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Thermal Energy Storage in Sensible Materials: A Review

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Abstract: The intermittent, variable and unpredictable nature of solar energy lead to mismatch the rate and time of solar energy collection and its thermal applications. As a result, it is necessary to have energy storage unit which stores solar energy when the collection is in excess of load and discharges the same when the direct collection is inadequate. To store solar energy in sensible heat storage materials, pebble bed systems are simpler, economical in design and development as compared to latent or thermo-chemical energy storages. A number of studies are available on heating and cooling of pebble beds describing their parameters like pebble size/diameter, bed porosity, surface area, a shape factor of storage media/pebbles to observe the behaviour and characteristics of storage devices. Many correlations are available to analyse the heat transfer coefficients, friction factors and pressure drops in between the solids and circulating fluids in pebble beds. The relations are of importance and best suited for energy storage system modelling.

Keywords: Pebble Bed, Solid-fluid Interface, Thermal Stratification, Heat Transfer and Pressure Drop in Beds.

I. INTRODUCTION

Availability of cheap and abundant supply of energy is an index of national prosperity. The man has needed and used energy at an increasing rate for his sustenance and well-being ever since he came to the earth. The large scale use of commercial energy has led man to a better quality of life. Indeed, energy starvation could be more widespread than food starvation. But the conventional energy supplier fossil-fuel resources are finite, depleting fast and this fossil fuel-era is gradually coming to an end. The potential applications of solar energy in space and water heating, industrial process heating, refrigeration/air conditioning, cooking and power generation can reduce the dependence on fossil fuel usages, environmental pollution, and global warming issues.

But the intermittent, variable and unpredictable nature of solar heat lead to a mismatch of the rate and time of energy collection and thermal applications. As a result, it is necessary to have thermal energy storage (TES) unit in between the energy demand and supply to alleviate the energy mismatch. The storage system stores solar energy when the collection is in excess of load or in no load conditions and discharges the same when the direct collection is inadequate of load/demand for off sun shines hours' applications. Storage system allows the more effective use of capital equipment by improving capacity and permit cost effective substitution of scare conventional fuels. Thus, thermal energy storage is required to ensure round the clock heat supply. A relation between solar collector average collection temperature and heat delivered directly to load / thermal storage can be written as,

$$T\text{ (collector)} - T\text{ (delivery)} = \Delta T\text{ (collector to storage)} + \Delta T\text{ (into storage)} + \Delta T\text{ (storage loss)} + \Delta T\text{ (out of storage)} + \Delta T\text{ (storage to application)} + \Delta T\text{ (into application)} \quad \ldots \quad (1)$$

The thermal energy can be secured as shown in Fig. 1, sensibly/latent heat storage, chemical and solid sorption processes. Sensible and latent heat storages systems are in practical use while thermo-chemical reaction and fuel cell systems are proposed for medium and high temperature applications. The choice of material depends on the product of density and specific heat of material ($\rho.C_p$) values and temperature limits, water being used for less than 100°C heat storage and refractory /bricks for high temperature applications, about 1000°C.

In sensible heat storage systems, energy is added or extracted in the storage media which do not change their phase during heating and cooling processes. In case of solids, the material is porous and heat is stored or extracted by flow of gas or liquid, heat transfer fluids (HTF) through the pores and voids of bed materials.

