Thermal Energy Storage in Packed Pebble Bed Heat Exchanger – A Review

S. Benjamin Franklin, K. Ramesh, S. Ramesh, M. Thoufeekahamed, B. Rahesh, A. Prakash

ABSTRACT

On account of decreasing carbon fuels, we are in search of renewable resources. One such alternative is the use of renewable energy sources. These are considered to be capable of overcoming the energy crisis and environmental threat, which are the results of continuous use of fossil fuels. Solar energy is most important among renewable energy resources due to its quantitative abundance. Although the solar energy is available everywhere but its availability is intermittent. It is therefore, necessary to provide a storage system with solar collectors to store energy and to meet the demand in the absence of solar radiation. Packed bed is generally recommended for thermal energy storage in solar air heaters. A packed bed is a volume of porous media obtained by packing particles of selected material into a container. A packed bed has been of interest in view of its several important applications. The heat transfer and pressure drop in the bed have been the subject of several theoretical and experimental investigations. Generally small size storage materials have been used to store thermal energy. Small size storage material having large effective surface area can provide high rates of heat transfer however; it is also accompanied by large pressure drop in the bed. This paper deals with literature review on thermal energy storage unit to select for best suitable PCM’s and materials for the design of test bench of thermal energy storage unit of packed pebble bed heat exchanger.

KEYWORDS: Phase change material (PCM), Thermal Energy Storage, Latent Heat of Thermal Energy Storage, Sensible heat storage

INTRODUCTION

There exist several TES (Thermal Energy Storage) technologies and applications. The selection of a TES technology for a specific application depends on many criteria, including the storage duration, cost, supply and utilization temperature requirements, and storage capacity. For many years, TES devices and systems have been utilized in building designs and integrated into solar power-generation, but the application of TES in the automobile industry did not start until the late 1970’s. There are various potential applications of TES in the automotive industry. First, a TES device could be charged from an engine’s waste heat during normal operation. In addition, TES devices could be utilized to provide heat during warm-up to reduce fuel consumption and emission. The drivers can avoid waiting for preheating and warming the engine. Moreover, TES devices have potential applications in hybrid and electric vehicles powered by batteries. Since the batteries operate poorly at low temperatures, the use of a TES device for rapid heating of the batteries could alleviate the degradation of battery performance in cold weather. Finally, a TES device could be used to enhance passenger comfort and aid in defrosting of windshields. In cold weather, it could take several minutes to provide significant warming in the...
passenger cabin before the internal combustion engine could spare enough heat. For electric vehicles, the situation would be even worse due to the lack of a high-temperature heat source. Since TES devices could produce heat directly without sharing with other compartments, they would be able to provide the thermal energy more efficiently and thereby greatly enhance the operation of vehicles during winter.

Thermal Energy Storage (TES) devices have attracted profound interest from researchers for their use in eliminating environmental problems and increasing the efficiency of energy consumption in general. TES devices store thermal energy (heat) in hot or cold materials for later use. It is an important technology in bridging the gap between the supply and demand of energy. Thus, TES devices allow the reutilization of stored energy to drive energy systems and prove to be extremely beneficial for renewable energy applications. They can also be used to mitigate the cold engine startup problem. As there are various potential applications of TES in the automotive industry. First, a TES device could be charged from an engine’s waste heat during normal operation. In addition, TES devices could be utilized to provide heat during warm-upto reduce fuel consumption and emission. The drivers can avoid waiting for preheating and warming the engine.

Types Of Energy Storage System:

The following are the various types of energy storage system.

Sensible Heat Thermal Energy Storage:

This type of storage systems store thermal energy by heating or cooling storage material through heat transfer. Sensible heat type storage system uses temperature change to charge the material and discharges while required. The amount of energy stored in a sensible TES device depends on the mass, temperature difference and the specific heat of the storage medium between its initial and final states.

Among all the potential medias for sensible heat storage, water has been the most capable runner. Due to its high heat carrying capacity (~4.2 kJ/kg · K) and low cost, it is repeatedly used in storage devices over the temperature range of 20-70°C. Also, as a liquid storage medium with high convectonal heat transfer, water allows the storage device to have higher heat addition and extraction rates compared to other solid heat storage media. Due to their easiness and low cost, sensible heat TES devices have been used in the automotive industry. Generally, they store a hot coolant in the storage phase and release the hot coolant into the engine cooling circuit during the cold start. However, sensible heat storage devices are not great runners for long-term because of the following drawbacks.

