International Journal of Analytical, Experimental and Finite Element Analysis (IJAEFEA), Issue. 1, Vol. 2, March 2015.
e-ISSN: 2394-5141, p-ISSN: 2394-5133, pp 6-11.

Performance of Solar Collector for Thermal Storage System Using Nanofluids: A Review

Vednath P. Kalbande[1],
Research scholar,
v.kalbande@raisoni.net

K. S. Rambhad[2],
Research scholar,
kishorsrambhad@gmail.com

P. V. Walke[3],
Professor,

Department of Mechanical Engineering, G. H. Raisoni College of Engineering, Nagpur- 440016, India

Abstract **- Globally there is profuse literature on the continuous developments of solar based thermal storage system. The performance characteristics of a solar based thermal storage system can be effectively improved by using circulating fluid in different types and content. Abundantly available solar energy utilization for domestic and industrial applications is hindered because of its intermittent nature. The thermal energy storage (TES) system using both sensible and latent heat has many advantages like large heat storage capacity in a unit volume and its isothermal behavior during the charging and discharging processes. In the present literature the efforts have been made to focus on diverse development of solar energy based thermal storage till now. The rural and urban population, depend mainly, on non-commercial fuels to meet their energy needs. Solar cooking is one possible solution but its acceptance has been limited partially due to some barriers. Solar cooker cannot cook the food in late evening. That drawback can be solved by the storage unit associated with in a solar cooker. So that food can be cook at late evening. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar cooking system incorporating with phase change materials (PCMs). Thermal energy storage system plays a critical role in developing an efficient solar energy device. Many research works is being carried out to determine the suitability of thermal energy storage system to integrate with solar thermal gadgets. This review paper summarizes all the research and development work carried out in the field of solar cooker in particular the storage type solar cookers. A novel concept of PCM-based storage type solar cooker is also presented which is under experimental investigation.**

Index terms— phase change material, solar colector, solar cooker, thermal storage system

I. INTRODUCTION

Due to the increasing economic and environmental tensions on fossil fuels and biomass, solar energy becomes more and more attractive throughout the years. It is especially true in the southern countries where sun is available; deforestation becomes a major problem and the income per capita remains low. In the 5th century B.C., the Greeks took advantage of passive solar energy by designing their homes to capture the sun’s heat during the winter. Later, the Romans improved on solar architecture of buildings by covering south-facing windows with clear materials such as mica or glass, preventing the escape of solar heat captured during the day [1]. In recent years, attention has increased to decrease the cost of solar energy equipment and improve the efficiency of heat energy storage systems. To store the heat energy, basically two types of storage systems are developed. One is a sensible heat storage system and another is a latent heat storage system. To store a large quantity of heat in a small unit volume, combined sensible heat and latent heat storage systems are developed. Solar cooking is an interesting option for spreading solar energy: indeed, cooking is one of the basic needs of humankind and represents an important source of energy consumption. Using solar cooking in sunny areas may then help to reduce poverty and deforestation, gain significant time usually spend on collecting wood, and reduce health diseases due to indoor smoke. Solar cookers have been deeply investigated during the last two decades; the most common principle is direct cooking with boxes or parabolas. Direct cooking is powerful and sufficient when there is sunshine; however, cooking occurs very often during the evening when the sun is already down. Using heat storage can help to make a solar cooker competitive even by night: by storing heat during the day, the system enables cooking by night.

II. LITERATURE SURVEY

Maxime Mussard et al. [1] conducted comparative experimental study of two solar cookers. The first is the widespread SK14 cooker (Fig. 1); the second is a prototype of a solar concentrator (parabolic trough) using a storage unit. The SK14 is a direct solar cooker where the cooking pot is placed on the focal point of a parabolic dish; in the trough system heat is transported from an absorber to a storage unit by means of a self-circulation loop filled with thermal oil. Cooking takes place directly on the top of the storage. Cooking experiments are conducted to compare the performance of these two methods of heat extraction. Both boiling and frying was tested to estimate the cooking efficiency of the heat storage system. The glass protecting the absorber is proved to be more efficient, and is required in order to reach the melting temperature of the PCM (see Fig. 2). With the glass absorber, the storage can be fully charged with the sun in 6 hours. A solar cooker based on heat storage is a concept which can be developed and used in a sustainable way, knowing that it is possible to reach the performance of conventional direct solar cookers.