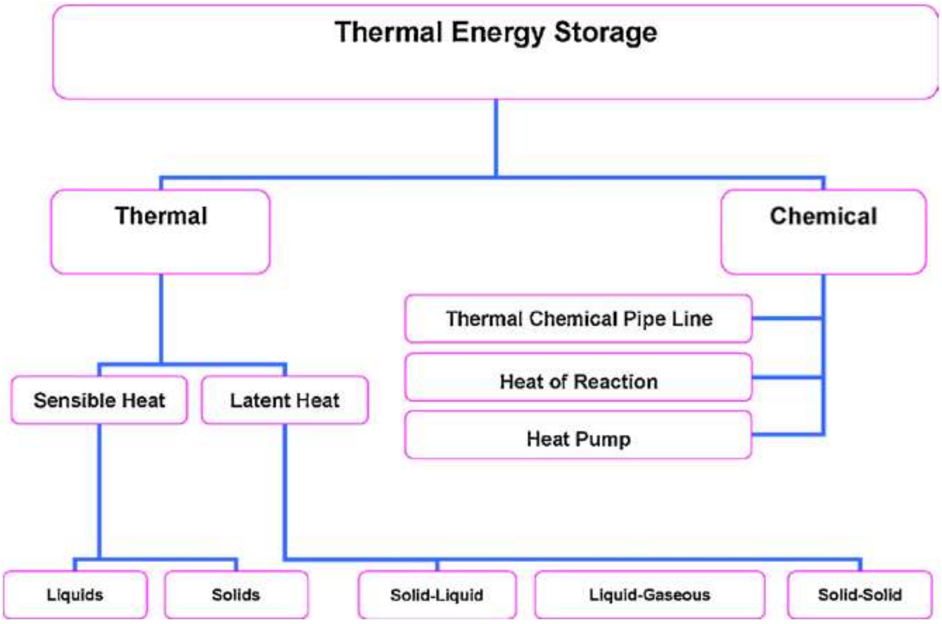

Fig. 1: Overview of TES Systems [8]

The paper is concerned with the modes of thermal energy storage (TES) systems, stressing on the sensible heat storage (SHS). The pebble bed thermal energy storage systems and their literature are reviewed. Conclusions are drawn based on analytical/experimental results and systems performances.

II. A REVIEW OF THERMAL ENERGY STORAGE

Sun is the source of all energies which provides abundant clean and safe energy to whole earth but it is dilute source of energy and its intensity varies according to the season and location. Intermittent, variable and unpredictable nature of solar radiation and its mismatch with the rate and time of energy demand necessitate the use of some sort of suitable thermal energy storage material. The thermal system stores solar energy when heat collection is in excess of load and discharges the same at no collection or shortage of available energy supply. According to Arce *et al.*, [1], thermal energy storage reduces the time and rate of energy mismatch which can play an important role in energy conservation and reduction in CO_2 emissions. Kuznetsov [2] reported that development of efficient and inexpensive TES is as important as developing a new source of energy.

There are three basic modes (media) of TES: sensible heat storage, latent heat storage and thermo-chemical energy storage in bond form. Sensible heat storage materials store heat without a change in phase while latent heat is stored with a change in phase of materials (PCM). Kuznetsov [2] reported that PCMs are more compact but are much expensive. Several of them are corrosive in nature, degrade with time, may deform and loose contact with the heat transferring surface area. Rock piles used in thermal energy storages are free from corrosion/scale formation or deformation problems. Sensible heat storage materials and unit construction are simple and inexpensive, but usually work out to be larger in size, higher initial cost and cannot be operated isothermally.

Pebble bed (PB) is a volume of porous media got by packing the pebbles of selected material in a container. According to Coutier and Farber [3], pebble bed thermal storages are most suitable for air based heat transferring solar systems. Ataer [4] reviewed different techniques and aspects of pebble bed storage system selection after accounting for material heat capacity, mass, application temperature, heat retention time and economic viability.

There are analytical studies available on pebble bed design, pebble material selection, heat transfer enhancement, heat transferring fluid flow phenomenon, and pressure drop and bed performance analysis. Telkes [5] was first who patented a loosely packed thermal energy storage for her solar box type cooker. Baker [6] carried out extensive literature survey on the fluid to particle convective heat transfer for different shapes like spheres, cubes and commercially available materials for air as a heat transfer media, a few for gases/water etc. and observed the lack of data in many areas which could be corrected by experiments. MacCracken [7] patented thermal storage system utilizing low cost anhydrous sodium sulphate pebbles and claimed the higher thermal energy storage due to high material bulk density, specific heat, and latent heat content capacity. Singh et al. [8] have also reported in detailed literature survey on pebble bed storage systems in which hot fluid pass through the heat storage media.