1. Low energy storage density (~100 kJ/kg),
2. Heavy insulation required to minimize heat loss to the ambient,
3. Non-isothermal behavior during charging and releasing processes.

Thermochemical Energy Storage:

Thermochemical energy storage system uses a reversible chemical reaction to stock and relief energy. It stores heat in the process of separation reaction and releases the energy in the exothermic step of a reversible chemical reaction. Its advantages have drawn significant attention high energy storage density (~2MJ/kg), low heat losses, long distance transport possibility and small storage volume.

Latent Heat Storage:

The latent heat storage system is the most capable among different methods of thermal energy storage system. In latent heat TES; energy is stored to the phase change materials (PCMs) by changing of a substance state from one phase to another. As the temperature of the material grows, the material transforms from solid to liquid phase and engages heat in the endothermic process. When temperature decreases, the material undergoes phase change from liquid to solid state by releasing heat. Since PCM’s store energy in the form of latent heat of fusion, there is no substantial temperature drop in the heat release process. The energy storage has to go through several phase transitions: solid-solid, solid–liquid, solid–gas and liquid–gas. In first type, energy is stored by the crystalline transformation of the material. This transition contains much smaller latent heat and minor volume changes. As a result, solid-solid PCMs have the advantage of less severe container requirements that allow greater design flexibility. Solid-liquid transformation plays a major role in the latent heat TES since it offers a high energy storage density and has much larger latent heat of fusion. Solid-gas and liquid-gas transitions have the advantage of higher latent heat of fusion, but their large volume alteration during the phase change process increases the struggle and difficulty of the storage system.

Packed Bed Geometric Properties:

Packed beds have been used extensively in engineering processes such as filtration, heat and mass storage, industrial stripping and catalysis. A packed bed can be defined as a number of particles dumped into a container. The particles form a matrix like structure which contains voids or pores in which a fluid is free to percolate. A packed column is a specific case where the packed bed is confined inside a cylindrical tube. The packed column
can either be fixed or fluidized. As the name suggests the particles in a fixed bed are static and fixed in position and unable to move. A fluidized bed is the phenomena when the particles are in motion, excited by the stream of fluid thus able to follow the random non-deterministic movement of the fluid. In this work we are only concerned with the study of fixed beds, their geometric properties and their influence on the flow.

**Particle Equivalent Diameter:**

A packed bed consists of particulate matter which is influential in determining the properties of the bed in regard to the flow properties. The bed particles can be uniform in size and shape, such as mono-sized spheres, or can be irregular such as coal or gravel. In order to study a packed bed mathematically, the bed has to be described by a number of parameters. In the case of bed particles, the parameter of interest is the particle diameter. When the bed particles are not spherical they are represented as an equivalent sphere of the same volume which can be characterized by the equivalent diameter or by the sphericity (a particles deviation from a perfect sphere). When the particles are spherical the equivalent diameter simply reduces to the particle diameter.

To get a mean representation of bed equivalent diameter, it is coupled with the bed surface area per unit volume giving the relationship

\[
\frac{a_p}{(1 - \varepsilon)} = \frac{\pi d_p^2}{\pi/6d_p^3}
\]

which re-arranging for \(d_p\) gives

\[
d_p = \frac{6(1 - \varepsilon)}{a_p}
\]

where \(a_p\) is the specific particle surface area, \(S_p/v_p\) (m\(^{-1}\)) where \(S_p\) is the particle surface area and \(v_p\) is the particle volume, \(\varepsilon\) is the porosity, given as the volume of voids or pores \(V_v\), divided by the total volume, \(V (\varepsilon = V_v/V)\). However the particle equivalent diameter does not completely eliminate the effect of the particle shape. For example, a particle may have the same equivalent diameter, but may be geometrically completely different, changing the flow pathways through the bed considerably. In the case of beds with varying diameter particles a mean average can be introduced. However, this does not give a realistic representation of the beds properties as the assumption is the bed packing will behave as if the bed particles are mono-sized. In reality, bed particles of varying sizes will pack more closely than mono-sized particles.