Fig.1 SK 14 system [1]

Fig. 2. System in use – absorber without insulation coupled with heat storage. [1]

Jegadheeswaran et al. [2] studied the Conductivity particles dispersed organic and inorganic phase change materials for solar energy storage–an exergy based comparative evaluation. The performance enhancement of a shell and tube latent heat thermal storage (LHTS) system due to dispersion of conductivity nano-particles was investigated. Two phase change materials (PCM) was considered, one is organic PCM (paraffin wax) and the other is inorganic (hydrated salt). The numerical study involves both charging and discharging modes. The performance enhancements of the two PCMs are compared in terms of exergy stored/recovered and exergy efficiency. The transient numerical calculations were performed using CFD code FLUENT. The results indicate that hydrated salt composites exhibit better exergy efficiency than paraffin wax composites due to their higher thermal conductivity. However, the former cannot be stated as better choice because of its inability to store /recover more exergy. Hence, the choice of PCM should not be based on its high thermal conductivity alone. The transient numerical calculations were performed using CFD code FLUENT. The results indicate that hydrated salt composites exhibit better exergy efficiency than paraffin wax composites due to their higher thermal conductivity. However, the former cannot be stated as better choice because of its inability to store /recover more exergy. Hence, the choice of PCM should not be based on its high thermal conductivity alone.

Chee Woh Foong et al. [3] investigate a small scale double-reflector solar concentrating system with high temperature heat storage. NaNO3-KNO3 binary mixture was used as the phase change material (PCM) in the heat storage and the thermal behavior of this salt was analyzed using differential scanning calorimeter (DSC). The latent heat storage unit was modeled numerically using a finite element model (fig. 3). Effective heat capacity method was adopted to simulate the phase change process. The model developed in this study is able to predict the experimental results quite satisfactory (less than 15% error). With the given experimental setup, the direct illuminating system was able to melt the PCM within 2-2.5 h and reached the temperature range of 230-260 ^{0}C. This temperature range is quite suitable for cooking or baking purposes. The ultimate objective of this study is to develop a small scale solar concentrating system with high temperature storage which can charge the PCM thermal storage during day time and use it in the night time for cooking purpose.

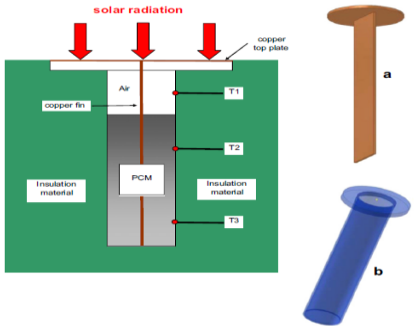

Fig. 3. Schematic diagram of the PCM test module; (a) copper top plate and fin, (b) stainless steel container. [3]

Huseyin Benli et al. [4] performed the analysis of a latent heat storage system with phase change material for new designed solar collectors in greenhouse heating. A detailed analytical and experimental study was conducted to evaluate the thermal performance of five types of ten pieced solar air collectors and PCM, under a wide range of operating conditions. This system was considered predominantly useful for heating applications significantly increased. The solar air collectors and PCM system created 6–9 ^{0}C temperature difference between the inside and outside the greenhouse. The system worked more efficiently in day with high solar radiation air temperatures. The proposed size of collectors integrated PCM provided about% 18–23 of total daily thermal energy requirements of the greenhouse for 3–4 h, in comparison with the conventional heating device. This system proved that it could be used efficiently for heating of the greenhouse night and cold days. In case of in an overcast day, this system is unsuitable for heating of the greenhouse and charging of the PCM. Experimental results show that univalent central heating operation (independent of any other heating system) cannot compensate for the overall heat loss from the greenhouse if the ambient temperature is very low. Bivalent operation (combined with another heating system) can be suggested as the best solution in Eastern region in Turkey, if peak load heating can be easily controlled.

A.J. Gallego et al. [5] mathematically analyze modeling of a PCM storage tank in a solar cooling plant as shown in Fig. 4. Presented a mathematical model and the parameters estimation procedure of a PCM storage tank to be used it in hierarchical control strategies. In the first part, process dynamic equations have been described and assumptions which simplify the model in order to reduce the computational burden are given. A study of the parameters to be estimated, their values range and the optimization procedure have been described. The model has been

© 2015 RAME IJAEFEA

validated in an ample range of temperatures, working properly throughout the PCM operational range, producing an adequate trade-off between complexity and modeling accuracy.

