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A Review on Phase Change Material (PCM) Heat Exchanger with Spiral-Wired Tubes

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Abstract – The current rapid economic growth, demands for energy are progressively increasing. Energy shortages have attracted significant attention due to the shrinking availability of non-renewable resources. Therefore, thermal energy storage is one of the solutions that lead to saving of fossil fuels and make systems more cost-effective by the storage of wasted thermal energy. In particular, the application of phase change materials (PCMs) is considered as an effective and efficient approach to thermal energy storage because of the high latent heat storage capacity at small temperature intervals. Present research is study in effect of heat transfer rate of spiral wired tube heat exchanger when PCM is used as energy storage medium. In the present study, the PCM will be mixed nanoparticles such as Al2O3 in order to enhance the performance of the spiral wired tube heat exchanger. Complete study will be carried out analytically using simulation tools and software to get the results.

Keywords: Solar Assisted Heat Pump, PCM Heat Exchanger, CFD Modelling, Model Validation and Application

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I. INTRODUCTION

Energy supply from many sustainable sources, such as solar thermal or wind, is intermittent in nature. Therefore efficient energy storage is critical for practical applications of these sustainable energies. For residential solar thermal applications, conventional hot water systems have relatively low efficiency and limited capacity particularly at night and days without sunshine. To overcome these problems, phase change materials (PCMs) have been proposed to store thermal energy. PCMs have advantageous features such as nearly isothermal solid-liquid phase change and high energy storage capacity due to the latent heat of fusion (Samui, 2018).

Many types of phase change energy storage systems have been studied. A tube and shell unit is one of the simplest designs and among the most commonly used. Materials used in a latent heat storage tank must be easy to find, inexpensive and environmentally friendly. The benefits of using an organic PCM is that they are generally abundantly available have a high latent heat of fusion, are chemically stable, and do not corrode other materials. The disadvantages include flammability and low thermal conductivities. Inorganic PCMs are typically used in the high temperature range. The disadvantages of inorganic PCMs are the sub-cooling issue, as well as corrosion of the containment material.

Now a days PCM is used as a heat storage medium in the heat exchanges. The PCM Heat exchanger was designed to be employed in an indirect expansion solar assisted heat pump (IDX-SAHP) system for hot water production. Therefore, the PCM melting/solidification temperature, the HX capacity, Heat transfer fluid (HTF) inlet flow rate and inlet temperatures were selected based on this application (Al Siyabi, et. al., 2017).

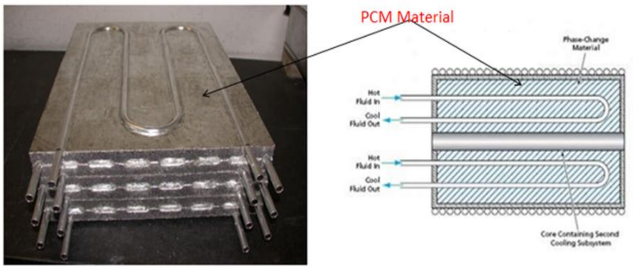

Figure1 PCM Material

2. NANOPARTICLES

Nanotechnology is a known field of research since last century. Since ‘‘Nanotechnology” was presented by Nobel laureate Richard P. Feyn-man during his well famous 1959 lecture ''There's Plenty of Room at the Bottom", there have been made various revolutionary developments in the field of nanotechnology. Nanotechnology produced materials of various types at Nano scale level. Nanoparticles (NPs) are wide class of materials that include particulate substances, which have one dimension less than 100 nm at least. Depending on the overall shape these materials can be 0D, 1D, 2D or 3D. The importance of these materials realized when researchers found that size can influence the physio-chemical properties of a substance e.g. the optical properties. A 20-nm gold (Au), platinum (Pt), silver (Ag), and palladium (Pd) NPs have characteristic wine red color, yellowish gray, black and dark black colors, respectively (Ibrahim, et. al., 2017).

2.1 Classification of NPs

NPs are broadly divided into various categories depending on their morphology, size and chemical properties. Based on physical and chemical characteristics, some of the well-known classes of NPs are given as below (Ibrahim, et. al., 2017).

