Experimental Study of Heat Storage and Heat Elimination in Packed Bed using Nylon 6 Spiral Balls

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Abstract

In the spectrum of renewable energy solar energy has enormous capability. Presented work elaborates construction of a system which has the ability to accumulate radiation radiated by the sun while the sun time is on and deliver space heating during night by moderately discharging it for purpose of control volume heating and radiation drying application. In accordance a parametric evaluation has been recorded on the basis of alpha numeric equations for the substance Nylon-6 reservoir working as a [PEC] for soaking heat under 4 different temperatures is embedded in packed i.e., 30°c, 35°c, 40°c, 45°c and 3 diversified flow gradients of mass i.e. (0.285 kg/s, 0.387 kg/s and 0.486 kg/s). Considering the consequences optimum charge period at 30°c, 35°c temperature zone with favourable flow gradient 0.486 kg/s has been attained 0.75 Hr and 0.834 Hr and ideal dischargeduration at 30°c, 35°c temperature zone with favourable transfer gradient 0.285 kg/s has been attained 2.2 Hr and 2.35 Hr in case of control volume heating application. The optimum charge period at 40°c, 45°c temperature zone with favourable flow gradient of 0.486 kg/s has been attained 0.95 Hr and 1.05 Hr min and ideal discharging period at 40°c, 45°c temperature zone with favourable flow gradient of 0.285 kg/s has been attained 147 min and 153 min for insolation radiation drying application provided minimum 3 [PEC] having characteristic dimension of bed 1.6 m, which is adequate for 8 hours interrupted supply when the atmospheric temperature is very low, for control volume reheating end solar radiation drying implementation..

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1. Introduction

Packed bed has the ability to store insolation energy in the state of (thermions) Thermal energy and utilize the heat of solar radiation, although it's major downside that solar radiation cannot be collected every time. The factors on which it depends are weather and condition of climate and affected adversely due to limited sun time of earth. To overcome this downside, most appropriate technique is to accumulate the insolation energy in the state of heat inside the charging bed embedded within suitable medium like Nylon-6 for getting 24 hrs uninterrupted heat for control volume heating and radiation drying application.

Energy stored directly whenever solar radiation is accessible and consume it accordingly in the unavailability of radiation from sun. Schumann's research was the inspiration for this system of accumulating the insolation energy. Afterwards huge progress has been done in the domain of storing thermal energy. Compressed air has been used to accumulate thermal energy. With considerable modernization in technology, a modern material: Phase changing material (PCM), observed commendable use in such type of storages in encapsulated form. Even though PCM, these are great at their function, PCM's increments the price of entire assembly by many folds. Thus, more economical options were used by researchers like rocks and waste material. Modern energy systems, provides thorough knowledge over essential perspectives of power accumulation systems that are crucial in the designing and implementation of power systems. BaylinF,. executed a thorough research to introduce a collective study of low degree of temperature thermion power accumulation apparatus and finding their implementation in the field of renewable energy. It examines numerous prospects also delivers an analysis over adoption of PCM accumulators and unused energy regeneration. Multiple data sets on latent energy depository substances, PCM has been re-evaluated determine the characteristics of PCM storage like preferable substances to be utilized. Also, the particularized assessment has been thoroughly investigated to obtain a wide understanding. Analysis also regarded of papers to evolve a preferable understanding about thermos fluidic characteristics of flow passing via [PEC] which includes flow mechanics, flow of air, transmission of heat and its instantaneous response. All these findings have been cautiously examined all overusing simultaneous correspondence to sensible and latent energy accumulation systems. Parametric evaluation was organized for pressure variation, porousness, appropriate implementation of these kind of accumulation apparatus, temperature. As described earlier, post evaluation of these outcomings of all the research work, it was perceived that economical thermal energy accumulation apparatus are appropriate. Hence, the upcoming segment of work will exclusively be concerned about sensible heat depository apparatus. Maximum of these apparatus have storage chambers filled with Rock bed. Rocks have ideal properties for storing heat. Supplementary exploration has been performed to recognize other characteristics of sensible thermal energy depository systems i.e., Heat transfer, dynamic response, pressure drop, flow rate, design, and their performance. On comparing these outcomings with a polyethylene-based accumulation system, it was recorded that maximum characteristics of flow doesn’t depend on the selected material rather depending upon physical characteristics like porosity, size, flow conditions like rate flow and heat relocation etc. Also, it was observed that the thermionic characteristics and accumulation system alters with accumulating media and connecting these conclusions with different accumulating materials. The suitable material selected to perform this experiment was Nylon-6. Design of system was done by inspecting preceding works. To make an adaptable apparatus for space heating model, a few space heating apparatus have also been evaluated. The motive of presented research paper is to hand out a less complex and economically feasible apparatus for thermic energy accumulating system where Nylon-6 is the medium to stockpile the energy. Objectives of study are as follows. Optimization of fluid flow under consideration under four distinct working temperatures: 30°c, 35°c, 40°c, 45°c. Optimization of charging time and gradient of charging for control volume heating application. Optimization of gradient of discharge and time of discharge for control volume heating application. Optimization of the charging gradient and charging period for insolation drying application. Optimize the gradient of discharge and period for discharging in radiation drying application. To optimize heating [PEC] characteristics like1). Length of bed. 2). Diameter of particle. 3). Batch size of beds. 4). Transportation traits of bed.