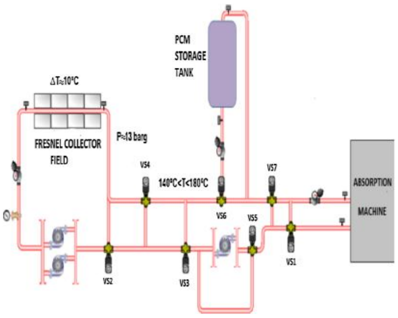

Fig. 4. Solar cooling plant [5]

Chi-ming Lai et al. [6] studied the thermal performance of an aluminum honeycomb wallboard incorporating microencapsulated PCM as shown in Fig. 5. The combined building construction and thermal technology by using mPCM (core material: paraffin; melting temperature: 37^0C) and aluminum honeycomb structures (25.4 mm thick; 8 mm core cell) to construct a mPCM honeycomb wall board prototype (10 cm (H) × 10 cm (L) × 2.54 cm (W)) and analyzed the heat transfer characteristics of this prototype using experimental methods. The main control parameters were the time variant heat flux of the hot wall and heat convection condition of the cold wall, which mimicked typical solar irradiation and air conditioned indoor environment, respectively. The time-variant heat flux at the hot wall was derived from measured meteorological data and described as a sine function with peak values of 400, 600, 800, and1000 $W/^{m2}$. For thermal protection applications, the instantaneous fractional heat flux across the module into the interior is of practical interest. A shorter effective thermal protection period due to the accelerated melting rate in the mPCM layer.

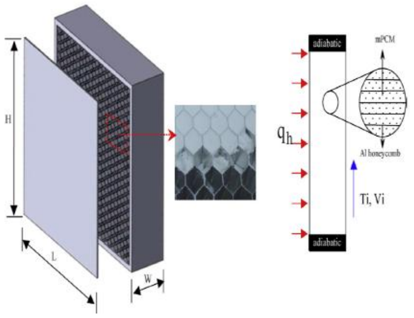

Fig. 5. Investigated target (mPCM honeycomb wallboard) and physical model. [6]

Wei-Wei Wang et al. [7] numerically studied the heat charging and discharging characteristics of a shell-and-tube phase change heat storage unit. To design high efficiency PCTES, details physical phenomena of the transient performance of a shell-and-tube phase change thermal energy storage unit are addressed (see Fig. 6). The effects of temperature difference between the inlet of heat transfer fluid (HTF) and melting point of phase change material (PCM). Heat charging and discharging processes have three stages for the change of PCM temperature and heat charging or discharging rate regarding time: rapidly changing period, slowly changing period and more slowly changing period. Under the same inlet temperature and mass flow rate of HTF, discharging process has comparable larger heat transfer rate than charging process, thus, discharging process would reach steady state quickly. The HTF inlet temperature has great effect on the time to complete heat charging or discharging process, at the same time more energy is stored for higher HTF inlet temperature, the heat storage increases nonlinearly with increasing the inlet temperature. The HTF mass flow rate has little influence on the amount of energy stored, but greatly affects charging or discharging time. The time needed to complete charging or discharging process decreases nonlinearly regarding to the increase of the HTF mass flow rate.

Suvhashis Thapa et al. [8] performed Fabrication and analysis of small-scale thermal energy storage with conductivity enhancement. A thermal energy storage device using phase change material (PCM) has been fabricated, tested and modeled under a variety of conditions and constructions. Real devices were constructed with thermal conductivity enhancements; one contained only paraffin as the PCM, a second incorporated a copper foam mesh along with the wax to increase the thermal conductivity. A third was comprised of a copper matrix which was combined with the PCM. The maximum achieved average conductivity for the TES device was 3.78 W/m K given the copper foam enhancement. Results indicated diminishing returns as conductivities exceeded 4–6 W/m K. The total time for phase change to occur throughout the material was 7400 s at 0.5 W/m K and 2050 s at 6 W/m K. The difference in elapsed time between phase change at 3 and 6W/m K was only 450 s. Operation of a TES system with simulated thermoelectric generator was also studied.

