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Mathematical Prospective of Latent Heat Storage System with CuO Micro Particle Enhancement

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Abstract: Energy consumption for room heating and cooling is a major crisis in several countries. The energy efficiency could be increased by storing the excess heat energy for using in various applications and heat recovery systems. Latent heat storage holds a major advantage of longer retaining ability than other conventional means. The phase change material selected for this study is paraffin wax as it is useful in high temperature storage. The embedment of metal oxides has proven to be more effective in increasing the thermal conductivity and heat storing ability. A specially designed cylindrical shell was employed along with the property enhancement of PCM by including copper oxide (CuO) micro particles. Temperature of water storage was studied at various positions inside the container. The storage efficiency was increased by 10.16% and the heat releasing rate was decreased by 21.37% for CuO-PCM. Overall, the heat storage efficiency of the setup was increased by 41.99% compared to the performance using water. By reducing the size of the heat storage medium, the volume of PCM required and cost could be reduced by 5%.

Keywords: copper oxide micro particle; paraffin wax; heat storage; temperature distribution; phase change material

1 Introduction

The heat storing time of any phase change material (PCM) could be reduced by embedding thermally conductive solid particles in them [1]. The geometry also played an important role in effectively storing heat energy for longer time period. A cylindrical shell filled with coconut oil and enhanced with CuO nano particle was studied. For addition of 1% CuO, thermal conductivity was raised up to 7.5%. Height of PCM definitely influenced the melt fraction. Melting of solid PCM was extended by 20% for addition of 1% nano powder. The nano enhancement could also be applied for commercially available shell & tube heat exchangers [2]. The performance of latent heat storage system (LHS) with aluminium oxide, aluminium nitride and Graphene nano platelets were studied numerically and experimentally. The storage capacity was improved by 28%, 36% & 45% respectively for the nano materials. Optimum volume fraction for Al2O3 was estimated to be 3% from reduced dynamic viscosity of paraffin, resulting in reduced heat liberation rates. Natural convection of nano PCM was observed inside a triplex tube with fins for heat storage performance [3]. The PCM solidification time was substantially improved by augmenting the nano particles and fins assembly. For using the same volume fins could be considered a better alternate than nano PCM. Providing longer fins with minimal thickness would result in increased natural convention and in turn affects the solidification time. Alumina nano particle was used along with PCM for energy storage enhancement in photovoltaic module [4]. The inclusion of Al2O3-PCM to the panel increases the efficiency by 13.2%. The temperature drop exhibited by this nano PCM was around 10.6°C.

The vertical fin attached on plate was used for improving thermal efficiency of the shell and tube heat exchanger [5,6]. The fluent software was used for numerical simulation of the system [7]. Storage in the form of sensible heat can be made possible with the help of various techniques like water tanks, underground tanks, packed bed storage and so forth [8,9,10]. The nano PCM can be further utilized in various fields of automobile for waste heat recovery [11,12]. Pentaerythritol with Al2O3 was used as an engine heat recovery medium with an

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improved charging efficiency of 14.77%. A solar heating system was studied for water and air collecting by means of heat storage [13]. Inorganic material of sodium acetate trihydrate (SAT) nano composites have been prepared and tested for thermal energy storage [14]. An optimal value of 1% by weight has been added to enhance heat transfer ability by 35%. Finite element modeling was conducted for analyzing CuO water nano fluid for latent heat storage system [15,16]. The latent heat storage system for various applications including heat storage, cooling system, solar energy, and so forth using different phase change materials with alumina and copper oxide nano materials acan be found in [17,18,19,20]. The direct contact latent heat storage studies were conducted and experimentally investigated the separation process [21].

2 Materials And Methods

The phase change material chosen for this experimentation is Paraffin wax C25H52 (fig.1) as it has a good heat storage capacity (Cp) of 2.14 to 2.9 kJ/kg K [9, 10]. Typically its melting point lies between 46 to 68°C. It was used in cooling of electronic components in Lunar Rover in combination with retractable radiator. The micro particle copper oxide was chosen because of its high thermal conductivity. This property in particular will be helpful in storing higher heat energy in shorter time period and space. Thermocouples used are of K type, with an extensive range of 1260°C, and an accuracy of ±0.75%.