- Carbon-based NP
- Metal NPs
- Ceramics NPs
- Semiconductor NPs
- Polymeric NPs
- Lipid-based NP

2.2 Physicochemical properties of NPs

A various physicochemical properties such as large surface area, mechanically strong, optically active and chemically reactive make NPs unique and suitable applicants for various applications. Some of their important properties are given below: (Ibrahim, et. al., 2017)

- Electronic and optical properties.
- Magnetic properties
- Mechanical properties
- Thermal properties

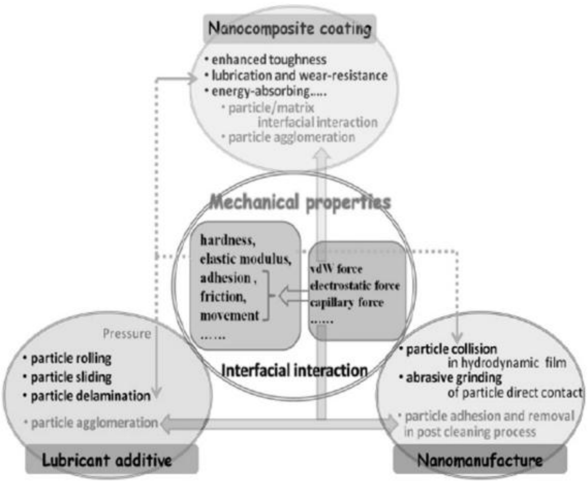

Figure 2 Schematic view of the mechanical properties and their applications (Ibrahim, et. al., 2017)

3. LITERATURE SURVEY

W. Youssef et al. [1] Latent thermal energy storage technologies with PCMs are essential to be applied to solar thermal systems considering the intermittent nature of solar energy resource and requirement of system compactness. However, the PCM thermal conductivity needs to be greatly enhanced so as to speed up the processes of energy storage and replacement. In this paper, a PCM HX is purposely designed, manufactured and installed in an indirect solar assistant heat pump system. The PCM HX consists of eight spiral-wired tubes and enclosed with metal sheets in which organic PCM is charged on the outer tube side with wire fins while heat transfer fluid (HTF) flowing through the tube side. The spiral-wired tube is firstly applied by this project into the heat transfer enhancement of the designed PCM HX. The special design of a spiralwired tube can improve the thermal conductivity of PCM and allow free movement of PCM during phase change processes which could further enhance the heat transfer. Even so, further detailed evaluation and analysis are necessary. Correspondingly, to fully understand the dynamic charging and discharging processes of the PCM HX with spiral–wired tubes, a 3D CFD model of the heat exchanger has been developed and validated with experimental results. It is found from the simulation results that at specific operating conditions the charging times are much faster than the discharging time. This is due to the contributions of convection heat transfer and buoyancy effect generated on the PCM side during charging or liquefying process. In addition, the HTF side temperature and flow rate can also affect the discharging and charging processes of the PCM HX. The higher HTF inlet flow rate can speed up both discharging and charging processes. Meanwhile, the lower and higher HTF inlet temperatures can improve the discharging and charging processes respectively. However, the effects of these parameter changes in the sensible heat storage and replacement are not significant. The simulation results can help to understand the dynamic charging and discharging processes of the PCM HX and instruct efficiently the operation of the heat exchanger and its integration with the solar system.

Xi-li DUAN et. al. [2] APCM heat exchanger for latent storage of solar thermal energy was designed, fabricated, and analyzed numerically and experimentally. The unit contains paraffin wax, a cylindrical shell, and spiral tube for heat transfer fluid flow. CFD simulation of this design provided fundamental insight to the effects of design parameters. A prototype heat exchanger was successfully assembled for lab testing, which served as proof of concepts, confirmation of assumptions in the simulation, and provided useful preliminary data for future work to improve the design.

Idris Al Siyabi et. al. [3] The other three PCM heat sinks are denoted by A, B and C and are made up of clear acrylic to monitor the PCM melting profile with inner dimensions of 30 × 30 × 30 mm, 60 × 30 × 30 mm and 62 × 30 × 30 mm, respectively. As PCM thickness increases from 30 to 60 mm, the thermal regulation period increases by 50 min and 35 min for 1.5 W and 2.0 W power ratings, respectively. As the PCM melting temperature increases from 47 (RT47) to 58 ◦C (RT58), However, the heat sink temperature also increases from 63 to 74 ◦C. The following conclusions are:

- Two PCM techniques with arrangement of RT50–RT55 increases the thermal regulation period by 110 min and 130 min as compared to RT50 and RT55, respectively. Using RT50–RT55, the heat sink temperature at the end of the operation is reduced by 10.3 C and 6.10C as compared to RT50 and RT55, respectively, for 2.0W.