A number of studies exist on bed convective heat transfer coefficients, pressure drop and correlations also available for bed performance parameters evaluation. The majority of work focused on 1-dimensional time-dependent parameters in which instantaneous solid and fluid temperatures are equal.

Ergun [9] analyzed the pressure drop (Δp) / energy loss in pebble bed and concluded that pressure drop was the sum of viscous energy loss and kinetic energy loss due to fluid flow over the bed particles. Waked [10] studied the effect of bed height and rock size with heat transferring fluid flow rates, bed pressure drop and circulation pumping power. He commented that energy storage in the rock pieces could successfully be used being well-stratified and more than 60% of stored energy in rocks can be recovered at maximum temperature. Achenbach [11] presented the state of the art of packed beds as shown in Fig. 2 for Nu number and Gnielinski for different gases for prediction of forced convection heat transfer in void fraction, ε ranges of $0.26 \leq \varepsilon \leq 0.935$ and pressure drop for Reynolds number ratio Re to void fraction ε, $Re/\varepsilon = 2 \times 10^4$.

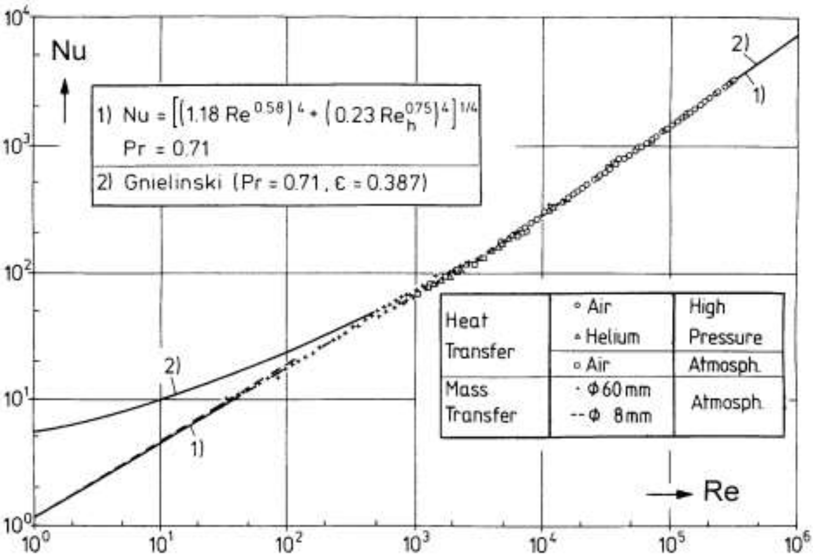

Fig. 2 Convective Particle to Fluid Heat Transfer for Pr = 0.7 and e = 0.387 [11]

The experimental work was extended by accounting the errors due to natural convection; contact points heat loss, bed effective thermal conductivity (k_e) and introduced the effects of bypass flow and wall heat transfer. Pushnov [12] statically gave the relationship for bed porosity having diameter of bed d_b to diameter of pebble d_p ratio should be greater than 2 ($d_b/d_p > 2$) for bed height of greater than 20 times the pebble diameter ($h_b > 20 \times d_p$). The correlations between the storage vessel diameter to pebble diameter ratio; shape and average porosity was given by relation,

$$\varepsilon_B = \frac{A}{(d_b/d_p)^n} + B \qquad \ldots \qquad (2)$$

Where

A B and n are constants depend on the shape of pebbles.