Fig. 1: Paraffin wax $C25H52$

The experimentation was conducted on a specially designed setup with complete schematic layout as shown in figure 2 and the original setup is shown in figure 3. It is made up of stainless steel 304 grade owing to its high temperature and corrosion resistant. The outer wall of the setup is made of SS304 grade having a specification of ϕ325 x 450mm. The total height is split into 4 stages starting from top to bottom. The top portion consists of section 1, while section 2 is in the middle of the tank with mild steel. Section 3 is at the bottom of tank, which is in contact with the water entering the system for charging. The paraffin wax is positioned at top and is utilized for storing heat energy during the charging process in section 4. Insulation material of mineral wool is placed in between the outer shell and paraffin wax for restricting the heat transfer [1,2].

The copper oxide micro particles were evenly distributed with paraffin wax using ultrasonic stirrer [9, 13,17]. The micro particles were prepared by the ball milling process considering purity during the processing. The sonication is done for sufficient time such that CuO particles will not settle down during experimenting. The ultrasonic cavitation provides intense micro mixing and dissipates high power locally into the medium. The thermal conductivity of the prepared composite was measured using the KD2 Transient Hot wire thermal conductivity apparatus. The accuracy of measuring is within a range of ± 0.01 W/mK.

The insulation medium used is the glass wool of mineral type, with insulating temperature range of 230 - 260°C. Water immersion heater is provided on top of the setup for heating the water with reduced risk of heat liberation. Insulation medium provided around the storage setup would maintain the temperature of the hot water inside the system. A thermocouple provided inside the tank was used for measuring and monitoring the hot water temperature. The valve at bottom is for releasing heated water from the tank and regulating mass flow rate. The flow rate was estimated based on the collecting time per litre drained from the valve. The mass flow rate has proved to be a significant factor in estimating the amount of heat transfer [22,23,24]. Three thermocouples were inserted at various sections to monitor the water temperature and one thermocouple is provided for measuring the wax temperature. Monitoring of wax temperature is essential to avoid overheating.

3 Experimental calculations

The Copper oxide micro particles were incorporated within paraffin PCM to develop its thermal conductivity. An improvement of thermal conductivity in PCM has been achieved when copper oxide particles are embedded. The Maxwell-Garnett equationand Rayleigh equation were utilized in this chapter to define the thermal conductivity of PCM composite. The same is provided in equations 1 & 2. Experimental value was estimated using KD2 probe type thermal conductivity apparatus. From table 1, the value of thermal conductivity gets saturated for 5% addition of CuO and remains almost constant thereafter.

$$\frac{K_{eff}}{K_m} = 1 + \frac{3\phi}{\frac{K_1+2K_m}{K_1-K_m} - \phi} \qquad (1)$$

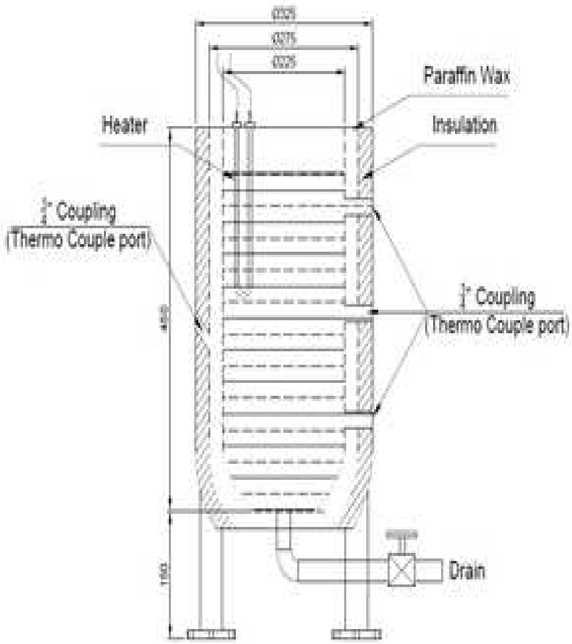

Fig. 2: Schematic layout

Fig. 3: Experimental setup

$$\frac{K_{eff}}{K_m} = 1 + \frac{3\phi}{\frac{K_1+2K_m}{K_1-K_m} - \phi + 1.569(\frac{K_1-K_m}{3K_1-4K_m})\phi^{\frac{10}{3}}} \quad (2)$$

where K_{eff} - Effective thermal conductivity of composite medium (W/ m K), K_m - Thermal conductivity of PCM (W/ m K), K_1 - Thermal conductivity of CuO micro particle(W/ m K), ϕ - Volume fraction of CuO micro particle (%).

