NUMERICAL INVESTIGATION OF A NEW PACKED BED STORAGE SYSTEM FILLED WITH DIFFERENT PHASE CHANGE MATERIALS

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ABSTRACT:

This article displays a numerical investigation of another stuffed bed utilizing a stratified stage change material (PCM). The PCM is infused into steel spheres as phase change containers. Water is utilized as heat exchange liquid (HTF) for charging or releasing warm vitality to the PCM. Three sorts of paraffin that have been distinctive dissolving focuses are utilized as the PCM and put in the stuffed bed at various statures. The PCM at the higher liquefying temperature is set closer to the boiling water channel. The numerical count of HTF depends on the one-dimensional Schumann's model, while the temperature of the PCM is mimicked utilizing the clear warmth limit strategy. Both charge and release procedures of this new stratified stuffed bed have been considered. The impacts of HTF normal speed and bay temperature have, likewise, been researched.

Keywords: **Phase change material, packed bed, Mathematical analysis.**

1. INTRODUCTION

Due to much higher-energy storage density, the latent heat storage has magnetized an immensely colossal number of applications in recent years with more temperature ranges as compared to traditional sensible heat storage techniques [1-4]. In order to solve the problem of low thermal conductivity properties of different phase change materials, different enhancement techniques are used by the distinct researchers from time to time. Along with this, various methods are purposed so that heat transfer rate could be enhanced. For example: metallic fillers, structures with metal matrixes, finned tubes, etc. are purposed and also used to increase the thermal conductivities of different phase change materials. Furthermore, to increase the energy transfer rate a sizeable improvement was made by encapsulating PCM into small polycarbonate spheres [5, 6].

Three main aspects should be kept in mind while designing packed bed storage systems, which is (I) selection of suitable phase change material (ii) heat exchanger (iii) numerical calculations of the performance of the system. First of all, Phase change material should be selected according to the thermal physical as well as chemical properties. In general, phase change materials can be categorized into two main groups: Organic PCM and inorganic PCM which both have low thermal conductivity. This problem could be improved through the second part which is designing of a heat exchanger. The geometry of the container, material's placing, materials of containers, size and shape of the encapsulated materials and many more could be used to overcome this problem. Some of the common geometries which were used earlier were cylindrical or rectangular. Both have their own advantages. The shape which will have high storage density could be used. Not only this, conductive metallic structures, metal matrixes and honeycomb structures are some of the modern techniques, which could be employed to enhance the heat-transfer techniques. Composite materials can also be used, but it depends on the selection of the PCM. The nano particle storage of PCM is also used by few researchers just to enhance the heat-transfer technique so that the efficiency of the entire system could be increased.

A numerical study was conducted by Lei yang et al. [7] on a packed bed storage consisting of three different phase change materials. They used spherical capsules to encapsulate PCM, which is connected to a flat plate solar collector. According to the melting point range, capsules were arranged in the packed bed. In whole experiment, water was used as a heat-transfer fluid. Now the energy which is stored in the PCM from the solar energy is latent heat because the energy is stored in the PCM when it changes its phase from solid to liquid. Finite difference method was adopted to analyze the heat-transfer process of the HTF as well as of the phase-change material. To study the natural convection on the heat transfer, especially during the melting process, the thermal conductivity of liquid phase was taken into account. In addition, the energy and exergy performances of the system were also calculated from the Schumann model. Besides, these performances of the multi type packed bed were compared to the system having single phase change material. Along with this, the performance of solar collector was also calculated. It is concluded in the study that the new storage packed bed with different phase change materials have more overall efficiency as compared with the traditional single type packed bed system.

To analyze the melting behavior of PCM, which was paraffin wax Regin et al. [8] did an exploratory and numerical study of the system. The outcomes from the study indicate that there is a great impact of the Stefan number of the melting process of the PCM. Not only has this, the temperature range of the PCM and the size of the capsules also had a significant effect on the performance of the packed bed. A new solar heat storage unit was presented by Qarnia [9] in which the theoretical model was introduced into the energy equations to enhance the performance of the system. They used identical tubes embedded with the PCM in the experiment. Along with this, various numerical simulations were done for the distinctive kind of PCMs like n-octa decane, paraffin wax and stearic acid. Simulations were done in order to find the effect of different flow rates in the discharging process.

