, etc.* When nanoparticles were dispersed in base fluid, improvement in the thermophysical properties were observed via enhanced thermal conductivity and specific heat capacity. Aljehani *et al.* [10] studied cold thermal energy storage using composite PCM comprised of paraffin wax and expanded graphite. Upon comparison with the standard air conditioning, the efforts downsized the compressor by 50%, reduced electrical consumption by 30% and reduced CO_2 emission by 30%. Giro-Paloma *et al.* [11] studied microencapsulated PCM as active energy storage system. The PCM at 50 °C and 1-2 μm size with tetracosane, polystyrene and PMMA as shells. The encapsulation ratio at 1:1 and 1:3 were taken as core. Encapsulation ratio of 1:3 performed well by displaying enhanced thermal and mechanical properties of Young's modulus and deformation with best shell and core materials. Arshad *et al.* [12] investigated the passive cooling in electronic devices by PCM based pin fin heat sink for increasing reliability and functionality. Heat sinks were composed of aluminum fins with the thickness of 1, 2, and 3 mm were experimented at 20 mm constant height. Volume concentrations of 0%, 0.33%, 0.66%, and 1% were used for verifying the thermal performance of heat sink. The performance was higher when the volume concentration was high. Griffin *et al.* [13] studied the solar-thermal and geothermal storage systems used for space heating and cooling. Here magnesium nitrate hydrate eutectic was used as PCM. The total energy density was approximately measured to be 1170 ±94 KJ/kg at 145 °C. It had a 10% increase over thermochemical energy density got increased.

Li *et al.* [14] used a thermal energy storage medium consisting of flake graphite in hydro peroxide solution and stearic acid. It possessed good thermal stability at 230 °C and higher latent heat value (61.05 J/g for melting and 61.00 J/g for freezing). These properties were good for the system. Cheng *et al.* [15] studied the light weight wall composite material synthesized by vacuum impregnation containing expanded graphite. The results revealed a comprehensive strength of 2.853 MPa and a bulk density of 0.445 kg/m^3. The latent heat value observed was 16.26 J/g during melting and 15.98 J/g during solidification. A good thermal conductivity of 0.76 W/mK was exhibited during operation. Dayou *et al.* [16] used carbon nanofiller with MgO ceramic in the PCM. Carbon nanofiller was directly grown on the surface of the MgO ceramic. The synthesization process was carried out, and the same was investigated with the aid of a high resolution TEM and SEM. The thermal conductivity was checked by transitory plane source thermal characterization technique for heat storage applications. Ebadi *et al.* [17] evaluated PCM comprised of CuO nanoparticle dispersed in coconut oil. It had increased the thermal conductivity and decreased the phase change time requirement. This work investigated about the height of PCM, the temperature of hot wall and weight fraction of CuO in PCM. The thermal conductivity was improved by 7.5% and the melting fraction was 15%. Virgone *et al.* [18] investigated paraffin based storage bricks. Hee-Biot number and material thickness were the parameters of interest. The characteristic behavior of developed bricks were studied using differential scanning calorimetry. Two different curves were obtained for the heating and cooling processes.

Gasia *et al.* [19] paraffin wax with 58 °C melting temperature was analyzed for various properties such as temperature range, specific enthalpy and specific heat capacity were evaluated. The shell and tube heat exchanger application showed good results at 80 °C at 1200 cycle of operation. The optimization for charging and discharging times were calculated. Wu *et al.* [20] used paraffin wax for solving chemical decomposition in a pharmaceutical plant. The optimum parameters of 47.56 °C melting temperature and 171.4 kJ/kg latent heat were identified for paraffin wax. The changes of melting radius, solidification radius and fluid temperature were simulated using software. It decreased the energy consumption in pharmaceutical plant by 10.25%. Wu *et al.* [20] investigated dynamic melting processes of PCM in a vertically oriented energy storage system. A concentric helical coil was inserted to improve the heat exchange performance. This CFD technique was used for simulating the unsteady melting process with various liquid fraction. This method was very sensitive for HTF inlet temperature determination. Hohlein *et al.* [21] made an attempt to convert the high phase change temperature to low phase change temperature for a PCM. This study was to discover an alternative PCM with an operating temperature ranges between 90-150 °C. The phase change temperature, enthalpy, density and thermal diffusivity were observed for xylitol, erythritol and $MgCl_2{\cdot}6H_2O$. In this work, an attempt to enhance the specific heat capacity of the PCM by embedding Al_2O_3 nanoparticle for the application of storage system. The addition of nanoparticles was expected to produce an increase in heat absorption capacity, stability, and thermal conductivity of the PCM. The proposed work is focused on thermal management system of EV by rapidly dissipating the heat developed during operation.

