Review On The Design Of Pcm Based Thermal Energy Storage Systems

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Abstract—Thermal Energy Storage has become very important in the recent years since it balances the energy demand and improves the efficiency of the solar systems. It is important that the thermal energy storage systems have the necessary characteristics to improve the performance of the storage systems. Usage of Phase change materials for energy storage provides a great benefit but their low thermal conductivity becomes a major drawback. This can be compensated with the use of phase change material in an appropriate design for effective functioning of the system. This review article summarizes the recent designs of thermal energy storage systems containing Phase Change Material that has been adopted for effective energy storage.

Keywords—PCM, Thermal Conductivity, Energy Storage, Phase Change, Latent Heat

I. INTRODUCTION

Solar energy is a basic need of living plants and human beings on the earth. It is intermittent in nature, eco-friendly and non-polluting energy. For effective utilization of the solar energy, it is highly important to develop solar thermal energy storage systems. Thermal energy storage is essential for both domestic water heating and space heating applications and for industrial applications. Energy can be stored by the heating, melting, or vaporization of material and the energy is made available as heat, when reversed. The size of a storage system is related to the energy density or the amount of energy stored per unit mass of the storage material. Larger energy density provides smaller storage size and lesser amount of storage material. This paper summarizes the designs that have been used by several authors in order to improve the performance of the TES system for various practical applications.

II. DESIGN OF PCM STORAGE

T. Kousksou et. al [1] investigated PCM in the form of small cylindrical containers for the application in Solar Domestic Hot Water (SDHW). PCM was implemented in cylindrical form of diameter 0.04m in order to increase the surface area for heat transfer. The PCM used in the investigation was a composite of NaOAc_3H_2O-graphite with the melting point of 57.31°C. On analysis, the authors found that the Phase change temperature of the composite PCM was higher. Hence another PCM with a phase change temperature of 50°C was used and investigated which indicated improved performance. Further suggestions were made by the authors that apart from the geometry of the PCM, the phase change temperature of the selected PCM, environmental conditions were also important.

Kamal El Omari et al [2] studied the effect of the shape of container on the melting of PCM contained within it. Five geometries containing PCM of equal volume was considered for the investigation as shown in Fig 1. The PCM used in the investigation was a mixture of Paraffin wax and graphite nano-particles, whose thermal conductivity was higher than the original pure paraffin wax PCM. The authors carried out numerical investigation to determine the effect of container shape containing PCM that can be utilized for electronics cooling. The melting effect of PCM was determined for each container and the results were compared.

Fig 1: Different shapes of containers containing PCM

It was found that as the melting proceeds, thermal stratification occurs which makes most of the PCM to be melted in the upper portion. Solid PCM was left at the bottom of the container for melting at the last. For electronics cooling, the PCM should maintain the electronics temperature low enough. The first container having curved surface had a great impact on maintaining the temperature.
Thus the authors conclude that when considering the geometry of a PCM container, it is better to avoid sharp corners and provide smooth curves to support complete melting of the PCM.

E. Halawa and W. Saman [3] made a numerical study on the performance of PCM based TES for space heating applications. The storage unit was made of 45 rectangular slabs of length 1m and width 0.89m. Numerical investigation was conducted with variations in the thickness of the PCM slab and air gaps between the slabs. The PCM used in the slab form is Calcium chloride hexahydrate (CaCl₂·6H₂O) with melting temperature of 28°C. The results of the experiment shows that the thickness of the slab had impact on the heat transfer rates. Thicker slabs reduced the heat transfer rates which led to the increased melting and freezing time, but with a higher mass flow rate the melting and freezing time was reduced. Hence the authors come to a conclusion regarding the importance of the design chosen for energy storage.

57 vertical PVC tubes containing encapsulated PCM were used by A. de Gracia et al [4] in hot water cylinder to reduce the amount of electricity used for producing hot water. The tubes containing PCM had dimensions of length 0.75 m and 0.04 m diameter placed inside the hot water cylinder of length 1.02 m and 0.474 m insulated with polyurethane of thickness 5cm. On examining the results of the different cases, it was found that the PCM in smaller diameter of PVC tubes was melted and solidified faster. The usage of PCM in the hot water cylinder reduces the electricity consumed for heating the water.