**Packing Regimes:**

In addition to the particle geometry, the arrangement in which they are ordered within the bed is highly influential in regard to the ease in which a fluid can pass through the media. In the case of random irregular size/shape particles (coal, gravel etc), the packing regime will always be random and unstructured with no known mathematical description to describe the particles orientation and position. Beds can be loosely packed or densely packed, based on the number of particles packed into a known volume, and this is sometimes referred to as packing efficiency. In addition, the packing can be structured or random unstructured. If a packing regime is considered to be structured, the coordinates of each particle have a full mathematical description and constant respective porosities and packing densities.

The astronomer Johannes Kepler (1611) studied the packing of mono sized spheres to determine which was the most efficient way of packing in regard to packing densities and efficiency. He questioned, should the spheres be packed directly on top of one another, known as simple cubic packing, or should the sphere layers be staggered so the spheres on the second layer sit within the hollows formed by the first layer, known as face centered cubic packing. Kepler conjectured that face center cubic packing was the densest possible packing scenario, but could not prove this mathematically.

For a simple cubic arrangement the packing density is \(\rho = \pi/6\), approximately 0.52. For a face centred cubic arrangement the packing density is \(\rho = \pi/3\sqrt{2}\) approximately 0.74. In addition, if the central coordinate of the first sphere in a pack is 0, 0, then the next spheres centroid in the series will be one diameter \((d_p)\) width away in the x, y and z directions. The relative ease in which simple mathematical relations can be applied to describe the packing regime makes the structured packing regimes.

![Fig. 1: Packing Regime](image)
When a packing regime is considered unstructured, the location of each particle is random and stochastic and there is no deterministic mathematical algorithm to describe the particle location. A unstructured pack can be created physically by simply dumping a number of particles into a container. However, due to the stochastic nature of unstructured packing, it is virtually impossible that an unstructured pack with the same disordered structure can be replicated. In the case of a few particles (<5) there is a chance statistically that the same bed structure may be replicated. In the case of several thousand particles the chance of replicating packed bed by dumping particles is near impossible. This phenomenon has posed a problem to researchers when trying to separate different phenomena from the packing regime as the same bed structure cannot be replicated. This issue further poses a problem in respect to reinforcing CFD data with empiricism. Unstructured beds can be generated computationally, but there currently exist no method in which they can be reproduced with geometric fidelity. The other option available to researchers is to create a random unstructured pack physically and use non-invasive methods, such as MRI or CT to create a computational model.

Aspect Ratio:
In order to compare similar scenarios with varying dimensional values it is often desirable to use a dimensionless property. The primary dimensionless property used to characterise a packed bed is the ratio between the equivalent diameter ($d_p$) of the particle and the container diameter ($D$). This is referred to as the aspect ratio given as

$$A_{ratio} = \frac{D}{d_p}$$

Packed beds are categorized as being low or high aspect ratio; a tube of sand would be considered high aspect ratio, a tube snooker balls would be considered low aspect ratio. As we might expect, the velocity profile through the high aspect ratio bed would be fairly uniform across its profile and can be considered as a pseudo-homogeneous network of capillaries with uniform flow rates. The network of flow through a low aspect ratio bed would be highly disordered due to the varying sizes of the voids as a result of the inhomogeneities in the packing leading to a variation in local porosity. The exact value at which a low aspect ratio bed becomes a high aspect ratio bed or vice versa is not well defined. However, $A_{ratio} = 50$ is often suggested as a reasonable value to distinguish between a low and high aspect ratio bed.

In addition to the aspect ratio, the bed length can be defined as the dimensionless bed depth ratio, which describes the ratio of bed depth to the particle equivalent diameter given as

$$H_{ratio} = \frac{L}{d_p}$$

Porosity:
A packed bed can be described as a restriction or a partial blockage in a pipe which interacts with the fluid in some way. The ease with which the fluid can pass through the medium is determined by the volume of voids within the bed, $V_v$ and is governed by the area available for the flow to pass. This can be represented in a dimensionless form as porosity ($\varepsilon$) or void fraction given as the volume of voids divided by the total volume.