Experimental procedure

Experimental lay-out

In this study, a concentric tube heat exchanger with spiral coil and circular fin was used. The outer tube material was made up of mild steel having an outer diameter of 60 mm, thickness of 3 mm, and 600 mm long. The inner tube was made up of copper with an outer diameter of 40 mm, thickness of 1 mm, and 1700 mm long. The copper tube was bent into a spiral form with 10 turns following oil bending technique. The gap between the spirals were 50 mm. Thermocouples were placed in the exchanger at 0 mm, 120 mm, 240 mm, 360 mm, 480 mm, and 600 mm positions, respectively. When the flow was from the left position the right position, the system was undergoing a charging cycle. Similarly for discharging cycle, the flow was made to be vice versa. The whole set-up was completely insulted to avoid the heat transfer with the surrounding. The schematic lay-out is presented in fig. 1.

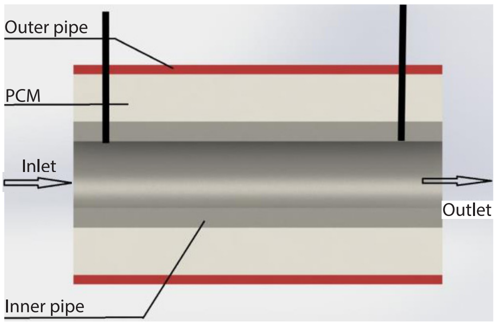

Figure 1. Schematic lay-out of the test set-up

Preparation of nanoPCM

The PCM material taken was pentacosane paraffin wax ($C_{25}H_{52}$), most suited for small scale energy storage application. The Al_2O_3 nanoparticles were achieved by ball milling of larger particles for about eight hours. The nanoPCM was developed by embedding the Al_2O_3 nanoparticles into the PCM. The addition of nanoparticles into PCM was carried out at fixed volume fraction of 0.833% and the mixture was stirred at 85 °C (melting point of pentacosane) for 30 minutes to achieve uniform distribution. After blending, it was allowed to solidify at room temperature. Now, the nanoPCM is in its solid phase. The nanoPCM thus developed was placed in the gap available between the two tubes. The property values of Al_2O_3 nanoparticle, PCM wax and nanoPCM were presented in tab. 1. A SEM image of the alumina nanoparticle was presented in fig. 2.

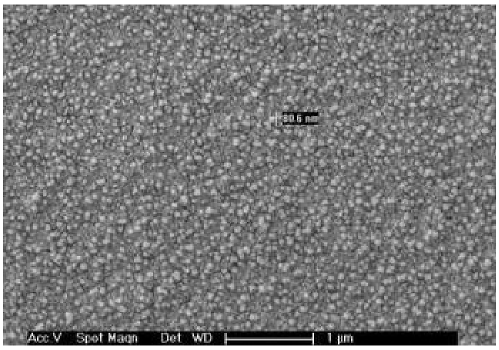

Figure 2. The SEM image of Al_2O_3

Table 1. Property values of medium used

Parameter for	Al_2O_3 nanoparticle	Paraffin wax	nanoPCM
Specific heat capacity	765 kJ/kgK	2.2 kJ/kgK	2.7 kJ/kgK
Thermal conductivity	36 W/mK	7.1 W/mK	11 W/mK
Density	3600 kg/m^3	900 kg/m^3	1350 kg/m^3
Diameter	20-30 nm	–	–

Result and discussion

Heat transfer with PCM

Based on the temperature readings at the steady-state condition, the graphs were presented. During the charging cycle, the heat energy was transferred into the PCM via heat transfer fluid with a flow rate of 5 Lph. There was a dip in temperature of fluid-flow between inlet and outlet due to energy absorption, as shown in fig. 3(a). Compared to the heat transfer rate for 15 Lph of flow, the former had a lower rate. This is due to the fact that the available amount of heat to transfer was lower. For higher mass-flow rate, the amount of heat energy available to transfer was more, as shown in fig. 3(b). Hence, the temperature difference between the inlet and outlet of fluid was observed to be high. The heat absorbed by the PCM was increased gradually increased with the increase in mass-flow rate of heat transfer fluid.