Mehmet et al [5] experimentally investigated the influence of natural convection on the design and flow parameters of a shell and tube heat exchanger. Two concentric tubes formed the heat exchanger. The interior cylinder was 400mm long with internal and external diameters of 15mm and 25mm respectively. The exterior cylindrical tube material and diameters were varied and investigated, while the shell material was Plexiglas. The tube materials considered for the investigation were copper, stainless steel, and Polyethylene (PE-32). The heat exchanger was insulated with 15mm of armaflex and 30mm of glass wool. Water was used as the PCM and Ethylene-glycol-water solution was used as the HTF. Charging and discharging experiments were conducted on the heat exchanger with different values of HTF flow rate and inlet temperatures. Charging process included the complete freezing of water and discharging the complete melting of the ice under environmental conditions. The experimental results indicated that conduction process followed by natural convection dominated the charging and discharging process as the buoyancy forces came into play. As a result, two regions are formed along the interference, top layer called as natural convection dominant region and the other bottom region called conduction dominant region. The freezing process results in the formation of ice, which is affected by the axial flow direction. The influence of HTF flow rate and inlet temperature was determined and resulted that increase in HTF flow rate and decrease in inlet temperature leads to higher energy storage. It was also found from the results that the thermal conductivity of the tube material affects the energy storage. With the use of material of higher conductivity for the tube, the energy stored was high. Considering the influence of the tube diameter on the energy storage capacity of the system, the authors found that the solidification speed was slower with the shell diameter of 114mm. When the shell diameter was increased to 190mm, thermal stratification was induced leading to higher energy storage. It could be understood from the experimental investigation that along with the HTF flow rate, inlet temperature, the design parameters of the heat exchanger for energy storage must also be considered so that a greater amount of energy can be stored.

M.J Huang et al [6] examined the performance of Phase Change Slurries (PCS) in residential energy storage applications along with a helical coil heat exchanger. A Phase Change Slurry (PCS) consists of small microencapsulated PCM particles in a fluid medium. The PCS serves as an energy storage medium with the help of PCM present in them and also as a HTF, used for improving the heat transfer. The coiled heat exchanger was fabricated for an outer diameter of 200mm with copper tubes having outer diameter as 22mm. The coiled heat exchanger was placed at the bottom end of the tank whose dimensions were with diameter as 0.270m and height 1m. The tank was well insulated. The PCS used in the investigation had paraffin with melting point of 70°C enclosed within plastic capsules of 2 to 8µm. The authors compared the performance of the storage system when PCS as the storage medium with water as storage medium. Temperature variations were measured with natural circulation of water and with flow rates of 20kgmin⁻¹ and 30kgmin⁻¹. Results were obtained that energy storage is faster with flow rate of 30kgmin⁻¹ and convection process dominated the heat transfer when water is used as the storage medium. Similar analysis was made when the PCS was used as the storage medium. In this case, the volume concentration of the PCS had a major role. 25% volume concentration of slurry produced similar results that were closer to the case of water as storage medium. But when 50% volume concentration of slurry was used, the heat transfer and increase in temperature was much low. This is due to the low thermal conductivity of the PCM, high viscosity and high specific heat. Natural convection was observed around the helical coil heat exchanger. As a result, the PCS around the heat exchanger got heated up and became less dense and started to move to the top of the tank and the denser PCS started heating and the process continued. From the results obtained, the authors come to a conclusion that PCS with 50% of volume concentration are not suitable for energy storage applications. Also it is found that the size and location of the heat exchanger had a
Isabel Cerona et al [7] developed a new tile containing PCM for cooling of room. The newly designed tile was of length 660mm and width 660mm. It consists of four pieces of pure clay of thickness 20mm, a metal container of 32mm thickness containing 4.8l of PCM followed by a thermal insulation of 22mm thick. The tile was experimentally investigated and the results were compared with the tile without PCM. Experimental evaluation took about 60 days and found that the tiles stored the excess heat energy and maintained the room temperature around 4°C to 10°C. The tile was found useful in storing the heat energy and maintaining the room temperature. Also the tiles exposed to higher temperatures had a higher effectiveness. Similarly Chengbin Zhang et al [8] used PCM in brick walls to control the temperature fluctuations of buildings. Wei-Biao Ye et al [9] described the detail process of thermal storage and release in a aluminium plate-fin storage unit. Numerical investigation was carried for plate-fin thermal storage/release unit using paraffin PCM for determining the effect of temperature difference. The authors described the detailed thermal storage/release process that might be useful for practical applications. The storage/release unit consisted square channel with inner plates and outer plates. The inner plates carried water as the HTF and paraffin in the fins space. The height and width of the fins were 12mm and 1.6mm while the width of the PCM layer was 4mm. When heated, PCM closer to the fin and plate wall melts and the liquid is affected by gravitational force as well as buoyancy forces. Gravitational force comes to play with lower temperatures while buoyancy forces affect the liquid PCM during greater temperatures which makes the liquid PCM to flow upwards. With higher temperatures, heat transfer takes place from bottom plate to the top and the melting occurs and a circulating flow is observed closer to the bottom heating wall which leads to higher melting rates. The results show that with higher temperature differences, the liquid fraction development rate was quicker leading to shorter completion time. Also increase in temperature difference causes the increase in temperature gradient which finally results in the increase of heat flux. Higher heat flux leads to reduced thermal storage time. Similarly during the energy release process, volume of the PCM reduces and it is noted that a part of the unsolidified PCM remains for a long time. At the end of the release process, the heat flux reaches to zero indicating the end stage. The authors state that the dimensions of the storage unit can also induce natural convection that increases the heat transfer coefficient.