Total energy transferred inside the system is governed by the steady flow energy equation [1]. The constant difference in temperature would represent the equal amount of heat transfer by the immersion heater. The fluid temperature exhibiting varying temperatures in accordance with storing capacity of paraffin wax. The governing equation of the system is given in equation 1 with assumptions of no heat loss to the surroundings and negligible potential and kinetic energy change. In order to decide the performance of the experimental setup with various phase change material and storing capacity, attention is paid to fluid temperature and mass flow rate. Temperature of fluid is noted at 3 different sections as mentioned earlier and the formula for calculating their average value is given by equation 3 & 4.

$$Q = m * C_p * \{T_{avg} - T_{in}\} \quad (3)$$

$$T_{avg} = \frac{T_1 + T_2 + T_3}{3} \quad (4)$$

where, m is mass flow rate, kg/s, C_p is specific heat of fluid at constant pressure, kJ/kgK, T_{in}, T_1, T_2, T_3 is temperature of fluid, °C. Following the above equations, the heat transferred in water was estimated. Initial temperature of water at the time of experimentation was measured to be 30°C with heat capacity value of 4.187 kJ/kgK.

4 Results & Discussion

Experiments were conducted on the setup described earlier. The water flow was restricted to a constant value of $1kg/s$ rate with the aid of the valve provided. Temperatures were noted at a uniform time interval of 5 minutes for both charging and discharging of heat into PCM & CuO enhanced PCM. Distribution of temperature during the time period was plotted over the figures 4 to 7. During the first 30 minutes of the time period, the setup was charging the PCM and the heat stored was discharged during the consecutive 30 minutes for easier understanding of PCM performance.

The charging temperature of all the heat storing media namely water, paraffin wax and CuO enhanced paraffin wax shows similar trend. The heat absorption capacity of plain water is poor as is generally known owing to its poor thermal conductivity. The ability of PCM paraffin wax to store and discharge heat energy shows equal tendency. It is almost symmetric during both operations. Temperature rise of CuO micro particles embedded paraffin was very slow as seen on all three plots. Micro material added to PCM increases the thermal conductivity and heat retaining ability. Presence of copper oxide in the structure of wax retards the heat evolution from PCM during discharging. Hence, it is evidential that heat energy

Table 1: Manufacturing details of Components

Volume concentration ()	Experimental value (W/mK)	Maxwell Value (W/mK)	Rayleigh value (W/mK)
0	0.214	0.214	0.214
0.01	0.2169	0.22035907	0.220450964
0.02	0.22191	0.226845375	0.227032872
0.03	0.22467	0.233462772	0.233749706
0.04	0.23567	0.240215276	0.240605568
0.05	0.239706	0.247107066	0.247604677