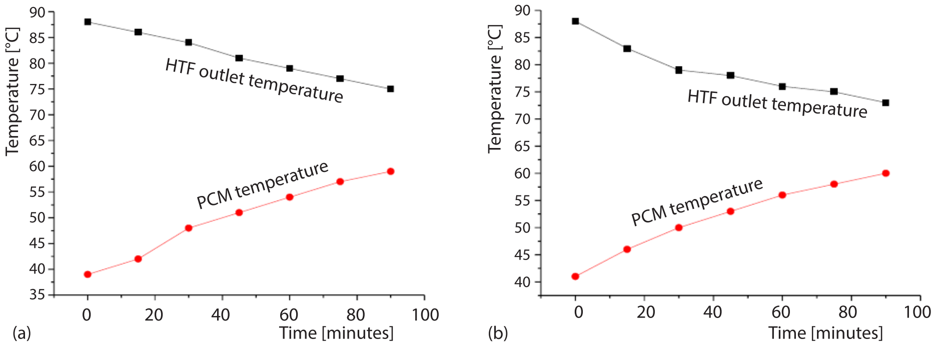

Figure 3. (a) Charging process at 5 Lph flow rate and (b) charging process at 15 Lph flow rate

During the discharging cycle, the direction of heat flow was reversed by sending in normal water in the inner tube. The heat energy stored within the PCM was released and carried out by the water. The difference in temperature between the inlet and outlet of water was smaller compared to that of the charging cycle as the temperature gradient was very narrow. The flow of heat was occurring in a slower manner arriving to equilibrium at each step of the way, as shown in figs. 4(a) and 4(b).

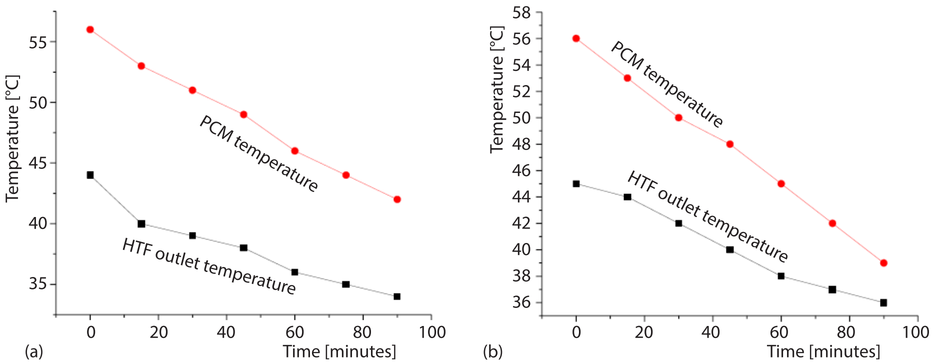

Figure 4. (a) Discharging process at 5 Lph flow rate and (b) discharging process at 15 Lph flow rate

Heat transfer with nanoPCM

In this study, an effort to improve the latent heat storage capacity of phase change medium was done by embedding nanoparticles into the PCM. The developed nanoPCM containing alumina nanoparticles was used in place of the normal PCM. Based on the temperature results at steady-state in charging cycle, it could be observed that the mass-flow rate is directly proportional to the temperature gradient, presented in figs. 5(a) and 5(b). More amount of heat energy was absorbed by the incorporation of nanoparticles into the PCM structure which increased the surface area for heat transfer. Compared to the former storage medium, the nanoPCM had more amount of heat stored in it with higher mass-flow rate of 15 Lph.