For latent heat storage method, phase change materials are the best choice for the researchers these days because of the high-heat storage density, low cost, easily availability, non toxic nature, small, and easy to handle [3]. Nevertheless, for the commercial purpose the use of the latent heat system, especially with the PCM is not up to the mark because of the poor heat transfer rate during the charging as well as discharging processes [4].

The charging and releasing rates are unequivocally subject to the contrast between liquid temperature and softening purposes of PCMs. Since the temperature of HTF alters in its stream course, this temperature contrast between the liquid and the PCMs additionally diminishes in a solitary kind PCM warm capacity framework, which causes a diminished charging and releasing rates as liquid streams crosswise over PCMs. In any case, the latent heat storage framework with PCMs having distinctive softening focuses gives almost consistent temperature contrast. So the heat motions from liquid to the PCMs are about steady as well. The exergy loss of the framework is, likewise, diminished, and improvement of vitality charge release can be accomplished.

2. SYSTEM DESCRIPTION

A new thermal energy storage system with packed bed encapsulated with different phase change materials in spherical steel balls is shown in figure 2. The dimensions of the storage tank are of 1 meter in height and .38 meter in diameter. The whole system will be insulated with polycarbonate foam of 9mm thickness. The diameter of the PCM capsule is 55 mm approximately. Total of 180 capsules will be used in the experiment. Each 60 number of capsules have one kind o PCM. All the encapsulated PCM spheres will be placed randomly in the TES tank layer by layer. The PCM having the higher temperature will place on the top portion of the TES tank or nearer to the inlet of heat transfer fluid. Hot water is used as a heat-transfer fluid throughout the system. Two heaters are also used to heat the water.

A centrifugal pump is used to circulate the hot water throughout the system. This hot water is used to melt the PCM which is encapsulated in the steel spheres so that heat is transferred and stored in the material during the phase-change process. While in the discharge process water at ambient temperatures could be circulated throughout the system in terms of batches so that heat is extracted from the PCM which was stored earlier. In this way, energy is again restored or conserved. Hot water for the circulation could be produced by using solar panel or in the off-peak hours, the electrical energy also be used to make the supply of hot water. In this way heat, energy is transferred from PCM to the hot water or vice versa.

Another storage tank of high-density polyethylene material will be used to make the continuous supply of water. Suitable pipe and fittings will be done, and especially the leakage problem will be taken into serious consideration. A total of 16 thermocouples will be used to measure the temperature inside the packed bed or inside the PCM capsules. The temperature readings will be collected with the help of a data logger. Different experiments will be scheduled to perform at varying operating parameters like mass flow rate; inlet temperature of HTF, etc. once the readings are taken then the entire data will be studied deeply to calculate the various outputs and efficiencies.

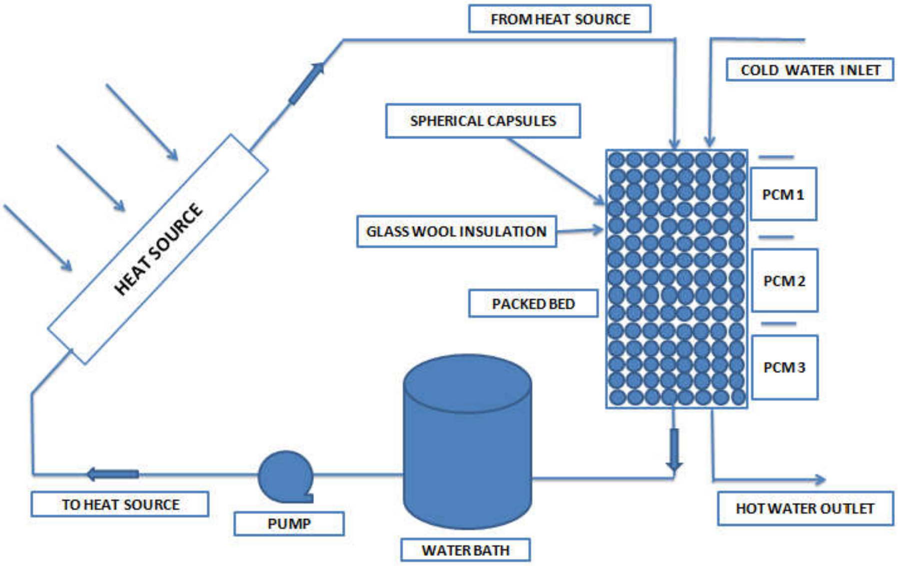

Figure 2: Schematic of an experimental set-up

In this experimental work, three different phase change materials will be selected from the literature [10-14] and also based on operating parameters. Properties of phase change materials are presented in Table. 1. The PCMs which are selected are well suited for the residential purpose, and the differences between their melting temperatures are almost same.