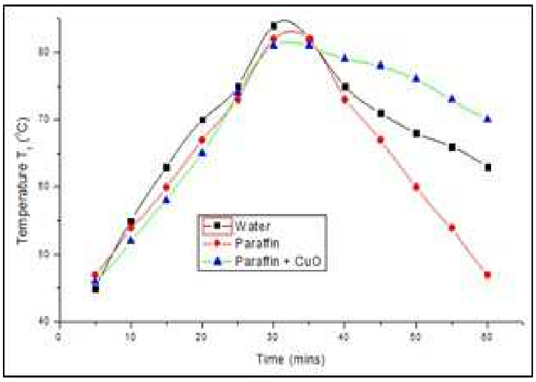

Fig. 4: Temperature distribution at section 1

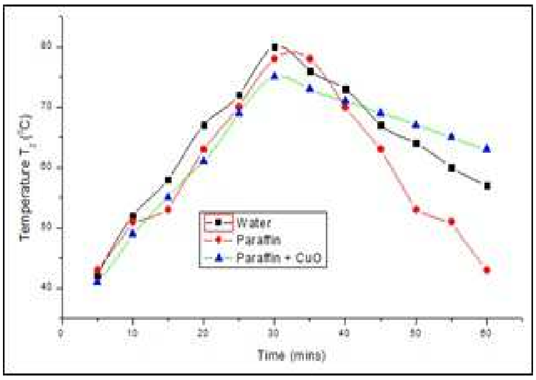

Fig. 5: Temperature distribution at section 2

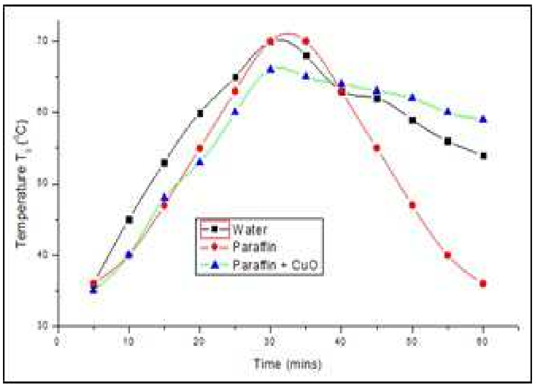

Fig. 6: Temperature distribution at section 3

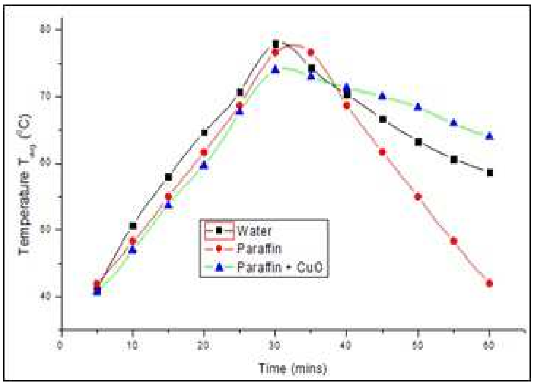

Fig. 7: Average Temperature of water

can be stored for a prolonged period by embedding micro metal oxides. The chosen oxide form of copper resulted in great improvement of heat transfer by enhancing the bonding nature with PCM. In this case, the efficiency of storage is increased by 10.16% compared to water.

The total heat transferred from heating coil to water is estimated over the period of experimentation and plotted in figures 8 and 9. During the charging operation, heat transfer showed higher values for water. Initially, the difference in heat transferred is lower and upon further increase, it rises. Almost a 10% difference in heat storage is observed. During the discharging operation, the heat transfer rate is very poor for paraffin wax PCM as it increases the energy easily. Water and CuO enhanced paraffin wax show a similar trend of slower liberation of heat. However, the heat drop in the enhanced PCM is appreciably small up on comparison with the others. Heat energy drop is about 36.84% for water, 74.36% for

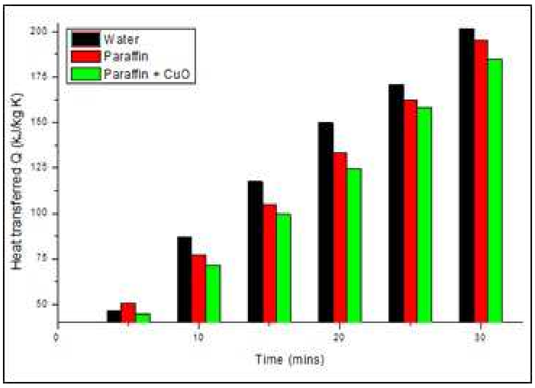

Fig. 8: Heat transfer during charging stage

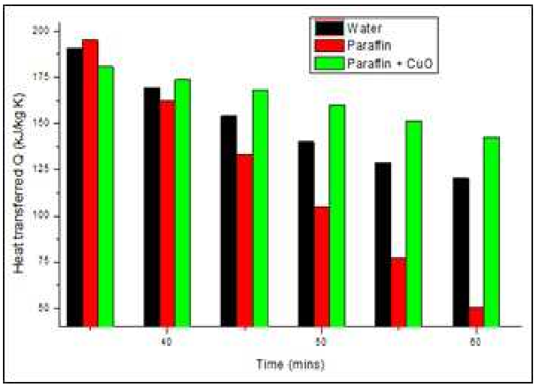

Fig. 9: Heat transfer during discharging stage

paraffin wax and 21.37% for CuO enhanced paraffin wax PCM. It is evident from figure 9 that the enhancement made in this study showed a great improvement of 41.99% reduced heat liberation in storage devices. The performance of heat storing device was improved to almost double times [25],[26].