2. Experimental details

For air-based radiation heating systems packed bed are highly appropriate storage units. Materials such as Nylon-6 has been used to store heat in [PEC] as illustrated in Fig. 2. Solar radiation air heater is used to charge the packed bed at daytime when adequate magnitude of solar radiation is present. At night when solar radiation is absent bed is charged by electric heater. The heat accumulated during sun time is used as reservoir of heating during absence of sun. [PEC] acts as a reservoir to store heat. A structured layout of [PEC] sensible heat accumulation unit shown in Fig.1 The heater as shown in Fig. 3 of cylindrical shape as illustrated in Fig.3 is formed by an Iron pipe having length 1 m with screws and wires of Nichrome. The hollow heater has a peripheral diameter of 106mm and internal diameter of 96mm. A coconut fibre rope is wrapped around it bonded by plaster of Paris (Calcium sulphate hemihydrate) to encapsulate it. The depth of insulation is about 80 mm, which provides a heavy insulation on the free surface of pipe. Heat is dispensed to the [PEC] from cylindrical heater by the help of blower Fig.4. The emplacement of heater is at a distance of 2.7 m from the [PEC] which is transmitting energy to the [PEC]. Bed diameter D_{bed}= 0.10m, Bed length L_{bed} = 1.6m while the heat accumulating substance is placed inside it. Current research criteria is concerned on storage of insolation energy In the state of thermions and it's utilization for control volume heating and radiation drying application In the mountain and plain regions.

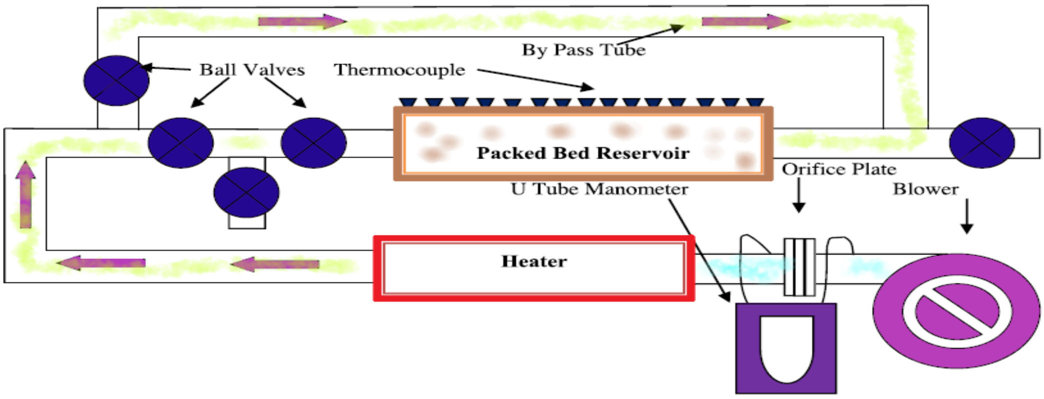


Figure Number 1: Diagram of [PEC]

Figure Number 2: Accumulating substance (NYLON-6)

Figure Number 3: Exterior appearance of heating chamber having outer coating of coconut fibre with POP