Table 1. Thermo physical properties of PCMs

Sr no.	PCM	Melting Point (^{0}C)	Latent Heat (KJ/Kg)	Density (kg/m^3)
1	Paraffin	50	213	788
2	Hybrid wax	60	270	1450
3	Bee Wax	70	177	970

Before performing experiments, following are some mathematical models which were developed by different researchers were analyzed in this paper to study the effect of various parameters on the charging as well as discharging processes. With the help of these equations the efficiency of the purposed system could be analyzed easily.

3. MATHEMATICAL MODEL

One-dimensional Schumann's model [15] is used to investigate the performance in terms of heat transfer from the PCM to HTF or vice versa. In this model, the following are some assumptions, which are made to simplify the calculations: (i) the fluid flow is steady state (ii) the velocity of the fluid is fully achieved (iii) the flow of fluid is in laminar state, and the fluid is incompressible (iv) heat losses to the surrounding are negligible (v) thermal resistance by the capsule wall is assumed to be constant (vi) thermo-physical as well as chemical properties of the phase-change material and heat transfer fluid are independent of temperature.

$$\varepsilon\rho_f c_f\{\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial x}=k_f\frac{\partial^2 T_f}{\partial x^2}+ha_p(T_p-T_f)\} \text{ .. Equation no. 1}$$

where T_f is the water temperature, ρf and C_f are the density and heat capacity, respectively, k_f the thermal conductivity, T_p the temperature of the PCM, a_p the superficial particle area per unit volume, € the void fraction of the storage tank, h the heat transfer coefficient between water and PCM capsules, which can be estimated from an empirical correlation proposed by Beek [16]:

$$Nu = 3.22\,\mathrm{Re}^{1/3}\,\mathrm{Pr}^{1/3} + 0.117\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \text{ .. Equation no. 2}$$

Whereas Nu is the Nusselt number, Pr is the Prandtl number and Re is the Reynolds number. Apparent heat capacity method is adopted for the calculation of the experimental data. In this method it takes the latent heat as apparent heat capacity in particular that temperature range. Also, it regards the small temperature range occurred during the phase change method. Therefore, the equation of heat transfer PCM and in the storage tank is:

$$(1-\varepsilon)\times C_p\frac{\partial T_p}{\partial t}=ha_p(T_f-T_p) \text{ .. Equation no. 3}$$

Where Cp is the apparent heat capacity of the PCM which can be determined as follows:

$$C_p=\begin{cases}\rho_s c_s & (T_p<T_m-\Delta T)\\ \dfrac{\rho_s c_s+\rho_1 c_1}{2}+\dfrac{\rho L}{2\Delta T} & (T_m-\Delta T\le T_p\le T_m+\Delta T)\\ \rho_1 c_1 & (T_p>T_m+\Delta T)\end{cases}$$

Where Tm is the melting temperature of the phase change material and L is the latent heat ρ and c are the density and heat capacity, respectively. Solid and liquid states are denoted by subscripts s and l. ΔT is the temperature range in semi phase. Control volume method [17] is denoted by Equations (1) and (3). Equation 1 is solved with the help of implicit manner and to solve the statement for the temperature of PCM, Equation 3 could be used. Various numerical simulations will be done in order to validate the mathematical model as well as the assumptions [18].

Not only this, the energy and exergy results of the packed bed during the charging and discharging will be investigated. The instantaneous energy transfer rate is:

$$q(t) = m_f c_f \left| T_{f,in} - T_{f,out} \right| \text{.. Equation no. 4}$$

Considering the storage tank acts as a heat exchanger, the energy efficiency can be calculated with the following relation:

$$\eta(t) = \left| \frac{T_{f,in} - T_{f,out}}{T_{f,in} - T_{f,ini}} \right| \text{.. Equation no. 5}$$

Whereas mf is the mass flow rate of water. Outlet and initial conditions are indicated by the subscripts out and in respectively. Therefore, from the above equations the numerical performance of a packed bed storage system could be performed.