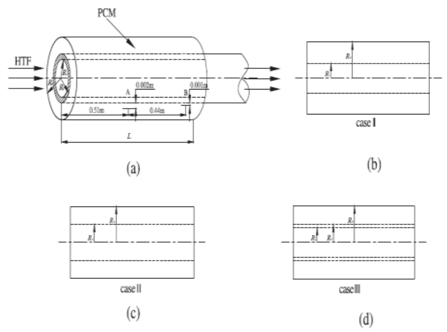

Fig. 6. Schematic of the phase change heat storage unit: (a) integral structure, (b) simplified model I, (c) simplified model II and (d) simplified model III [7]

Teppei Oya et al. [9] studied phase change composite based on porous nickel and erythritol. Prepared a phase change composite with porous nickel as a support for the enhancement of thermal conductivity and investigated its heat storage capacity in the form of latent heat. The vacuum impregnation of the porous metal with erythritol was effective in producing a phase change composite with high stability. The latent heat of the composites was virtually proportional to the impregnation ratio, and the pore size had no effect on the melting point of the PCM

(118 ^{0}C). Among the samples prepared, the composite with 15 vol% porous nickel having a pore size of 500 mm and 85 vol% erythritol showed the largest thermal conductivity, 11.6Wm^{-1} K^{-1} at room temperature, a value that was two orders of magnitude higher than that of pure erythritol.

Ehsan Mohseni Languri et al. [10] experimentally studied latent thermal energy storage system using phase change material in corrugated enclosures (see Fig. 7). The data suggest that the devised TES is more effective than a multi-tube system in terms of discharging and charging times. The significant enhancement is attributed to the higher surface area-to volume ratio of the devised TES. The experimental data suggest that a significant buoyancy effect enhances the charging (melting) process within the TES when the HTF flows upwardly, which decreases charging time. Furthermore, an increase in the HTF inlet temperature resulted in higher radial and axial temperature gradients throughout the TES in comparison to a multi-tube system. In summary, the design and performance of a thermal energy storage unit can be enhanced by using an inverted configuration where the HTF flows around the PCM. Moreover, system variables such as HTF temperatures and HTF flow direction are equally important when it comes to achieving the best thermal performance. Future studies should consider real-scale system to determine the effect of aspect ratio on thermal response time during the charging and discharging processes.

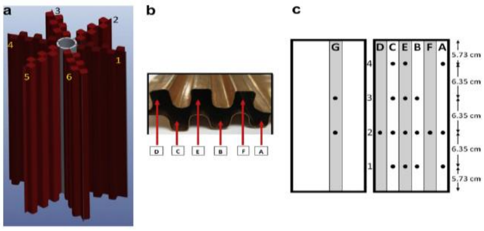

Fig. 7. (a) 3D schematic view of TES, (b) cross-section of TES panel and, (c) side view of PCM enclosures 4 (left side) and 1 (right side) showing thermocouple positions. [10]

Babak Kamkari et al. [11] experimental investigation was conducted to examine the effect of inclination angle on the thermal characteristics of the melting process in a rectangular enclosure heated from one side. A high Prandtl number PCM (lauric acid) was employed. Melting experiments were performed for different wall temperatures of 55, 60 and 70 ^{0}C corresponding to Rayleigh numbers in the range from 3.6 x 10^8 to 8.3 x 10^8 and different inclination angles of 0^0, 45^0 and 90^0. Qualitative time-dependent flow structures were deduced indirectly from the instantaneous shapes of the solid–liquid interfaces which were confirmed by quantitative temperature results. For the range of temperatures considered, the total melting time for the 45^0 and 0^0-inclined enclosures were, on average, 35% and 53% less than the vertical enclosure, respectively. The Nusselt number enhancement ratios, defined as the ratio of time-averaged Nusselt number in the inclined enclosure to that of the vertical enclosure (base case), were found to be 1.7 and 2.1 for the 45^0 and 0^0-inclined enclosures, respectively. These significant enhancement ratios were attributed to the formation of chaotic and multi-cellular flow structures which appeared by decreasing the inclination angle resulting in more heat transfer from the hot wall to the solid–liquid interface. Irrespective of the inclination angle, the time-averaged Nusselt number showed 11% and 35% enhancements when the wall temperature was increased from 55 ^{0}C to 60 ^{0}C and 70 ^{0}C, respectively (see Fig. 8). For each inclination angle, the variation of the local heat transfer rates on the solid–liquid interface clearly depicted the regions of the enclosure in which convection currents play the significant role of heat transfer between the liquid PCM and solid interface. The observed phenomena and measured values can be used to validate numerical simulations relating to the melting process of high Prandtl number PCMs in inclined enclosures.