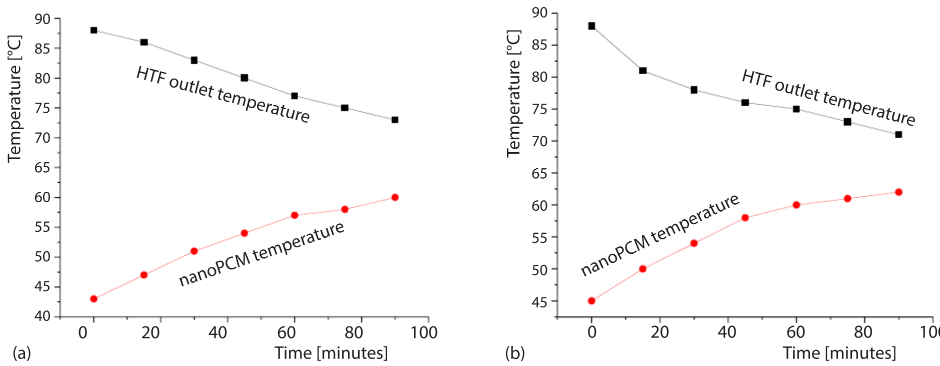

Figure 5. (a) Charging process at 5 Lph flow rate and (b) charging process at 15 Lph flow rate

Similarly in discharging cycle, more amount of heat energy was released to the normal water at the flow rate of 15 Lph. The energy stored were completely transferred back to the water in the presence of nanoparticles, presented in figs. 6(a) and 6(b). It is mainly caused by the increase in available energy for the nanoPCM.

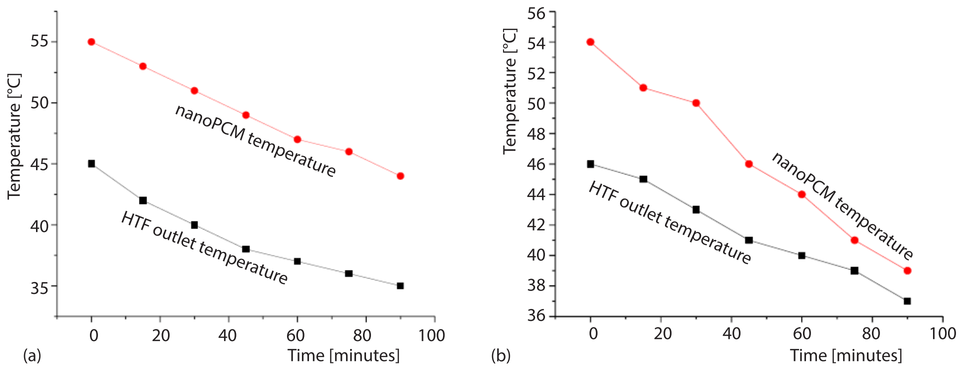

Figure 6. (a) Charging process at 5 Lph flow rate and (b) charging process at 15 Lph flow rate

Heat transfer efficiency

The heat transfer efficiency of the storage medium was compared between PCM and nanoPCM for both the cycles, as shown in figs. 7 and 8.

The graphs indicated that the temperature absorption rate was higher because of the addition of nanoparticles into PCM structure. The higher temperature absorbing capacity was caused by the improved surface area and heat capacity of storage medium. During charging and discharging, the available energy to absorb by the nanoPCM was higher compared to the normal PCM at higher mass-flow rate. It can be concluded that the incorporation of Al_2O_3 nanoparticles with PCM increased the thermal stability by increasing the melting temperature. An increment of 50% in the solidification time was observed for nanoPCM. It could be observed that the use of Al_2O_3 nanoparticles had enhanced the charging efficiency by 6% and the discharging efficiency by 4% as compared to that of the normal PCM. This phenomenon was observed due to the occupancy of interstitial sites of PCM by Al_2O_3 nanoparticles. It improved the bonding energy between the loosely packed atoms of PCM, thereby increasing the energy required to break the bond.