3.1 CHARGE PROCESS:

During the charging process, the fluid which is water in our case flows from top to down with the help of a pump. The energy in terms of heat is transferred from the HTF to the PCM capsules packed in the TES tank. So, the total exergy supplied by HTF to the PCM can be expressed as follows:

$$Ex_{\sup} = \int_0^t m_f c_f \left(T_{f,in} - T_{f,out} - T_0 \ln \frac{T_{f,in}}{T_{f,out}}\right) dt \quad \text{Equation no. 6}$$

Where T_0 is the reference temperature as **^{0}C**. Neglecting the exergy stored by steel capsules and exergy gain due to heat leakage, the total exergy charged is the sum of charged exergy of HTF and the PCM. The charged exergy at the PCM is as follows:

$$\begin{aligned} Ex_{PCM} = \; & \sum_i M_{PCM,i} c_{p,l} \left(T_{p,i} - T_{l,i} - T_0 \ln \frac{T_{p,i}}{T_{l,i}} \right) \\ & + \sum_i M_{PCM,i} c_{p,s} \left(T_{s,i} - T_{p,ini} - T_0 \ln \frac{T_{s,i}}{T_{p,ini}} \right) \text{.. Equation no. 7} \\ & + \sum_i M_{PCM,i} c_p \left(T_{l,i} - T_{s,i} - T_0 \ln \frac{T_{l,i}}{T_{s,i}} \right) \end{aligned}$$

In equation 7 the first term denotes the charged exergy during liquid state, second term denotes the charged exergy during solid state and the third term denotes two phase state. The charged exergy at the HTF could be calculated by the following equation:

$$Ex_{HTF} = \sum_i M_{HTF,i} c_f \left(T_{f,i} - T_{f,ini} - T_0 \ln \frac{T_{f,i}}{T_{f,ini}} \right) \text{.. Equation no. 8}$$

In the charging process, the exergy efficiency is the ratio of supplied exergy and charged exergy which is as follows:

$$\eta_{ex,char} = \frac{Ex_{HTF} + Ex_{PCM}}{Ex_{\sup}} \text{.. Equation no. 9}$$

3.2 DISCHARGE PROCESS:

During the discharging process, heat transfer fluid flows from top to the down through the packed bed and absorbs ail the energy in terms of heat from the PCM capsules. But there are some differences during the exergy analysis. In the discharging process, the initial exergy was the charged exergy in the charge process. The remaining exergy is kept decreasing even when the discharge is in process or progress. So, the discharge process ended when the remaining exergy reached at zero value. The total discharge exergy is:

$$Ex_{dis} = \int_0^t m_f c_f (T_{f,out} - T_{f,in} - T_0 \ln \frac{T_{f,out}}{T_{f,in}}) \text{ .. Equation no. 10}$$

The ratio of the net discharge exergy and the initial exergy is the exergy efficiency which is expressed as follows:

$$\eta_{ex,dis} = \frac{Ex_{dis}}{Ex_{ini}} \text{ .. Equation no. 11}$$

The exergy efficiency for a complete cycle with the charging and the discharging processes can be defined as the ratio of the net discharged exergy during the discharging process to the net charged exergy during the charging process [9]. Therefore, the exergy efficiency could be calculated by the product of the exergy efficiencies of the charging as well as discharging processes as follows:

$$\eta_{ex,cycle} = \eta_{ex,char} \times \eta_{ex,dis} \text{ .. Equation no. 12}$$

4. CONCLUSION

This paper presents a detailed mathematical analysis which could be done to predict the performance of any packed bed latent thermal energy storage system. Although, there may be diversity in the models but they can be grouped into single phase and two phase models. The charging and discharging processes are discussed with the help of above equations. So with this mathematical calculation as discussed above in the charge, discharge or the complete cycle, the exergy efficiency of the stratified packed bed could be calculated. Further these results can also be compared with the packed bed storage system having only single PCM used as storage medium. These mathematical analyses could be used in the future to optimize the process of phase change systems especially for the packed bed. The objective function could be the true energy density which is the function of phase change effectiveness and the compactness factor. All the past said philosophies utilized exact correlation to decide key physical angles, for example, convective warmth exchange at the strong liquid interface, and common convection inside fluid locale of PCM circles or viable warm conductivity. The most vital exact connections utilized as a part of the writing to portray these material sciences are additionally given in the present paper.

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