Qinbo He et al. [12] experimentally investigated the photothermal properties of nanofluids for direct absorption solar thermal energy systems; Adding nanoparticle to pure water can change the solar energy spectrum absorption characteristics of water. Nanoparticles with excellent optical absorption make the transmittance of nanofluid in 250–1370 nm wavelength range lower than that of pure water. Nanoparticle size, mass fraction and optical path can affect the transmittance of nanofluid. Transmittance decreases along with particle size increase, and decreases with mass fraction increase. The transmittance of Cu–H_2O nanofluids (0.1 wt.%) is closes to zero, and the highest temperature of it can increase up to 25.3% compared with deionized water. In conclusion, the photothermal properties experiments show that Cu–H2O nanofluids have good absorption ability for solar energy, and can effectively enhance the solar absorption efficiency. Thus, Cu–H_2O nanofluids can be hopeful to apply in direct absorption solar collector.

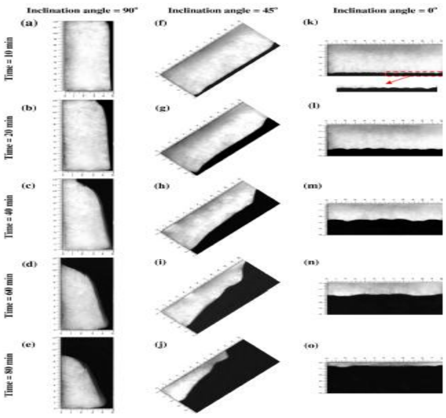

Fig. 8. Sequential photographs of the melting process of PCM in the rectangular enclosure for different inclination angles with hot wall temperature of 70 ^{0}C [11]

Abishake Arunasalam et al. [13] Performed analysis on solar integrated collector storage, the temperature histories of fin and PCM during charging process for two different flow rates is discussed. The thermal mass material undergoes sensible heating as well as phase change process inside the TES container. It is concluded from the repeated experimentation that the reusability and chemical stability of PCM are good enough to supply the hot air for the space heating application. The combined sensible and latent storage concept provides the flexibility of space heating operation during the non-solar periods. The combined sensible and latent heat based TES finds application in the medium to high temperature air dryer and space heating applications. The large scale fabrication of solar thermal energy storage set up will be more successful for the community space heating with increased collector area, improved solar rays concentration, effective high latent heat and high melting temperature PCMs, performance enhancement techniques like multiple PCM or Impregnation of metal powders to improve the thermal conductivity, use of Fresnel lens which leads to reduced maintenance of reflector dishes etc.

Oluwaseun S. Alajo et al. [14] Experimentally study on the performance of a pcm-based solar energy storage system, Solar energy storage system based on a vegetable-based, non-toxic, non-flammable, renewable and biodegradable phase change material (PCM) was developed. The system involves the two storage tank system, one for the PCM and the other for the hot water storage. The system used was designed such that the heated water can be diverted to a heat exchanger by means of a 3-way valve such that a fan can be made to blow air through one of the heat exchangers so that hot air for other purposes such as air heating can also be achieved through the system. Solar energy was applied in the system to power all the electrical components to ensure applicability of the system in parts of the world where electricity is not readily available. An experimental study on the performance of this system was done leading to a number of useful results. Based on the scale of this system, projections show that it can be extended to home building and commercial building applications. One of the results from this study shows that using the best or optimum low flow rate for the HTF for energy storage and energy recovery process gives the best performance by the system. The highest system efficiency of 63.6% was recorded for the summer period.

Alkilani Mahmud et al. [15] performed a paraffin wax-aluminum compound as a thermal storage material in a solar air heater, This paper presents a theoretical investigation of thermal and physical properties of a phase change material (PCM) consists of paraffin wax with 5% aluminum powder, this composite used as a thermal storage compound in a solar air heater, the compound supposed be encapsulated in cylinders as a solar absorber in cross flow of pumped air. An indoor simulation supposed that the PCM initially heated by solar simulator until liquid phase temperature (50°C) while the pumped air over the cylinders at room temperature (28°C), results show that the air temperature gained due to thermal energy discharge process decreases with increasing of air mass flow rate, and the freezing time for this compound takes long time interval for the lower mass flow rates.