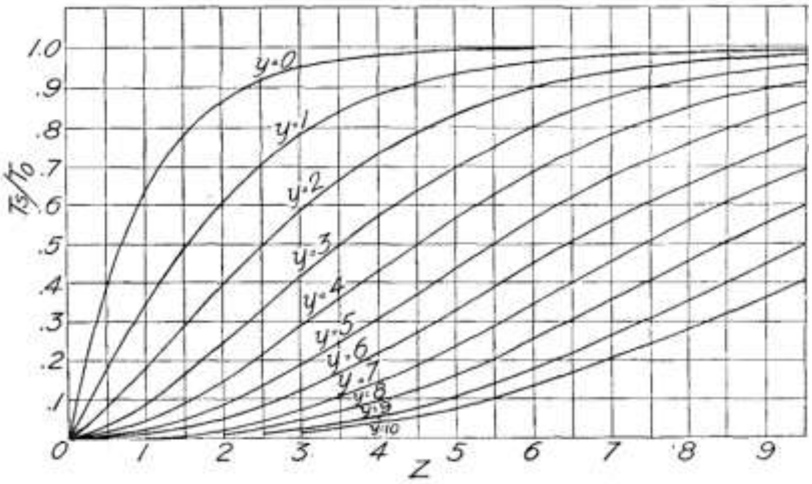

Fig. 3 Curves Showing the Temperature in Solid [13]

The two-phase model allows the heat transferring fluid and pebble bed temperatures to be different with solid-fluid inter phase heat transfer which is described by mean of heat transfer coefficient. Two phase model was first studied by Schumann [13] as shown in Fig. 3 with simple initial and final boundary conditions in which a uniform temperature liquid passed through a porous prism bed. The model could present a mean fluid and solid temperatures at a given point which was the function of axial positions and time parameters incorporating the solid-fluid heat transfer. Furnas [14] reported that coefficient of heat transfer varies along a straight line with a gas velocity which decreases with increase in particle diameter. Colburn [15] used granular materials, pebbles, and porcelain and zinc balls of different diameters in a tubular storage to study the heat transfer between air and bed materials.

He reported that heat transfer coefficient with balls was eight times higher than the empty tube and fluid mass velocity G_a varied as $G_a^{0.83}$ which was the function of d_b/d_p. Kaye and Furnas [16] reported that cooling heat transfer coefficient was much higher than heating for same values of $d_b.G_a/\mu$ (μ - dynamic viscosity) due to thin boundary layer formation on vessel walls for heat transferring oil, water, and air at turbulent flow with a discrepancy of about 270%. Loff and Hawley [17] conducted experiment as shown in Fig. 4 with air and loosely packed solids in a container of size, 6'×12.9"×11.25" with 4" thick fibre glass insulation to calculate the heat transfer coefficient for gravels of 4-mesh to 1.5" with air temperature of 37.8°C to 121°C and flow rates of 12.05 to 66.3 $ft^3/min.ft^2$.

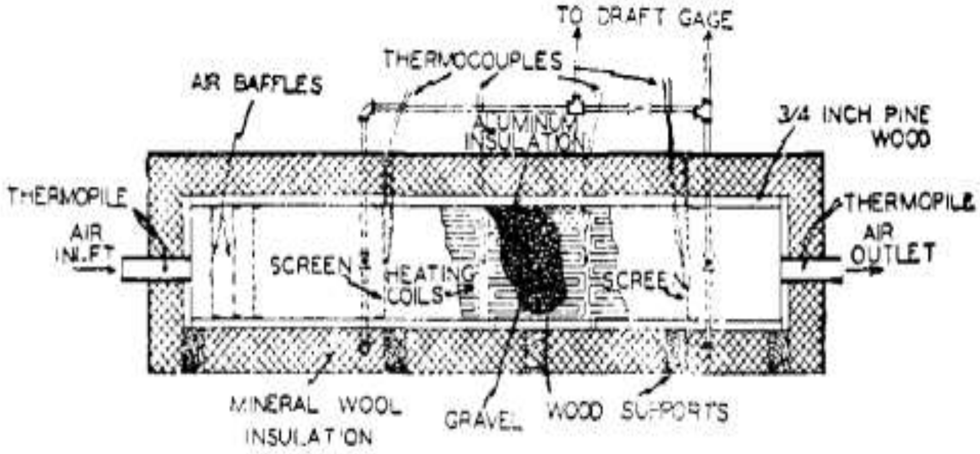

Fig. 4 Experimental set-up of Loff and Hawley [17]

Heat transfer coefficient increased along a straight line with the increase in air flow rates and it decreased with increase in particle diameter when presented on a logarithmic graph. Average slope of heat transfer lines was 0.69, hence the heat transfer coefficient varies as the following relation,

$0.79\,(G_a/d_p)^{0.7}$. … (3)

Where

Ga – mass velocity and

d_p – diameter of a pebble.