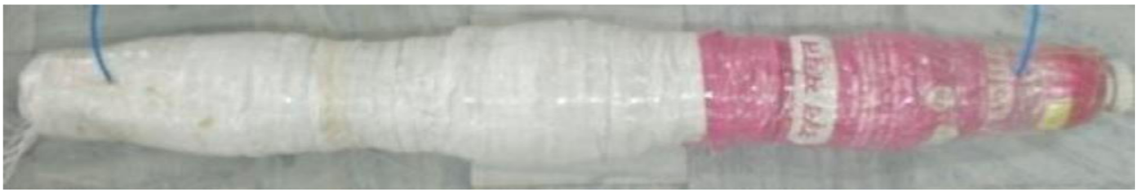


Figure Number 4: Diagram of [PEC]

Temperature selection criteria has been set with the consideration of human and crop comfort. The temperatures selected for control volume heating application are 30°c and 35°cand for radiation drying application are 40°c and 45°c.Markus Hanchen's past research has been utilized to select appropriate value of flow rate.Multiple measuring instruments such as variac, temperature indicator, cylindrical heater and electrical connections has been installed at appropriate places on the experimental setup. The aerator draws the ambient air and transfers it to the [PEC].

Before starting the process of heating the packed bed each thermocouple was checked by making some adjustment in the corresponding selector switch position. Before performing the experiment, all necessary precautions were taken. To prevent leakage at joints M-seal and Araldite were used. The adjustment of voltage was done by variac.

Steady state was obtained after running the heater for 1.5-2 hr. After reaching at static state the temperature at various locations of Nylon-6 balls and empty air zone was observed by using various thermocouples and data was observed by data acquisition system.

A gate valve was mounted at the blower two alter the flow rate. Multiple readings were taken at distinguished flow rate and temperatures to understand the behaviour of bed material under various conditions.

3. Governing equation

The experimental values are used to establish the Nusselt number for packed bed. Experimentally derived value of Nusselt number has been collated with values acquired from Dittus-Boelter equation (Nun).

Nun = 0.23Re0.8Pr0.4 (1)

- Bed Porosity P bed

Porosity of bed is determined on the base of geometric characteristics and quantity of laminas of wire screen.

$$P = \frac{V_t - V_s}{V_s} = \frac{P_t^2 D - [{}^{\pi}/_{2}(d_w^2)P_t]N}{P_t^2 D} \quad (2)$$

- Mass flow rate, m

Following equations are used to find flow rate.

$$m = C_d A_2 \left[\frac{2\rho\Delta P_\circ}{1-\beta^4}\right] \quad (3)$$

Here Cd = discharge coefficient, Ao =orifice area, β = fraction of orifice to pipe diameter, ρair= air density. The orifice plate is calibrated with reference to a standard Pitot tube and its value is observed to be 0.62. Orifice plate area, A2

- Reynolds number, Re

Calculation of Reynolds number can be done by following equations

$$R_e = \frac{\rho v D}{\mu} \quad (4)$$

Here, characteristic length(m)is denoted by L*, μ denotes the dynamic viscosity coefficient (N.s/m2 or kg/m*s) of fluid, ρf is the density of working fluid (kg/m3) and V* is the working fluid velocity (m/s).

- Nusselt number (Nus)

Nusselt number (Nus) is a trait termed in the honor of Wilhelm Nusselt, having no dimension. Mathematical statement for this expression is the fraction of transfer of heat by convection with regard to transfer of heat by conduction inside the fluid across the boundary. The component of conductive heat is observed by imagining a hypothetical fluid at rest and in contiguity with given working fluid. Convectional transmission of heat is measured by the same process.

$$Nu_s = \frac{H_{cond}}{H_{conv}} = \frac{\text{convective heat transfer coefficient}}{\text{conductve heat transsfer coefficient}} \quad (5)$$

Here, Lo = Specified length, KCo = Thermal conductivity of fluid, h = coefficient of convective heat transfer.