$$\varepsilon = \frac{V_v}{V}$$

Because regular packing have a complete mathematical description their porosity can be represented by a simple geometric relation. For a face centred cubic pack this is given as

$$\varepsilon = 1 - \left( \frac{\pi}{6} \right)$$
and for close hexagonal as

\[ \varepsilon = 1 - \left( \frac{\pi}{\sqrt{32}} \right) \]

The porosity of most concern to packed beds is the bulk average porosity as described. We have discussed the fact that a high aspect ratio bed is random and disordered in structure, and due to this its porosity can vary quite considerably throughout the bed. Conversely, in a high aspect ratio bed there is little variation in porosity throughout the bed. Due to the porosity's simple volume fraction relation, determining an experimental value for porosity is relatively simple. Water displacement is the traditional method, where the volume of the confining container (V) is measured. Water is added to the container filled with the particulate matter filling the void volume and as a result the volume of water entrained is equal to Vc. However, this method is susceptible to inaccuracies from entrained air and wetting issues associated with porous particles. Other methods are also possible, such as non-invasive methods such as magnetic resonance imaging and X-ray computed tomography. However, these methods suffer from resolution issues resulting in questionable values of void volume, Vv.

**Packed beds Reynolds Numbers:**

As with pipe flow, the flow through packed beds can also be slackly categorized by the Reynolds number, but this is complex further by the presence of several forms of Reynolds number, based on changed parameters and length scales and each with unique perilous values for the onset of turbulence. In various applications of packed beds the Reynolds number is defined as

\[ \text{Re}_{dp} = \frac{\rho Ud_p}{\mu} \]

where the scaling length is simply the particle equivalent diameter, and this is therefore known as the particle Reynolds number. We can see that this equation is solely dependent on the properties of the fluid and the particle diameter and makes no reference to the bed porosity, \( \varepsilon \). Experimentation has shown that a bed can be loosely packed or densely packed and this can be represented by a large or small value of porosity respectively. Based on this equation and experimentation, a new established set of values for critical flow are formed, based on the particle Reynolds number where the flow can be characterized as laminar (\( \text{Re}_{dp} < 10 \)), transitional (10 < \( \text{Re}_{dp} < 300 \)) or turbulent (\( \text{Re}_{dp} > 300 \)).

**Literature Review:**

Performance of man and weapon system get adverse effects in harsh environment of desert, various times, leading to letdown of critical equipment’s. Use of PCM can provide practical solutions to many of these problems. Defense Laboratory, Jodhpur (DLJ) had taken up a R&D program to progress PCM-based yields to meet needs of Armed Forces. Present paper describes status of science and technology of PCM along with materials and products developed at DLJ. PCM is very vital topic for more innovations, because this material can be attractive for more special applications. This material has wide range of applications and it can be enlarged by enhancing the PCM by adding some proper additives [3]. This paper presents results of an innovative system for the temperature control in the interior section of a immobile automobile facing the solar energy from the sun. A very thin coating of PCM inside a pouch located in the ceiling of the car in which the heating energy is captivated and released with melting and solidification of phase change material. As a consequence the temperature of the car interior is kept in the relief condition [7].

Latent heat storage in a Phase Change Material (PCM) is very much impressive because of its high storage density with small temperature fluctuate. It has been demonstrated that, for the growth of a latent heat storage system. The choice of the PCM plays a vital role in addition to heat transfer mechanism in the PCM. Latent heat storage can be consummate through solid-liquid, liquid-gas, solid-gas, and solid-solid phase transformations, but the only two of real-world attention are the solid-liquid and solid-solid. Of the two real-world systems, the solid-liquid system is the most considered and most commonly commercially available. Solid-solid systems show much potential, but are only recently being intentional and most commonly commercially available. Many phase change materials (PCMs) have been considered for real-world use. This paper is a collation of much of real-world statistics on different PCMs and system developed based on latent heat storage expertise [2].

This exertion examines experimentally the performance of a thermal energy storage unit with phase change material captured in cylinders. Air is the heat transferral fluid that flows acrossways the tube banks to charge and discharge the storage system. The study analyses the storage system in terms of its storage size and the heat transferral rate to the phase change material. The aim of the examination is to offer a solid ground for climbing...
up and execution on solar housing domestic heating uses [6]. The use of a latent heat Eutectic aluminum silicon alloy, AISi12, is a striking phase change material because of its temperate melting temperature, high thermal conductivity, and high heat of fusion. A model thermal energy storage test attire has been built and tested as to better recognize the behavior of latent heat thermal energy storage system. A mathematical prototypical model was developed to predict the performance of such a heat storage unit. The model was compared with the behavior of the test attire during discharge. The model proved to simulate the latent heat thermal energy storage with rational accuracy. It is suggested that more accurate material property data be acquired and that the thermal energy storage test rig be modified as to improve readings [5].