S.F. Hosseinzadeh et al [10] has done an detailed experimental and numerical investigation on the effect of number of fins, fin thickness, fin height, power input level of PCM based heat sinks used in the thermal management of electronic components. The heat sinks had a common dimension of 60mm*40mm made aluminium 6061 alloy with different dimensions of fins. With power inputs of 25W, 35W and 45W, it was observed that higher the power input, the higher the heat absorbed was. With increase in number of fins, the volume of PCM decreases and as a result melting time is reduced. Similarly a thicker fin has lower volume of PCM which causes delayed melting of PCM. Increase in thickness of fins also reduces the thermal resistance of fins, which obviously leads to delayed melting of PCM. An increase in height of the fins delays the start of melting and the melting period which leads to increased usage time of the electronics component.

Nithyanandam and Pitchuman [11] attempted to investigate the influence of heat pipe, parametric and geometric parameters on the performance of a shell and tube latent thermal energy storage systems with embedded heat pipes. The LTES used in the investigation was a high temperature LTES commonly used in CSP plants. The LTES was examined as two modules. Module 1 had the HTF flowing through the pipe surrounded by PCM, while Module 2 had the PCM contained within the tube and the HTF was made to flow transversely to the axis of the tube. The arrangement was in such a way that the surface area exposed to the HTF was equal for both the modules. The geometric parameters considered by the authors were length of module (0.08 to 0.2), length of evaporator section of the heat pipe (0.2 to 0.4), length of condenser section of the heat pipe (0.05 to 0.243), outer radius of the tube (0.2 to 0.4), radius of vapor core of heat pipe (0.007 to 0.038), thickness of the wick of heat pipe (0.007 to 0.032). The influence of the above parameters on the performance of the LTES was determined during charging and discharging process. The mass flow rate values taken for the investigation were 0.589 kg/s, 2.80 kg/s, and 5.89 kg/s. During the charging with module 1, the combined effect of natural convection and conduction came into play. The performance of the LTES with the above parameters was determined. With increase in the mass flow rate, the melting rate of PCM increased with increase in the melt fraction as a result of which the charging rate of the PCM was found to be increased. Thus by increasing the mass flow rate, the thermal performance of the LTES was found to be decreasing. Considering the module length, the authors found that with lower values of the module length, which leads to horizontal configuration of closely packed heat pipes will result in an improved performance of the LTES system. The heat pipes with longer evaporator section seem to produce a higher charging rate with improved effectiveness of the LTES, which was similar with the case of increasing the length of the condenser section. The increase lead to a larger surface area for the melting of the PCM in a slower process due to which the onset of natural convection was delayed leading to an improved effectiveness. When the tube radius was increased, the effectiveness of the LTES decreased, but the
increase in the vapor core radius of the heat pipe increased the effectiveness of the LTES than the increase of the wick thickness of the heat pipe. The results were almost the same when examined with module 2. The results obtained for charging with module 1 and 2 was close to the results of discharging process. The authors also tried and succeeded in identifying the optimum design with operating parameters which would increase the charging/discharging effectiveness, effective charging/discharging rate and effective energy transfer rate for charging/discharging.