5 Exergy analysis

The total amount of energy available in LHTS system or removed from the storage is expressed by the exergy performance. Exergy analysis during chargining phase is provided by the equations 5-7. Exergy analysis during dischargining phase is provided by the equations 8-10.

$$Ex_{htf} = m * C_p * ((T_{in} - T_{out}) - T_{atm} * ln\frac{T_{in}}{T_{out}}) \quad (5)$$

$$Ex_{pcm} = Q * (1 - \frac{T_{atm}}{T_{avg}}) \quad (6)$$

$$Exergyefficiency = \frac{Ex_{pcm}}{Ex_{htf}} \quad (7)$$

$$Ex_{htf} = m * C_p * ((T_{out} - T_{in}) - T_{atm} * ln\frac{T_{out}}{T_{in}}) \quad (8)$$

$$Ex_{pcm} = Q * (\frac{T_{atm}}{T_{avg}} - 1) \quad (9)$$

$$Exergyefficiency = \frac{Ex_{htf}}{Ex_{pcm}} \quad (10)$$

The overall performance shown by the CuO composite PCM is superior to the plain PCM storage medium. The exergy value depends on several factors such as the volume fraction of particle, flow rate of HTF, convective heat transfer coefficient, viscous forces produced, etc. During the chagrining period, a maximum of 95.8% is achieved. The melting of PCM progresses with decrease in exergy efficiency of the system. The exergy efficiency of LHTS shows a decreasing trend during the discharging process, as the relative outlet temperature of HTF is higher than inlet temperature. The increased temperature raises the viscous force inside system and hence the velocity is disturbed. The migration of metal oxide in PCM medium is influenced by the amount of heat energy stored. The moving of CuO in PCM improves the conduction ability of storage medium. All the efficiency values during discharge is initially higher and upon further progress starting to decrease. The overall efficiency performance of the system is shown in fig 10.

6 Conclusion

The present work aimed at studying the heat storing capacity of Paraffin wax PCM enhanced with CuO micro particles inside a specially designed cylindrical shell with various sections [1]. The shell was properly insulated on the inside by mineral typed glass wool. Temperature of water content was measured using K-type thermocouples at all sections in the shell. The temperature distribution patterns of water, paraffin wax and CuO enhanced paraffin wax were studied for heat storage applications. Ability for absorbing heat energy of enhanced PCM was slightly lower, yet there was about 10.16% rise in storage

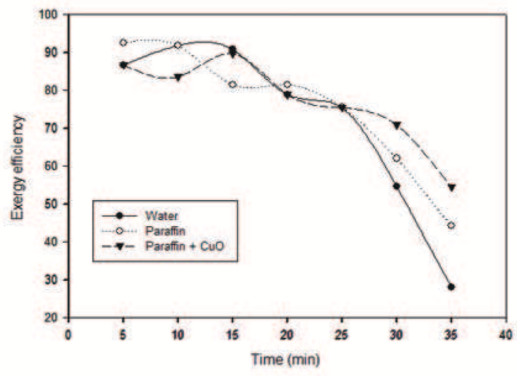

Fig. 10: Overall exergy analysis during the process

efficiency compared to water. Tendency to liberate the heat energy was lower for enhanced PCM by 21.37%. The storage efficiency was thus improved by 41.99%, which is approximately double than that for water. The improvement in storage capacity could be further used for other applications or requirements. If the energy demand is met by the available setup, the volume of PCM used could be reduced which in turn reduces the cost and space requirements. On average, the storage tank capacity could be reduced by 5% for storing the same amount of energy by using this PCM composite.

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