- Two PCMs with the arrangement of RT58-RT47 reduces slightly the maximum temperature as compared to RT47–RT58.

- As PCM thickness increases from 30 to 60 mm, the thermal regulation period increases by 50 min and 35 min for 1.5 W and 2.0 W power ratings, respectively. As the PCM melting temperature increases from 47 (RT47) to 58 C (RT58), the thermal regulation period increases from 30 to 70 min for 2.0W. However, the heat sink temperature also increases from 63 to 740C.

- The thermal regulation period significantly decreases as power rating increases from 1 to 2 W. Also, the heat sink temperature increases by 29.50C with an increase in power rating.

Tian Zhou et. al. [4] results have shown good agreement with experimental data, even though the PCM (RT58) used in the experiments does not have a fixed melting point, as assumed in the model. When comparing samples having metal foams embedded into PCM with a pure PCM sample, it was found that the addition of metal foams can considerably enhance PCM heat transfer performance (about 10 times) through effectively transferring heat from the metal skeleton to the PCM. It was found from the simulations that the velocity driven by the buoyancy force is not strong enough to produce dominant influence on heat transfer in the PCM. This is due to the high viscosity (about 1000 times higher than air) and low thermal expansion coefficient (30 times lower than air) of RT58, as well as the high flow resistance in metal foams. The simulation results also indicated that metal foams with smaller pore size and porosity can achieve better heat transfer performance than those with larger pore size and porosity. In addition, a series of detailed evolutions of velocity and temperature distributions have been obtained; these illustrate clearly the phase change processes of the PCM.

Shivangi Sharma et. al. [5] experimentally investigates the feasibility of using PCM for thermal management of BICPV systems, which has not been reported so far. APCM containment/heat sink was designed and developed and integrated with an in-house manufactured BICPV module. This BICPV–PCM system was tested in naturally Ventilated module (without PCM) and then with PCM. An organic PCM (RT42s) was used to regulate the aluminium back-plate Temperature at 1000Wm2 in the first instance. The stable BICPV temperature (46.5 °C) was achieved at temperatures lightly higher than the PCM maximum melting range (38–43 °C). A steep increase in temperature and corresponding reduction in maximum power was observed during the first 30min of the experiment. This initial investigation resulted in a relative electrical efficiency improvement of 7.7% using PCM and relative VOC improvement as 4.4% with PCM than with no PCM at 1000Wm2. Average temperature reduction of 3.8 °C was attained at the BICPV module Centre integrated with PCM containment as compared to the non-PCM system. The test was performed at other irradiance levels (500,750and1200Wm2) and the relative electrical efficiency improvedby1.15%at500Wm2, 4.20%at750Wm2 and 6.80% at1200Wm2. In the past, numerous studies have been performed on BIPV systems and have primarily focused on the temperature and melt fraction with respect to time,(the PCM containment part of the system).In the present study, however, a thorough investigation on the effect of PCM cooling on the solar panel (BICPV side) including ISC, VOC and Pm output are also targeted. Asyet, the proposed mathematical model for a BICPV–PCM system is the only optimized numerical model for designing such systems. In future, the experiments could be iterated for longer durations to explore PCM cooling characteristics. Studies on PCM containment bottom plate temperature is e could help in assessing whether the rejected heat could be used for regeneration purposes. The experiment proves that the utilization of PCM could contribute to effective thermal management of BICPV modules. However, building regulations, economic and environmental impact analysis could contribute to the further development of the technology.

Ravichandra Rangappa et. al. [6] Mesh was generated using ANSYS meshing tool with 81540 elements.. The heat generation rate was considered to be 25000 j/m3 with 3A discharge rate. Four Li-Ion cells per each module were considered. For an initial testing, only one row of battery modules were considered, and successful results can be applied to the second row of battery modules without any specific conditions. The study was focused on numerical study to analyze the active cooling system. a numerical analysis is carried to investigate the possibilities of passive cooling system using PCM. the suitable PCM or PCM composite which can be adapted to be used in a passive thermal management system, replacing the active (forced air) thermal management system.