Colas Hasse et al [12] examined a honeycomb wall board filled with paraffin PCM. The honey combs had cell size with 6mm and wall thickness 70µm and were 2cm deep. Heat exchanger was placed over the wall board and water was used as the HTF. The set up is as shown in figure (43). The honey comb structure has a larger heat transfer area in contact with the PCM which helps in uniform distribution of the temperature to the PCM. Pandiyarajan et al [13] designed a TES to store sensible and latent heat from the exhaust gas of an IC engine with the help of a heat exchanger. The heat exchanger used in the investigation was a shell and tube type with finned copper tubes, in which the exhaust gas from the IC engine passed through the shell side thereby providing a higher heat transfer area. The tube side of the heat exchanger carried castor oil. The heat exchanger was used as the heat recovery system. The heat from the exhaust gas is transferred to the castor oil which is then passed to the TES system for storage of the thermal energy.

The TES tank is a cylindrical vessel of 450mm inner diameter and 720mm height with 48 cylindrical caps of diameter 80mm and height 100mm containing 320g of paraffin as the PCM. The TES tank contained a total of 15 kg of paraffin and 55 kg of castor oil. The cylindrical capsules were mounted on a stand of 430mm diameter and 640mm height made of mild steel. (Fig.39).The castor oil served as the sensible heat storage medium and the paraffin as latent heat storage medium. The TES tank was completely insulated with glass wool and aluminium cladding. The performance of the heat exchanger and the TES was evaluated under different load conditions. From the results obtained, the authors come to a conclusion that by reducing the temperature of the exhaust below 100°C, most of the heat can be recovered from it. In order to determine the performance of the TES, the heat loss coefficient, temperature distribution of the tank, charging rate, charging efficiency, storage efficiency are to be determined. It is found that the overall heat loss coefficient of the TES tank increases with increase in the temperature. The TES tank is made of stainless steel therefore temperature variations cannot be observed in the tank which indicates the absence of stratification in the tank. The charging rate and the charging efficiency is found to increase with increase in the load. The reason for this is because of the increase of exhaust gas temperature at higher load conditions. It is found that the charging efficiency of the TES tank is increased to 99.34% as the load is increased to 100%. The implementation of such a system with TES has increased the percentage of energy saved from 10% to 15% as the load increases from 25% to 100%.

Yue-Tzu Yang and Yi-Hsien Wang [14] developed a heat sink with its cavity filled with n-eicosane as the PCM for cooling of electronic devices. Power levels of 2W – 4W, orientations of horizontal, vertical and slanted and charging and discharging modes were evaluated. Numerical results were obtained and the results proved that use of PCM in aluminium heat sinks can be useful in the cooling of electronic devices which would help in the prolonged use of electronic devices.
Fig 4: PCM containers stacked to form TES

V.V.Tyagi et al [15] developed a cool energy storage system with the use of PCM for the control of room temperature. Three stacks containing sixty rectangular high density polyethylene panels (HDPE) filled with a total of 225 kg of calcium chloride hexahydrate as PCM was assembled on the walls. The experimental setup consisted three fans and 1.5TR window air-conditioning system in a test room of dimensions 2.96m*2.41m*2.6m with an insulated door of dimensions 2.13m*0.92m as shown in fig.8. Three experiments were conducted, without the cool energy storage system, with energy storage system and air-conditioning switched on and with cool energy storage system with air-conditioning switched off. Blowers and heaters were also used in the experimental investigation. The room temperature was measured for all the three experiments and was found that temperature differences occurred between the PCMs in different location, based on their distance from the air conditioner. However, the thermal management system was found to be effective for space cooling applications as it maintained the room temperature within the range of 22°C to 24°C.