- Average bed temp (Tavg)

Mean temperature of the [PEC] has been calculated by taking an assumption that the temperature sensed by thermocouple is the mean temperature of whole bed. Following calculations has been done:

$$Tavg= \frac{t_1+t_2+t_3+t_4+t_5+t_6+t_7+t_8+t_9+t_{10}+t_{11}+t_{12}+t_{13}+t_{14}+t_{15}+t_{16}}{16} \quad (6)$$

Mean air temperature ΔT

$\Delta T = t_{\text{temperature of surface}} - t_{\text{temperature of fluid}}$

- Properties of air during charging and discharging

Necessary properties are density (ρf), specific heat (Cph), dynamic viscosity (μd) observed at a big scale mean temperature under any moment of operation. the mean or average off solid and air temperature at a particular instant is termed as bulk temperature.

$$Tb = \frac{T_{solid} + T_{air}}{2}$$

- Heat flux, Q_{fl}

Q_{fl} is the product of, V and I

$Q_{fl} = \frac{V.I}{A_b}$ and $Q_u = mCp(T_0 - T_i)$ (7)

- Coefficient of mean heat transfer

Following equations are used to determine coefficient of mean heat transfer (Hch) between air and the bed.

$(H_{ch}) = \frac{Q_u}{\Delta T}$ (8)

The variation of temperature between packed bed and air along the length and depth of bed is denoted by ΔT. The surface area of heat transfer, A_{ht} is calculated with the help of given relation.

$A_{ht} = \pi.d.L.A = \frac{4A_f L(1-P)}{D_w}$ (9)

4. Result and Discussion

The effect of 4 differentiating air channel temperatures 30°C, 35°C, 40°C and 45°C and the 3 mass transfer rate of air are 0.285 kg/s, 0.387 kg/s, and 0.486 kg/s with 3 unlike particle dimensions of 1 cm, 2 cm and 2.5 cm on charging and bring out the profile of [PEC].

It is determined for Nylon-6 material. Here the only ideal outcomings has been released for optimum functioning specification like charging mass transfer gradient of 0.486 kg/s, discharging mass transfer gradient of 0.285 kg/s and particle dimensions of 1cm, length span of bed 1.6m and bed diameter of 0.1m and forms the porosity of 0.12.

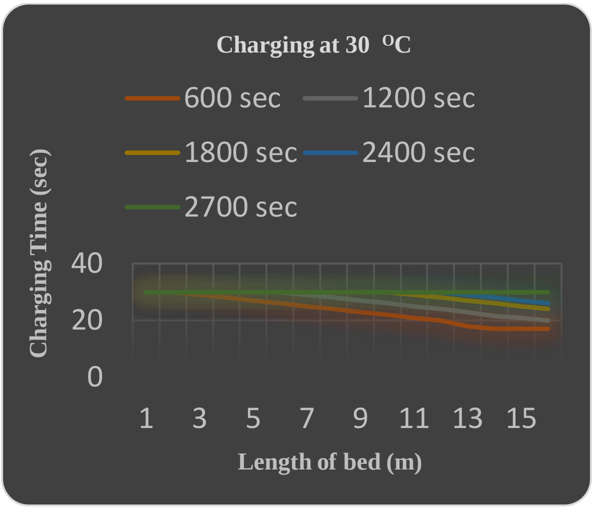
4.1. Characteristics during charging and discharging of [PEC] at 30°c and 35°c

At starting stage, the intake air temperature was constrained at 30°C in the initial series of experimental study and 35°C during the next series of experiments by a heater and flow limit fixed at 0.486 kg/s. As the hot air passes through the [PEC], and then passed to the Nylon-6 placed in the [PEC], i.e. Nylon-6, resulting a sudden increment in[PEC] temperature. The curve of temperature of the [PEC] is displayed on a gap of 10 minutes time gap. The bed temperature decreases as the experiment progresses beside the dimension span of the [PEC] aside from the source of air intake. The data is represented on the curve represents that the [PEC] takes 0.75 Hrs and 0.834 Hrs to attain a unvaried temperature of 30°c and 35°c. The after effect reflects that the flow rate 0.486 kg/s gives fastest charge time of 0.75 Hrs at 30°c intake temperature and 0.834 Hrs for an intake temperature of 35°c, as illustrated in Fig. 5, following by 0.387 kg/s at 1 Hrs and 0.285 kg/s is the slowest at 1.05 Hrs at an intake temperature of 35°c. While discharging, ambient air having temp `27°c circulates through the [PEC]. As it propagates through the [PEC], it slowly accumulates the energy from the heat storage materials, i.e., Nylon-6, embedded in the [PEC] and its temperature rises. This process of transfer continues until the ambient air can no longer accumulates energy from the [PEC], then the [PEC] will be discharged. The ideal temperature curve of the Nylon-6 embedded in the bed has been accomplished for a flow gradient of 0.285 kg/s at 30°c and 35°c at intake temperature of 27°c. It is observed in the data that the ideal [PEC] is totally discharged in 2.45 Hrs and 2.55 Hrs for the temperature of the charged [PEC] at 40°c and 45°c as is illustrated in Fig. 6. It is distinctly observed from the outcomings that increasing flow rate decreases the discharge period. The time of discharge for m = 0.387 kg/s is 1.98 Hrs and 2 Hrs for the charged [PEC] temperature at 30°c and 35°c, that is much less in case of m=0.285 kg /s. The discharging period again diminishes for m=0.285 kg/s with respect to the period of discharge for flow gradients of 0.486 kg/s and 0.387 kg/s, i.e., 2.2 Hrs and 2.35 Hrs for [PEC] at temperature 30°c and 35°c in order. The biggest required discharged profile was achieved by the m=0.486 kg/s, i.e.,2.45 Hrs and 2.55 Hrs for [PEC] at 40°c and 45°c as illustrated in Fig.5, Fig.6.