A comprehensive summary on pebble bed heat transfer was given by Balakrishnan and Pei [18], [19] and reported the basic modes of heat transfer, namely convection between gas and particles, conduction between bed particles themselves, radiation and mixing modes heat transfers. Balakrishnan and Pei [20] investigated the pebble bed performance further by taking in to the account of fluid properties, mass velocity, bed void fraction and transport coefficients for transient solutions with boundary conditions. Wako et al., [21] corrected the heat transfer data for axial dispersion coefficient in the range of Re 15 to 8500 and given the correlation as followings,

$Nu = 2 + 1.1\, Re^{0.6}\, Pr^{1/3}$ … (4)

Where

Nu – Nusselt number,

Re – Reynolds number and Pr Prandtl number.

Which is analogous to the mass of pebbles.

Beasley and Clark [22] predicted two dimensional transient responses of solid - fluid for Re of 90 to 660 and found suitable to conventional models when the Nusselt number was greater than 50% (Nu > 50%). Thermocline and temperature distribution pebble bed were favourable with analytical results for vide range of Re and void fraction, ε which was also a function of d_b/d_p. Kunni and Levenspiel [23] derived equations for considering the thermal properties of solids / gases, storage media particle sizes, state of solid/gas interface etc. indicated that up to 12 mm pebble diameter, the total heat transfer coefficient of gas was the sum of stagnant and flowing conditions with a constant value of 0.041 at container walls and in between the fluid-particle interfaces.

Sanderson and Cunningham [24] studied for fluid flow in the vertical container to investigate the effect of altering equivalent sphere diameter of packing material on the degree of axial heat dispersion and measured average temperature, wave velocities and significance of natural convection during heat transfer phenomenon. Duffie and Beckman [25] solved for the bed governing equations by finite difference method but this approach suffered from a lot of time consumption in computing the bed temperature distribution. Nsofor and Adebiyi [26] tested for forced convection gas-particle heat transfer and developed the correlations. He correlated the Nusselt number, Nu and reported the uncertainty in the range of 10 to 30% up to 1000°C for Reynolds number range of 50 to 120 ($50 \leq Re \leq 120$).

Neijemeisland and Dixon [27] reported that CFD studies can improve the understanding of fluid flow and heat transfer in pebble beds. The two aspects were observed near sphere-sphere contact points, the formation of (i) small trailing vortices and (ii) flow magnitude in contact area was very low due to closure proximity. In comparison, the computational model results were in good agreement with experimental data and CFD results give reliable information about the modelled system. Crandall and Thatcher [28] simulated a segmented bed as shown in Fig. 5 for solar thermal energy storage in rock media of different sizes.

The segmented bed had a higher degree of stratification i.e. the higher temperature at the top and lowest temperature at bottom containing 1% less energy than the maximum in standard bed; however the variation in temperature of the hot air from the solar air heater was limited between the range of 24 and 38°C.

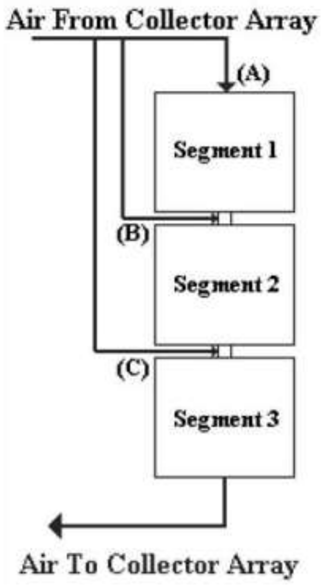

Fig. 5 Charging the Segmented by Hot Air [28]

Wen and Ding [29] reported for transient and steady-state heat transfer in the pebble bed with gas flowing through the bed under constant wall temperatures of the container. The large temperature drop in the container wall region was observed due to high effective thermal conductivities of container material and higher convective heat transfer coefficient. The heat transfer model predicted the axial temperature distribution as fairly well but radial temperature variations were not predicted well. Mawire and Taole [30] investigated for temperature variations in pebble bed when passing oil through the bed during the charging process to analyse energy and exergy efficiency of bed, stratification number, Reynolds number and Richardson number under different testing conditions. They concluded that temperature distribution in bed and stratification number gave adequate information of bed stratification, charging exergy efficiency and Reynolds number could give stratification number quantitatively.