Eduard Oro et al [16] found that without a refrigeration system, the use of PCM could be able to maintain the temperature of frozen foods low for a prolonged time. Low temperature PCMs Climsel C-18 and E-21 encapsulated in thin stainless steel containers were used in the investigation. The PCM was placed at the top of the evaporator tubes of a freezing compartment as shown in fig. 9, with 5cm polyurethane insulation. The total amount of PCM occupied 3.36% of the total volume of the freezing compartment. The results of the investigation shows that the PCM E-21 was most suitable than Climsel C-18 as it maintained the temperature of the freezing compartment within the range of -16°C to -12°C.

S. Karthikeyan and R. Velraj [17] performed a numerical study by comparing three different models of a packed bed LTES containing encapsulated spherical PCM as energy storage system. The storage tank was with diameter 0.35m and 0.7m and the PCM were encapsulated in a plastic ball of diameter 70mm with wall thickness 0.5mm. There was a total of 260 such PCM ball contained within the steel storage tank. Air was used as the HTF supplied from a blower and heated by an air heater.

Rajesh Baby and C. Balaji [18] investigated a finned heat sink for the cooling of electronic equipments. The heat sink was designed with 72 pin fins made of pure aluminium. The aluminium acts as a Thermal Conductivity Enhancer (TCE). In this investigation, n-eicosane is used as the PCM. The authors have also done a comparative study with the performance of the heat sink with PCM and without PCM. The heat sink without fin took 64 min to reach a specific temperature of 58°C, whereas the heat sink with PCM took about 165 min. This longer duration taken by the heat sink to reach a specific value, increases the usage time of the electronic device by storing a large amount of heat energy. Different fin configurations were tested and compared. The heat sink with 72 pin fins had the base temperature lower than the heat sinks with 3 plate fins and the heat sink without fins as shown in fig.23. The reason for this was a larger surface area available for heat transfer. The heat sink also had a maximum latent heating time as well as an higher operating time for the same reason. The comparison of the heat sinks with different configurations has proved that the pin fin heat sink with larger surface area for heat transfer has resulted in providing a better performance for longer duration. Thus the authors conclude that the performance of the heat sink is dependent on the fin configuration, heat source power level, material that is used as TCE, volumetric percentage of TCE and the amount of PCM used.

Fig 5: Heat Sink with 72 Pin Fins.

Maciej Jaworski [19] designed a heat spreader that can be used for cooling of electronic devices. The design consists of a solid base plate of thickness 5mm and dimensions 50*60mm onto which 320 pipes of outer diameter 1.5mm or 80 pipes of outer diameter 3mm is attached as in fig 27. Each tube was filled with 12 to 17g of lauric acid as PCM. The pipes functions as fins providing a
larger heat transfer surface and transfer of heat from the base plate to the PCM. Presence of PCM prevents the temperature of the microprocessor exceeding a certain value which depends on the melting point of the PCM, thus preventing the microprocessor from damages caused due to excess heat. Hence the choice of the PCM is important. Also the PCM increases the thermal capacity of the device. The results of the investigation shows the effect of PCM used in thermal performance of the heat spreader. The presence of PCM in the pipes which gives larger heat transfer surface area, specific air flow rate, keeps the temperature of the microprocessor low which is lesser than 50°C. The different configurations of the heat spreader reveal the difference in their performance is due to the variations in the diameter of the pipe, number of pipes. Heat spreader with larger pipe diameters is better when compared to thin pipe diameters.

Jianghong Wu et al [20] developed a cascade air source heat pump water heater with the use of PCM and investigated the dynamic performance of the pump. The cascade air source heat pump runs in the single stage heating mode when the ambient temperature is high and in the cascade heating mode when the ambient temperature decreases. The thermal storage tank of 350mm diameter and 320mm high was contained within a water tank of 370 mm diameter and 970mm high. 94 circular channels of diameter 15mm containing PCM was placed within the thermal storage tank which is shown in fig. 46. The PCM used was a mixture of 75 weight % of paraffin and 25 weight % of expanded graphite.