4.2. Characteristics during charging and discharging of [PEC] at 40°c and 45°c

Here, the intake air temperature is sustained at 40°c for the next group of analysis and 45°C for the further group of experiments, the plot for charging of the Nylon-6 within the [PEC] must be constrained on air gradient of 0.486 kg/s. Outcome show the temperature curve of the [PEC] throughout the time of charging for flow gradient of 0.486 kg/s and intake air at 40°c and 45°c temperature. It can be analysed by the illustrated fig.7 that the optimal time of charge after the [PEC] is fully charged is almost at 0.95 Hrs and 1.05 Hrs for supplied temperature of 40°c and 45°c. it is conjointly determined through the experimentation, that outcome for max temperature outstretch about 40°c and 45°c gradually comparison at the intake temp of 30°c and 35°c after that it achieves steady temp of 40°c for the previous group of experiment and

45°c for the further group of analysis. As flow rate of air increments, the bed charge time get reduce. This outcome is clearly observed in the outcomes, through which the flow gradients is 0.285kg/s and 0.387kg/s individually. The charging time has seen from the illustrated figure for 40°c was 0.95 Hrs and 1.05 Hrs of two different flow gradients and for a supplied temperature of 45°c. As previously determined the ideal result for charging the bed, the temperature of intake air is 40°c and 45°c at which flow gradient is 0.486 kg/s at 0.95 Hrs and 1.05 Hrs illustrated in Fig.8. When charging was completed at a temperature of 40°c and 45°c, the [PEC] release cycle considered for different rate of flow. The outcome analysis of the bed of temperature profile for different rates of mass flow at the time interval of discharging period and the time variant shows that optimal mass of stream circulates at charging and discharging durations. The outcome shows that, In the temperature bed profiles for the flow gradient of 0.486 kg/s and the air intake temp. is 40°c and 45°c.



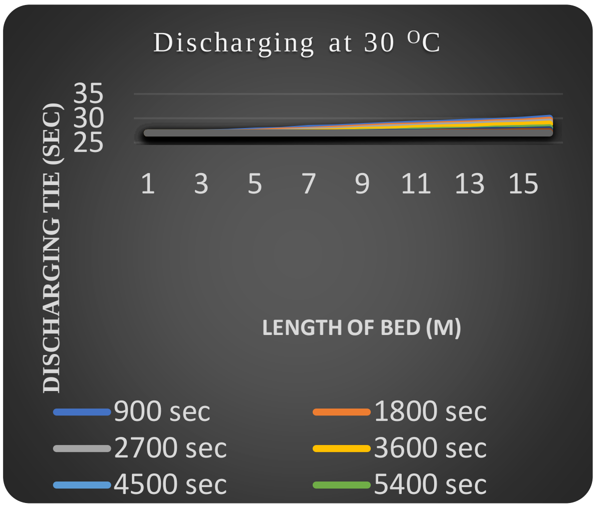
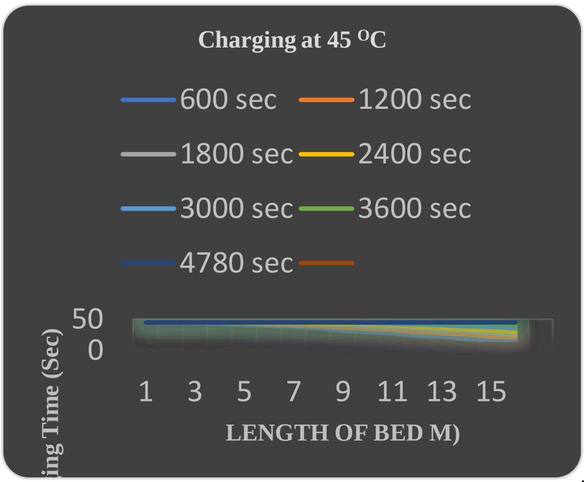