Abduljalil A. Al-Abidi et. al. [7] Heat transfer enhancement for a triplex tube heat exchanger by using internal and external fins to accelerate the melting rate of RT82 as a PCM were investigated numerically; different design and operation parameters include the fin length, TTHX materials, number of fins, fin thickness, Stefan number and PCM unit geometry were analyzed. Based on the simulation results, these parameters have a significant influence on the time for complete melting; the effect of fin thickness is small compared to the fin length and number of fins, which have a strong effect on the melting rate time. Different cases were studied, and according to the results, case G achieved the complete melting earlier with respect to other cases. Experiments were conducted to validate the proposed model. Simulated results agree with the experimental results.

Luís Esteves et. al. [8] The analysis of the fusion and solidification process of two commercially available PCM's was presented. To carry out such task a small laboratory scale installation was built. The heat was supplied and retired to the PCM being tested in a single pipe shell and tube heat exchanger and the evolution of the temperature in several points inside the material was analysed and commented. The time evolution of the overall heat transfer coefficient between the heat transfer oil and the PCM, was presented leading to data adequate for design and calculation purposes. The measured values were in the 100 to 1800 W/(m2K) range. The theoretical analysis and determination of such experimental results were based on an approximated definition of the mean logarithmic temperature difference, both for sensible and latent energy storage periods. As far as the heat transfer values are concerned both PCM's have similar behaviour and are equally suited for the application under consideration. Average values of the heat transfer coefficients of the phase change materials were also determined, either for the solid or for the liquid phase. From these heat transfer coefficients, the time evolution of the PCM temperatures and also from the time evolution of the overall conductance U, it is clear that the A82 is the best material leading to faster heat storage and delivery rates. Finally, its higher latent heat of fusion is another advantage.

Asit Baran Samui [9] Attempts are being made to utilize suitable PCM composite with carbon-based Nano materials to tap solar energy and store it to mitigate the over dependence on electricity. Carbon based Nano materials such as SWNT, GO, rGO etc. found to be ideal materials which make shape stabilization possible with very low dose incorporation in PCM. Nano carbons are responsible for absorption of photon from sunlight and PCM acts towards storage. Further, the physical blending allows minimum surrender of original enthalpy of PCM and the other important characteristics is the high thermal conductivity of nanocarbons, which makes the system to respond very fast. The search for most suitable material combinations has just started. This is expected to yield rich dividend in near future as more efficient materials will be developed with umpteen combinations.

J. P. Solano et. al. [10] The coupling of the PCM charging process with the irradiance-driven dynamics of a solar collector allows for obtaining realistic transient results for solar latent thermal energy storage. The low-intensity irradiance curves in winter conditions might lessen the capacity of a given PCM container and solar collector for thermal energy storage. The use of extended surfaces in the PCM side improves the capacity for thermal energy storage. An augmentation of the surface-to-volume ratio of 5.7 times yields a 2.2-fold increase of thermal energy storage.

4. PHASE CHANGE MATERIAL

A phase change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units (Tian and Zhao, 2011).

Latent heat storage can be achieved through liquid→solid, solid→liquid, solid→gas and liquid→gas phase changes. However, only solid→liquid and liquid→solid phase changes are practical for PCMs. Although liquid–gas transitions have a higher heat of transformation than solid–liquid transitions, liquid→gas phase changes are impractical for thermal storage because large volumes or high pressures are required to store the materials in their gas phase. Solid–solid phase changes are typically very slow and have a relatively low heat of transformation (Esteves, et. al., 2018).

4.1 Classification of PCM

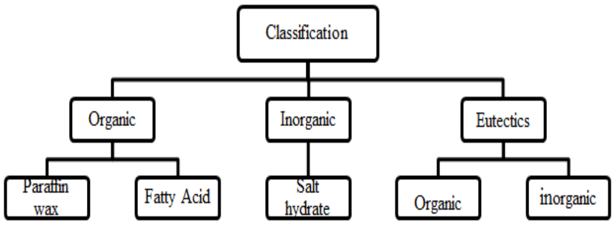

Figure 3. Classification of PCM

4.2 Advantages & Disadvantages Of PCM

Advantages

- High thermal performance at moderate contact pressures
- Material flows to provide contact between surfaces and fill air gaps
- Viscosity prevents leakage into surroundings