The authors also investigated the performance of the water tank with PCM and compared with the performance of tank without PCM. It was found that the stored energy of tank without PCM was higher. Also the efficiency of the tank without PCM was of 97.85% while the tank with PCM had an efficiency of 94.23%. The reason behind the reduced efficiency of the tank with PCM is due to the additional heat transfer process that took place within the tank. The tank with PCM supplied only 407kJ of energy more than that of the tank without PCM. The energy storage density of the PCM used here was 103,500kJ/m³ while that of water is 83,600kJ/m³. Thus it can be seen that the difference in storage density of PCM and water is not too high. As a result, the tank with PCM could not produce a higher efficiency. As discussed earlier, the thermal conductivity of the PCM is low which leads to lower heat transfer process. Thus the authors suggest that PCM with higher heat transfer rate and higher storage density is more preferable for energy storage purposes.

Hiroyoshi Koizumi and Yunhai Jin [21] came up with a new design of TES. The design consisted n-number of curved slab containers arranged one above the over to form the complete TES unit. (Fig.47). The curved slabs were designed with an outer arc configuration to induce close contact melting of the PCM contained within the slab. The curvature resembled a one third part of a cylindrical shell with radius R. The total height of the TES was varied between15mm to 45mm with corresponding number of curved slabs present in the TES. The TES had configurations of width 1m, length 1m, which is similar to the PCM container’s aluminium wall of thickness 1mm. The TES had a duct height of 5mm between the successive curved slabs that facilitated the flow of the HTF which was hot water. During the early stages of the investigation, melting experiments were performed on the curved slab and compared with a flat slab container. The flat slab container when heating melted the PCM contained in it. The melted PCM was found between the lower container wall and upper solid PCM. As melting continued, the thickness of the melted PCM became larger which resulted in incomplete melting of PCM. But in the curved slab, the solid PCM remained in the lower half of the container and the liquid PCM was found in the upper half of the container.

A thin layer of liquid PCM was found between the solid PCM and the inner curved wall of the container due to close contact melting. The solid PCM was melted continuously through this layer and the melted PCM moved to the upper portion of the container which increased the melting rate of the PCM. Thus the curved design of the slab plays a key role in promoting the close contact melting. The time required for complete the melting process for flat slab container was 27 min whereas it took only 17 min for the complete melting of PCM in the curved slab. The similar
concept was employed with the TES which was made of a number of curved slab containers. Stefan number and flow rate were the parameters involved in the study. When the Stefan number was increased from 0.02 to 0.12, the melting time was decreased. The authors made a feasibility study of the curved slab TES with another TES with spherical capsules containing PCM and found that the curved slab TES had large storage capacity and a high efficiency.

N.H.S Tay et al [22] carried out an experimental investigation of a tube in tank TES system filled with salt hydrate as PCM for cold storage applications. The authors investigated the influence of compactness factor (C.F) on the design of the storage tank. Compactness factor (C.F) is the ratio of volume of PCM to the total volume of the storage tank, which describes the effective energy storage density of the tank. Three designs with varying lengths of the tubes were proposed which are shown in fig.11. Design (a) comprised a single tube of 5.46m long coiled tube and (b) comprised two tubes of length 5.61m and 6.01m coiled tube while (c) comprised four tubes of length 5.95m, 6.05m, 5.79m and 6.04m respectively. The C.F of the designs was 98%, 95% and 90% respectively. The overall energy storage density of the tank is the product of C.F and average effectiveness. On examining and comparing the results of the three designs, it was observed that the effectiveness of designs (b) and (c) was greater than that of design (a). Effectiveness was found to be increasing with the decrease in mass flow rates which lead to larger temperature difference. The heat transfer area exhibited by designs (b) and (c) was also higher than design (a) and as a result the outlet temperature is closer to the phase change temperature. This resulted in higher average effectiveness. Also natural convection played an important role in improving the effectiveness by improving the heat transfer through the liquid phase. The results acquired from the experimental investigation concluded that higher the C.F is, lower the effectiveness is and larger the heat transfer surface area, the average effectiveness is high due to which the four tubes tank had higher effectiveness.

The authors also carried out an experimental investigation and validated the results using CFD model [23]. The four tube design of [22] was used in this analysis. The PCM used in the investigation was water, contained in a tank of diameter 290mm and height 330mm. The HTF was a non-combustible, aqueous based fluid with dissolved ionic solids capable of operating below -50°C which was made to flow through the tubes. Freezing and melting process were conducted and the results were compared with the simulated results obtained through CFD analysis. It was observed that the simulated results showed a slower melting process than the experimental result. Also the melting started from the bottom of the tubes and ended at the top of the tubes, whereas in the simulated results, the melting process started from both bottom and top and ended in the middle region. Similar results were obtained with the freezing process. The reason for such a behavior was that during the simulations, the effect of natural convection was neglected. The melting process of the PCM is primarily due to convection as a result of which the PCM surrounding the tubes start melting from the bottom and the process continues. Since such effect was avoided with simulation, the process is delayed.