I. Fernández et al. [16] Advances in phase change materials for thermal solar power plants Quality, There is a strong need to develop new LHTS that facilitate the reduction of cost energy produced by thermal solar power plants. An important possibility is the implementation of PCMs. However, these materials posses a low thermal conductivity, so it is needed a strong research in the development of techniques and systems which could increase the capacity of PCMs to storage solar energy. Nowadays, the development of efficient LHTS is in a research phase which is showing different potential solutions to implement PCMs in solar power plants. The next target is the implantation of these techniques in pilot scale which make possible the future application in real plants in order to make them more competitive through electricity costs reduction.

W. Saman et al. [17] performed the PCM thermal storage unit for a roof integrated solar heating system, Analysis of the thermal performance of a phase change storage unit has been carried out. It demonstrates the need to include the effect of sensible heat in analysing this particular application. The following conclusions can be drawn from the analysis. The effect of sensible heat is perceived in the initial periods of both melting and freezing. The effect is reflected in sharp increase in the outlet air temperature in the initial periods of melting and a sharp decrease in the initial periods of freezing. For heating purposes, this means a significant warming effect is perceived during the initial periods of delivering air to the living space. This is advantageous from the thermal comfort point of view. A higher inlet air temperature increases the heat transfer rates and shortens the melting time. Conversely, during freezing, a lower inlet air temperature increases the heat transfer rates and shortens the freezing time. Likewise, a higher air flow rate increases the heat transfer rate and shortens the melting time but increases the outlet air temperature. For freezing, a higher air flow rate increases the heat transfer rate and shortens the freezing time but reduces the outlet air temperature. The model employed in this study has been validated using existing experimental data and the comparison is quite satisfactory.

F.S. Javadi et al. [18] Investigated performance improvement of solar collectors by using nanofluids, Solar collectors have a great potential for producing heat and are highly suited to be applied in water heater and air heating systems. Unique properties of nanofluids, due to the smaller size and larger surface area, make a massive evolution in heat transfer. Nanoparticles, as suspension particles into a liquid, have what it takes to change the physical and thermal properties of the base fluid Therefore, by increasing energy transfer and decreasing energy losses, it can help to increase the performance and efficiency of solar collectors. This provides promising ways for engineers to improve highly effective green devices. According to the literatures, water is the best absorber in direct absorption solar collector due to its strong solar absorption, but it is not high enough (only 13% of the incoming energy). Suspension nanoparticles can improve the optical properties of basefluid, which are dependent on particle size, particle shape, the optical properties of the particle and basefluid. Extinction coefficient is a function of the particle diameter and wavelength of the light. Nanofluid with small diameter suspended nanoparticle has higher.

III. CONCLUSION

The use of a thermal storage system using phase change materials (PCMs) is an effective way of storing solar energy and has the advantages of high energy storage density and the isothermal nature of the storage process. Cooking on heat storage with optimized surface contact is proved to be competitive with standard solar cookers or other cooking devices. The choice of PCM should not be based on its high thermal conductivity alone.The transient numerical calculations were performed using CFD code FLUENT. NaNO3-KNO3 binary mixture was used as the phase change material (PCM) in the heat storage and the thermal behavior of this salt was analyzed using differential scanning calorimeter (DSC). The solar air collectors and PCM system created 6–9 ^{0}C temperature difference between the inside and outside the greenhouse. A shorter effective thermal protection period due to the accelerated melting rate in the mPCM layer. The difference in elapsed time between phase change at 3 and 6W/m K was only 450 s. Operation of a TES system with simulated thermoelectric generator was also studied. Qualitative time-dependent flow structures were deduced indirectly from the instantaneous shapes of the solid–liquid interfaces which were confirmed by quantitative temperature results. The photo-thermal properties experiments show that Cu–H2O nanofluids have good absorption ability for solar energy, and can effectively enhance the solar absorption efficiency. One of the results from this study shows that using the best or optimum low flow rate for the HTF for energy storage and energy recovery process gives the best performance by the system. the development of efficient LHTS is in a research phase which is showing different potential solutions to implement PCMs in solar power plants. Suspension nanoparticles can improve the optical properties of basefluid, which are dependent on particle size, particle shape, the optical properties of the particle and basefluid.

REFERENCES

[1] Maxime Mussard, Alexandre Gueno, Ole Jørgen Nydal "Experimental study of solar cooking using heat storage in comparison with direct heating" Solar Energy, Volume 98, Part C, December 2013, Pages 375-383.