Disadvantages

- Moderate contact pressures are required to bring surfaces together
- Lower thermal conductivities than thermal greases
- Strong adhesive bond between surfaces may produce a load that damages the electronic during shock loading or a drop

5. HEAT EXXCHANGER

One of the important processes in engineering is the heat exchange. The means of heat exchanger that to transfer the heat between flowing fluids A heat exchanger is a device that allows heat from a fluid (a liquid or a gas) to pass to a second fluid (another liquid or gas) without the two fluids having to mix together or come into direct contact. If that's not completely clear, consider this. In theory, we could get the heat from the gas jets just by throwing cold water onto them, but then the flames would go out! The essential principle of a heat exchanger is that it transfers the heat without transferring the fluid that carries the heat (Bhavsar, et. al., 2013).

In power plants or engines, exhaust gases often contain heat that's heading uselessly away into the open air. That's a waste of energy and something a heat exchanger can certainly reduce (though not eliminate entirely—some heat is always going to be lost). The way to solve this problem is with heat exchangers positioned inside the exhaust tail pipes or smokestacks. As the hot exhaust gases drift upward, they brush past copper fins with water flowing through them. The water carries the heat away, back into the plant. There, it might be recycled directly; maybe warming the cold gases that feed into the engine or furnace, saving the energy that would otherwise be needed to heat them up. Or it could be put to some other good use, for example, heating an office near the smokestack (Duan, et. al., 2016).

Spiral Tube Heat Exchanger

Spiral tube heat exchanger has excellent heat exchanger because of far compact and high heat transfer efficiency. Spiral-tube heat exchangers consist of one or more spirally wound coils which are, in circular pattern, connected to header from which fluid is flowed. This spiral coil is installed in a shell another fluid is circulated around outside of the tube, leads to transfer the heat between the two fluids.

Heat transfer rate associated with a spiral tube is higher than that for a straight tube. In addition, a considerable amount of surface can be accommodating in a given space by spiraling. In spiral tube heat exchanger, problem of thermal expansion is not probably occurring and self-cleaning is also possible. A spiral tube heat exchanger is a coil assembly fitted in a compact shell that to optimizes heat transfer efficiency and space. Every spiral coil assembly has welded tube to manifold joints and uses stainless steel as a minimum material requirement for durability and strength.

Spiral tube heat exchanger uses multiple parallel tubes connected to pipe or header to create a tube side flow. The spaces or gaps between the coils of the spiral tube bundle become the shell side flow path when the bundle is placed in the shell. Tube side and shell side connections on the bottom or top of the assembly allow for different flow path configurations. The spiral shape of the flow for the tube side and shell side fluids create centrifugal force and secondary circulating flow that enhances the heat transfer on both sides in a true counter flow arrangement. Since there are no baffles are provided in to the system, therefore to lower velocities and heat transfer-coefficients. Performance is optimized. Additionally, since there are a variety of multiple parallel tube configurations are not compromised by limited shell diameter sizes as it is in shell and tube designs. The profile of a spiral is very compact and fits in a smaller path than a shell and tube design.

Since the tube bundle is coiled, space requirements for tube bundle removal are almost eliminated (Bhavsar, et. al., 2013).

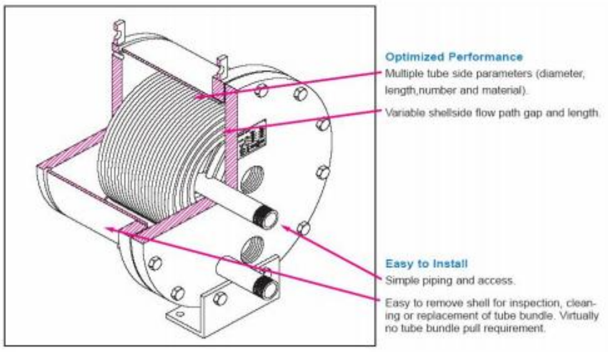

Figure 4 Spiral Tube Heat Exchanger

6. CONCLUSION

Based on the review study has carried on the research breakthrough to the CFD modelling development and experimental validation of a phase change material (PCM) heat exchanger with spiral-wired tubes. In this paper various research papers are studied related t to the phase change materials and spiral wired tube heat exchanger. It can be concluded that design methodology available in literature is in scattered manner. The previous works carried out by different authors were limited to helical coil heat exchanger. The spiral tube heat exchanger is compact in size and more heat transfer can be carried out.

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