The authors were also involved in validating a large- tube in tank model of TES system using CFD and an effectiveness Number of Transfer Units (NTU) model [24]. A larger PCM tank with dimensions of diameter of 550mm and height 870 mm having Compactness Factor 98% was used in this investigation. The TES unit was made with eight copper tubes of diameter 3.33mm. (Fig.12)
Heating/Charging and cooling/discharging experiments were conducted and the results were validated using the Effectiveness NTU approach and CFD. Comparing the effectiveness acquired by experimental investigation, NTU approach and CFD results, it was observed that the experimental values were higher than the results of the other two models. Similarly the experimental values of the cooling process was greater than the effectiveness NTU technique and CFD results due to the buoyancy effect that was observed during the melting process. Also the phase change duration for heating process was compared with the effectiveness NTU and CFD technique. The CFD approach had faster phase change duration than the experimental and effectiveness NTU results since heat loss to the environment occurred during the experimental investigation. But the phase change duration for cooling experiments showed delayed time in the CFD approach. The thermal resistance of PCM during the charging process was found to account for 40 to 60% of the total resistance and during discharging it was found of 70 – 80% of total resistance which was due to the buoyancy effect. The authors concluded that the reason for variation of the experimental results with CFD and effectiveness NTU approach was due to the tube to tube distance of 100mm in the design which reduced the heat transfer and increased the resistance.

Using the validated results obtained from [23] and [24] the authors developed and investigated three more models [25] shown in fig.13. The first model (Model 1) consists of 16 pin fins mounted on a copper tube of length 100mm with inner diameter and outer diameter of 9.5mm and 12.7mm respectively. The diameter and length of the pin fins were varied and tested. The diameters were varied with values of 3mm, 5mm, 7mm and 9.5mm and the length with 20, 30, 40 mm. The second model (Model 2) had 5 copper fins attached to the similar tube as that of model 1. Similar to the previous model the fin thickness with values 0.3, 0.5, 0.7 and 1mm and the fin diameter with values 52, 72, 92 mm was varied and investigated. Model 3 was a copper tube of length 100mm and outer and inner radius 12.7 mm and 9.5mm without any fins or pins. The HTF used in the investigation was similar with the previous. Model 3 is initially evaluated and the acquired results are used to compare the pinned and finned tubes. It is found that the finned tubes have a larger surface area as a result the effectiveness is improved by 20 to 40% than the pinned tubes. (Fig.14) .The larger the fins, the higher are the effectiveness. From the results obtained, the authors have suggests that for an effective design, the system needs to have a high heat transfer surface area, a high CF and at the same time faster charging or discharging rates. By comparing the two designs, the finned model performs better than the pinned tubes.

Abduljalil et al [26] used a triplex tube heat exchanger for thermal energy storage in the application of liquid desiccant air conditioning system. The heat exchanger comprised three horizontal copper tubes arranged concentrically of equal length 500mm. The diameter of the inner, middle and outer tubes was 50.8mm, 150mm and 200mm respectively. The middle tube of the heat exchanger was filled with paraffin PCM and was examined to determine the effect of mass flow rate in the melting of the PCM (Fig. 35). Three different heating methods were selected for the melting process, i.e. heating the inside tube, heating the outside tube and heating both the inside and outside tubes with average temperatures 95°C, 94°C and 90°C respectively. When the flow rates were increased from 8 to 32kg/min, the melting rate increased but when further increased to 40kg/min, the melting rate was found to decrease since it resulted in high Reynolds number and low prandtl number. Heating the inside tube was carried by passing the HTF through the inner tube. It was observed that the melting process started from inner tube wall where
conduction process came into act which resulted in a thin layer of liquid formation. The liquid fraction increased with time and natural convection and buoyancy forces came into play which leads to heat transfer process in the upper part of the storage and the melting process was improved. But it was observed that the PCM was not completely melted since heat transfer due to conduction and convection was not enough. Similar process was observed with the other two methods of heating but the heating started from outer tube walls in second case and uniform temperature distribution was observed in the last method of heating. It was also noted that complete PCM melting was observed in the second and third heating methods and the highest average PCM heating temperature was observed in the third method of heating. The reason behind this is the increase in the heat transfer surface area that is noted in the second and third heating methods. Temperature gradients along the axial, radial and angular directions were measured and analyzed. No variation in axial temperature was found with the three methods of heating, but on observing the radial temperatures, it was found that the heating inner tubes resulted in high temperature closer to the inner tube wall and while heating both tubes, inner tube wall and outer tube wall temperature was found high since the flow rate was high in the inner tube. The angular temperature measured was greater at 90° for all three heating methods. This was because of the natural convection and buoyancy forces.