[2] S.Jegadheeswaran, S.D.Pohekar, T.Kousksou, "Conductivity particles dispersed organic and inorganic phase change materials for solar energy storage–an exergy based comparative evaluation" Energy Procedia 14 (2012) 643 – 648 2011 2nd International Conference on Advances in Energy Engineering (ICAEE2011).

[3] Chee Woh Foong, Ole Jørgen Nydal, Jørgen Løvseth "Investigation of a small scale double-reflector solar concentrating system with high temperature heat storage" Applied Thermal Engineering 31 (2011) 1807-1815

[4] Huseyin Benli, Aydın Durmus "Performance analysis of a latent heat storage system with phase change material for new designed solar collectors in greenhouse heating" Solar Energy 83 (2009) 2109–2119

[5] A.J. Gallego, A. Ruiz-Pardo, A.Cerezuela-Parish, J. Sanchez, C. Martin-Macareno, L.F. Cabeza, E.F. Camacho, E. Oro "Mathematical modeling of a PCM storage tank in a solar cooling plant" Solar Energy 93 (2013) 1–10

[6] Chi-ming Lai, Shuichi Hokoi "Thermal performance of an aluminum honeycomb wallboard incorporating microencapsulated PCM" Energy and Buildings 73 (2014) 37–47

[7] Wei-Wei Wang, Kun Zhang, Liang-Bi Wang, Ya-Ling He "Numerical study of the heat charging and discharging characteristics of a shell-and-tube phase change heat storage unit" Applied Thermal Engineering 58 (2013) 542-553

[8] Suvhashis Thapa, Sam Chukwu, Abdul Khaliq, Leland Weiss "Fabrication and analysis of small-scale thermal energy storage with conductivity enhancement" Energy Conversion and Management 79 (2014) 161–170

[9] Teppei Oya, Takahiro Nomura, Noriyuki Okinaka, Tomohiro Akiyama "Phase change composite based on porous nickel and erythritol" Applied Thermal Engineering 40 (2012) 373-377

[10] Ehsan Mohseni Languri, Clifford O. Aigbotsua, Jorge L. Alvarado "Latent thermal energy storage system using phase change material in corrugated enclosures" Applied Thermal Engineering 50 (2013) 1008-1014

[11] Babak Kamkari, Hossein Shokouhmand, Frank Bruno "Experimental investigation of the effect of inclination angle on convection-driven melting of phase change material in a rectangular enclosure" International Journal of Heat and Mass Transfer 72 (2014) 186–200

[12] Qinbo He, Shuangfeng Wang, Shequan Zeng, Zhaozhi Zheng "Experimental investigation on photothermal properties of nanofluids for direct absorption solar thermal energy systems" Energy Conversion and Management 73 (2013) 150–157

[13] Abishake Arunasalam, Anjan Ravi, Bommu Srivatsa & R.Senthil "Thermal performance analysis on solar integrated collector storage" Undergraduate Academic Research Journal (UARJ), ISSN : 2278 – 1129, Volume-1, Issue-2, 2012

[14] Oluwaseun S. Alajo, Victor C. Ibekwe, Emmanuel C. Nsofor "Experimental Study on the Performance of a PCM-Based Solar Energy Storage System" American Journal of Engineering Research (AJER) e-ISSN : 2320-0847 p-ISSN : 2320-0936 Volume-02, Issue-11, pp-195-203

[15] Alkilani Mahmud, Sopian K., Alghoul M. A. and Mat Sohif "Using a paraffin wax-aluminum compound as a thermal storage material in a solar air heater" ARPN Journal of Engineering and Applied Sciences ISSN 1819-6608 VOL. 4, NO. 10, DECEMBER 2009, pp-74-77

[16] I. Fernández, C.J. Renedo, S. Pérez, J. Carcedo and M. Mañana "Advances in phase change materials for thermal solar power plants Quality" International Conference on Renewable Energies and Power Quality (ICREPQ'11) Las Palmas de Gran Canaria (Spain), 13th to 15th April, 2010

[17] W. Saman, F. Bruno, E. Halawa "Thermal performance of PCM thermal storage unit for a roof integrated solar heating system" Solar Energy 78 (2005) 341–349

[18] F.S.Javadi, R.Saidur, M.Kamalisarvestani "Investigating performance improvement of solar collectors by using nanofluids"RenewableandSustainableEnergyReviews28(2013)232–245.