Storage arrangement using phase change materials (PCMs) is an active way of storing thermal energy and has the benefits of huge-energy storage density and the isothermal landscape of the storage process. PCMs have been broadly used in latent heat thermal storage schemes for solar engineering, heat pumps, and spacecraft thermal control applications. The uses of PCMs that melt and solidify at a extensive range of temperatures, making them striking in a numeral figure of applications. This paper also recaps the investigation and analysis of the existing thermal energy storage systems integrating PCMs for use in different applications [1]. The composites can be made into mortar which is able to obey to the surface of building structure and captivate the fire heat. This aims to study the end product of the composites on the fire conflict building structure [4].

Energy storage methods:

There are several forms of energies and their storage approaches or mechanisms have been described below. Atul Sharma et al. [1] defines in their review paper on, thermal energy storage with phase change materials and uses, about diverse type of energy storage methods and their mechanisms. In this paper main importance is given to the latent heat storage method to accumulate solar thermal energy.

Thermal energy storage:

Thermal energy can be accumulated as a change in interior energy of a material as sensible heat, latent heat or thermochemical or mixture of these. Sensible heat storage is due to temperature modification of material while latent heat storage is due to the phase alteration either it is solid-liquid, liquid-gas or solid-solid.

Composite phase change materials:

Bhatt et al. [11] presents nine utmost suitable PCMs for thermal energy storage device. They studied thoroughly about sixty PCMs and select most suitable PCMs based on the assets like thermal conductivity, heat of fusion, melting point and density. For the improvement of storage capacity and altered properties of phase change materials for the suitability of thermal energy storage device. Moussa Aadmi et al. [12] present the composite PCMs, epoxy resin paraffin wax with melting point 27°C as a new energy storage system. Ahmet Sari et al.[13] defines the thermal properties of blends of Polyvinyl alcohol(PVA)-stearic acid(SA) and Polyvinyl chloride(PVC)-stearic acid(SA) as form stable phase change material for thermal energy storage. In the mixture, SA has a purpose of storing latent heat of fusion during its solid-liquid phase change while the polymer (PVC or PVA) acts as a supporting material to avoid melted SA leakage because of its structural power. A multiplicity of polymer matrices are available with a large range of chemical and mechanical properties [4].

Research Gaps in Literature Review & Future Research Directions:

The literatures revised till have a wide range of gaps which are to be talked in the upcoming years with focused allegiance so as to enhance the perception of Thermal Energy Storage Unit in order to bond a gap between the present and past research. Authors hereby proposed some vital directions in Thermal Energy Storage Unit research: Material durability tests should be conceded out to comfort the long-term thermal cycling performance of the TES device. Before commercialization of the product, the latent heat TES has to show dependability and durability closely corresponding the average lifespan of a vehicle. To further improve the performance of the latent heat TES device, compared to increase the cooling water flow rate which would require a larger pump and greater power, this method could be more economical. After hard review on phase change material, a conclusion must be drawn that future best suitable PCMs are composites which have the improved properties in comparison to any single phase PCM.

Conclusions:

The following conclusions are concluded from the present study:

1. The prime application of the latent heat TES devices is to store excess heat from an automobile engine during its operation and to deliver the stored energy to warm up the engine apparatuses in cold weather and at start.
2. Composite PCMs are the constituents that have the enhanced belongings like thermal conductivity, heat of fusion, density and melting point in appraisal to single PCM like paraffin wax etc. So, if serious consideration will be given to composite phase change materials then a better and the most efficient thermal energy storage unit can be made.

3. Latent heat thermal energy storage arrangement accumulate 6-17 times more heat than sensible heat thermal energy storage material. Choice of phase change material and its compatibility with the containment where PCM captured is the main issue to design the most efficient thermal energy storage unit.

REFERENCES