Ehsan et al [27] designed a TES made of corrugated copper panels. The TES was designed in such a way that it had a high surface to volume ratio of 506.5 m⁻¹ and high aspect ratio of 6.35. Six square corrugated copper panels were soldered together to the centre at 60° forming six corrugated fins as shown in fig.22. The square corrugations were of sides 0.8 cm with center to center distance of 1.6cm. There were totally six squares with three on each side of the fins. The copper panels enclosed the PCM for thermal energy storage and release and hence were sealed tight to prevent any leakage of the PCM in liquid phase.

A total of 900 cm³ of octadecane was used as PCM within the TES with 150 cm³ in each panel. The entire unit was placed inside a clear plastic pipe with both ends closed by perforated disks of diameter 16 cm at a distance of 15.2 cm from the TES. The experimental setup was in such a way that hot water (HTF) is allowed to flow through the plastic tube surrounding the TES unit in upward and downward directions. Parameters that the authors considered for the investigation were Reynolds number and Stefan number. From the results, the heat transfer rate was found to be increased when the HTF was made to flow upward through the TES. During the charging process, the melting of the PCM started from the bottom and buoyancy forces came into play. With buoyancy forces affecting the heat transfer, the melting time of the PCM was much reduced by 70% when compared to the HTF flowing downward. Similarly during the discharging process with HTF flowing upward, the solidification of PCM started from bottom which resulted in the discharging time three times faster than the downward flow of HTF. Stefan number was considered as one of the parameters for evaluating the TES system since it defines the effect of HTF temperature on the performance of the TES system. When higher values of Stefan number were obtained, stratification effect was noted in the system. Two flow rates were used and the axial and radial temperature gradients were recorded. The observations resulted that there was no effect in the axial temperature gradients due to internal conduction and convection. Similarly the radial temperature distribution was reduced with radial distance. The experimental results obtained with the corrugated TES were compared with a multi-tube system and was found that the corrugated TES had better results. This was due to the higher surface to volume ratio that was exhibited by the corrugated TES design and the flow direction of the HTF.

11. CONCLUSION

PCMs are widely used in cold storage applications as well as heat storage applications. Cold storage applications include frozen food preservation, refrigeration, cooling of buildings, turbine inlet temperature. Similarly heat storage applications include hot water tanks, air heating, waste heat recovery. Usage of PCM integrated TES system in such applications leads to improved performance, efficiency, and as well as the energy storage capacity of the total system. But PCMs have very low thermal conductivity, which is a major drawback of the PCMs. Hence the Thermal Energy Storage system or the PCM tank must be wisely chosen such that improved performance of the system is obtained. Performance improvement can be obtained through proper consideration of the material with high thermal conductivity, design with higher heat transfer areas and several parameters like input temperature, dimensions, C.F, flow rate. When A TES system designed effectively, promotes the melting/charging and freezing/discharging of the PCM faster. Avoiding sharp corners of TES systems promotes complete melting of the
PCM contained in the system. Use of pins and fins provide a larger heat transfer surface area thereby promoting faster melting and solidifying rates. Conduction process followed by Convection promotes the melting of PCM as energy is absorbed, while conduction process alone dominates the freezing process as the stored energy is released. Hence it is important that the design of the TES is in such a way that the melting and freezing process are improved and a proper PCM with required properties are selected for an effective performance of the thermal storage system.

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