III. CONCLUSIONS

It is clear from the studies on pebble bed thermal energy storage employed for experimental/ simulation/numerical models to predict the behaviour of porous media for heat transfer and energy storage which is later verified experimentally whose results are well in agreement with experimental data. The pebble bed performance analyzed during charging with the heat transferring fluid flow through the bed accounting for effects of particle size, porosity, pressure drop and vessel heat loss on heat transfer and temperature distribution using LMTD and energy balance concepts. Stored heat can be recovered by circulating a heat transferring fluid through the fully charged bed.

The effect of pebble size on bed heat transfer and pressure drop in storage vessel was studied with different diameter pebbles which were randomly packed. The literature results stated that bed heat transfer coefficient, h_a and pressure drop Δp go on decreasing with increase in pebble diameter, d_p. the bed pressure drops by a factor of four times from 1387.1 to 351.4 Pa, while h_a reduces from 208.9 to 140.3 W/m^{2}K, less than half rate for pebble size of 1 mm to 2 mm. Heat transfer coefficient and pressure drop decrease from 208.9 to 55.49 W/m^{2}K and 1387.1 to 15.46 Pa for pebbles of 1 to 10 mm. The heat transfer coefficient between air and solid is higher for small pebbles due to the increased surface area with restricted flow path which promotes thermal stratification. Bi and Re increase from 0.017 to 0.046 and 1.61 to 16.06 for an increase in pebble size of 1 to 10 mm diameter. Pressure drop is higher for small pebbles due to the smaller hydraulic diameter of passages and results in high fan power.

The collector concentrates incident solar radiations over the heat receiver which further converts the solar radiation into heat. The solar heat is then transferred to the solar system for end use. During charging process of pebble bed with constant heat flux or variable temperatures, the solar heat enters into the thermal storage and hot fluid starts releasing heat to pebble bed. Some amount of heat is lost during the charging process. Percentage heat loss increases as bed temperature goes on rising. The hot fluid further advances into the pebble bed, which further releases its heat into successive bed layers/segments. The length of transient period depends on heat transfer fluid flow rate and bed mass. Higher the hot fluid flow rate, shorter the transient heat transfer period. Consequently, the bed temperatures go on rising sharply and after several hours, the heat front reaches the bottom of the bed and the pebble bed gets saturated depending on the nature of heat storage media and bed capacity. This process continued till bed is fully charged and ready to release heat for off-sun shine applications. If this charging process continued during evening hours, the bed temperature will not rise but will lose heat. This is true because heat transferring fluid temperature from the solar collector reduces post solar noon session due to reduction in solar intensity. Bed heat loss can be minimized by deploying the optimally designed insulation over the storage vessel.

To retrieve the stored solar heat from storage, low/ambient temperature heat transferring fluid is passed through the fully charged pebble bed resulted in constant heat extraction and outlet temperature for about 86% of total stored heat and later the outlet temperature decreases till bed is fully discharged. During charging/recovery mode, some degradation of thermo-cline occurs due to diffusion of heat. If temperature gradients are large, the fluid convective motion will occur and accelerate thermo-cline degradation. Thermo-cline degradation reduces the temperature at which heat can be recovered from the bed. If the bed-to-particle diameter ratio is higher, it reduces the wall effects also.

Energy is lost from outer surfaces of storage vessel in radial and axial directions. This energy loss can be retarded by applying proper insulations in between the storage and atmospheric sink. Different insulation materials were evaluated for a cylindrical vessel and heat loss estimated for 12 h and 24 h. The optimum thickness of insulation for storage vessel depends on the initial cost of insulation, cost of maintaining it and cost of equipment to collect extra heat to compensate the heat loss from the vessel. Since the cost of solar collector is high, higher insulation thickness is likely to be justifiable for solar thermal energy storage systems.

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