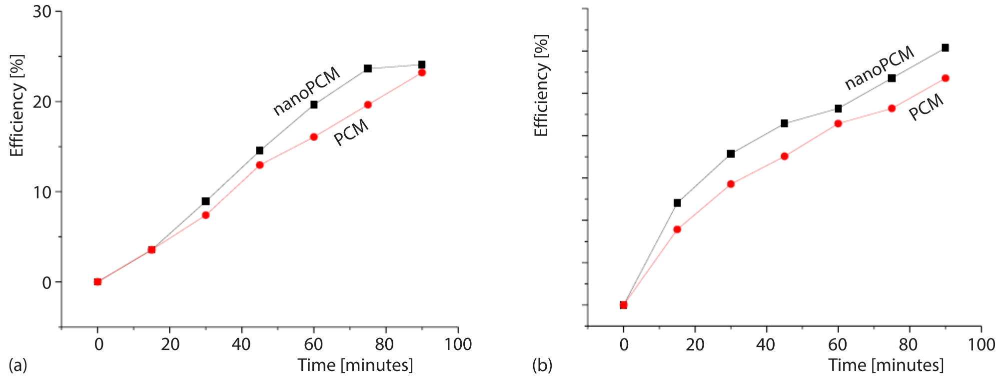

Figure 7. (a) Charging efficiency at 5 Lph flow rate and (b) charging efficiency at 15 Lph flow rate

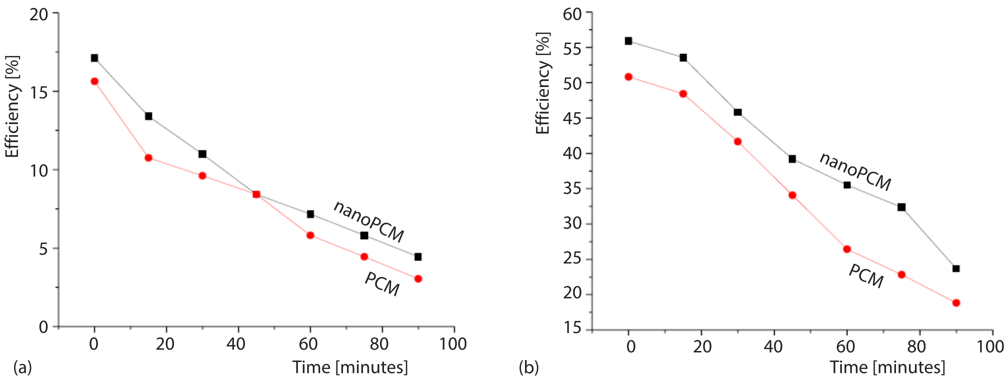

Figure 8. (a) Discharging efficiency at 5 Lph flow rate and (b) discharging efficiency at 15 Lph flow rate

Conclusion

Analysis on the energy storage capacity of nanoPCM containing alumina nanoparticles was carried out. With the addition of nanoparticles into the PCM structure, the energy storage capacity of the system has improved. The heat capacity of nanoPCM was superior to that of the plain PCM. The volumetric concentration of 0.833% nanoparticles increased the charging time by 50% and reduced discharging time by 25%. The increase of efficiency by 6% during charging and 4% during the discharging cycle was observed as the effect of addition of alumina nanoparticle in the system. It occurred due to the improvement in thermal stability, increased melting point and heat capacity due to the occupancy of interstitial sites available in PCM by the nanoparticles.

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References

[1] Venkitaraj, K. P., *et al.*, Experimental Study on the Thermal Performance of Nanoenhanced Pentaerythritol in IC Engine Exhaust Heat Recovery Application, *Applied Thermal Engineering*, *137* (2018), June, pp. 461-474

[2] Al Ghossein, R. M., *et al.*, Experimental Determination Of Temperature-Dependent Thermal Conductivity of Solid Eicosane-Based Silver Nanostructure-Enhanced Phase Change Materials for Thermal Energy Storage, *International Journal of Heat and Mass Transfer*, *107* (2017), Apr., pp. 697-711

[3] Ghasemi Bahraseman, H., *et al*., Fast Charging of Thermal Energy Storage Systems Enabled by Phase Change Materials Mixed with Expanded Graphite, *International Journal of Heat and Mass Transfer*, *109* (2017), June, pp. 1052-1058

[4] Sheikholeslami, M., Numerical Simulation for Solidification in a LHTESS by Means of Nanoenhanced PCM, *Journal of the Taiwan Institute of Chemical Engineers*, *86* (2018), May, pp. 25-41

[5] Venkatesh, R., Vijayan, V., Performance Evaluation of Multipurpose Solar Heating System, *Mechanics and Mechanical Engineering*, *20* (2016), 4, pp. 359-370

[6] Sakthivel, P., *et al.*, Experimental Heat Transfer Analysis on Heat Pipe Using SiO_2 and TiO_2 NanoFluid, *11* (2018), Special Issue, pp. 91-101

[7] Chinnarasu, K., *et al*., Analysis of Varying Geometri Structures of Fins Using Radiators, *Journal of Applied Fluid Mechanics, 11* (2018), Special Issue, pp. 115-119

[8] Pradeep, K., *et al*., Computational Analysis and Optimization of Spiral Plate Heat Exchanger, *Journal of Applied Fluid Mechanics*, *11* (2018), Special Issue, pp. 121-128

[9] Ahmed, S. F., *et al*., Recent Progress in Solar Thermal Energy Storage Using Nanomaterials, *Renewable and Sustainable Energy Reviews*, *67* (2017), Jan., pp. 450-460

[10] Aljehani, A., *et al*., Design and Optimization of a Hybrid Air Conditioning System with Thermal Energy Storage Using Phase Change Composite, *Energy Conversion and Management*, *169* (2018), Aug., pp. 404-418

[11] Giro-Paloma, J., *et al*., Comparison of Microencapsulated Phase Change Materials Prepared at Laboratory Containing the Same Core and Different Shell Material, *Applied Sciences*, *7* (2017), 7, 723

[12] Arshad, A., *et al*., Thermal Performance of Phase Change Material (PCM) Based Pin-Finned Heat Sinks for Electronics Devices: Effect of Pin Thickness and PCM Volume Fraction, *Applied Thermal Engineering*, *112* (2017), Feb., pp. 143-155

[13] Griffin D., *et al*., Reactive Phase Change Mateirals for Enhanced Thermal Energy Storage, *Energy Technology*, *6* (2017), 2, pp. 351-356

[14] Li, C., *et al*., The H_2O_2-Microwave Treated Graphite Stabilized Stearic Acid as a Composite Phase Change Material for Thermal Energy Storage, RSC Advances, *Royal Society of Chemistry*, *7* (2017), 83, pp. 52486-52495

[15] Cheng, F., *et al*., Preparation and Analysis of Lightweight Wall Material with Expanded Graphite (EG)/Paraffin Composites for Solar Energy Storage, *Applied Thermal Engineering*, *120* (2017), June, pp. 107-114

[16] Dayou, S., *et al*., Direct Growth of Graphene on MgO by Chemical Vapor Deposition for Thermal Conductivity Enhancement of Phase Change Material, *Materials Chemistry and Physics*, *202* (2017), Dec., pp. 352-357

[17] Ebadi, S., *et al*., Geometry and Nanoparticle Loading Effects on the Biobased nanoPCM Filled Cylindrical Thermal Energy Storage System, *Applied Thermal Engineering*, *141* (2018), Aug., pp. 724-740

[18] Virgone, J., *et al.,* 2-D Conduction Simulation of a PCM Storage Coupled with a Heat Pump in a Ventilation System, *Aplied Sciences*, *6* (2016), 7, 193

[19] Gasia, J,. *et al*., Experimental Evaluation of a Paraffin as Phase Change Material for Thermal Energy Storage in Laboratory Equipment and in a Shell-and-Tube Heat Exchanger, *Applied Sciences*, *6* (2016), 4, 112

[20] Wu, W., *et al*., A Functional Form-Stable Phase Change Composite with High Efficiency Electro-to-Thermal Energy Conversion, *Applied Energy*, *190* (2017), Mar., pp. 474-480

[21] Hohlein, S., *et al*., Thermophysical Characterization of $MgCl_2 \cdot 6H_2O$, Xylitol and Erythritol as Phase Change Materials (PCM) for Latent Heat Thermal Energy Storage, *Materialis*, *10* (2017), 4, 444

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