Figure Number 5: Temperature curve when the [PEC] is charged with $m_f = 0.486$ kg/s provided input temperature is 30 °C

Figure Number 6: Temperature curve when the [PEC] is discharged with $m_f = 0.285$ kg/s provided output air temperature 30 °C



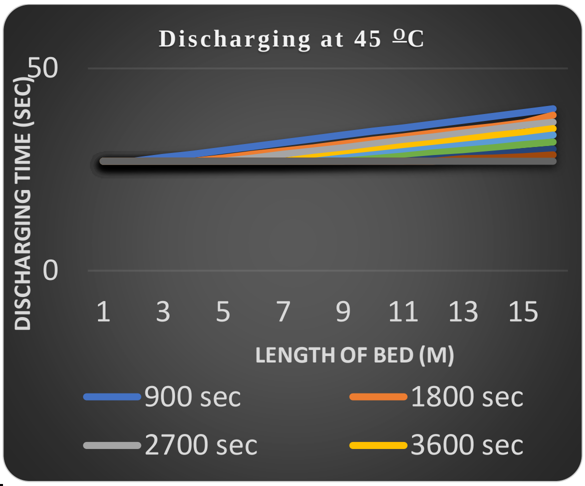


Figure Number 7: Temperature curve when the [PEC] is charged with $m_f = 0.486$ kg/s provided input temperature is 45 °C

Figure Number 8: Temperature curve when the [PEC] is discharged with $m_f = 0.285$ kg/s provided output air temperature is 45 °C

During the discharging duration the ideal air at a temp. of 27°c, passing from the [PEC] with a flow gradient of 0.285kg/s, 0.387kg/s and 0.486kg/s at air intake temperature of 40°c and 45°c, because of greater rate of flow, transfer of heat increases between the air to solid material, heat is collect at very high speed in the bed, now with the low flow gradient, the heat transmission rate reduces between the air and solid and the bed heat releases at a gradual rate, therefore it enhances the charge and discharge time. The [PEC] temp. goes down at 27°c because of complete discharge from the bed when heat of charged air leaves the bed. The bed is discharged thereafter 2.45 Hrs and 2.55 Hrs with flow gradient of 0.486kg/s for an ambient air temp. of 40°c and 45°c. While the air intake temp. was 27°c. The bed discharge time lowers as the flow gradient increases. The flow gradient of 0.387kg/s, and 0.486kg/s with respect to 0.285kg/s, exhibit a reduction in discharged time of 2.55 Hrs and 2.35 Hrs of 40°c temperature of bed charged at 2.25 Hrs and 2 Hrs as a charged air of bed of temp. of 40°c, respectively. As illustrated in figure 8, the time of discharging bed for maintaining a temperature of charged bed at 40°c. When the flow gradient is 0.285 kg/s in 2.34 Hrs, the best outcome for discharged bed is keep the temperature of charged bed at 45°c as illustrated in fig. 8.

4.3. Impact of flow gradient of air on charging and discharging of [PEC]

The time of charge reduces when the rate of air flow increases. This implies that the charging of bed with a higher the rate of flow takes less time than the charging of bed with a steady charging air temperature. The charging of bed profile the time rise as the flow gradient of air is ascended. This means that it takes longer to charge the [PEC] with a lesser flow gradient. The temperature of the air being discharged is kept constant.

5. Conclusions

The experimental analysis is attained at 4 unlike temperatures i.e., 30°c, 35°c, 40°c, and 45°c and 3 diversified flow gradients - 0.285kg/s, 0.387kg/s and 0.486kg/s with three unlike particle size 1cm, 2cm, 2.5cm. It appeared that while temperature is kept at 30°c, 35°c, 40°c, and 45°c the mass transfer provided 0.285 kg/s the time of charging is increasing and discharging the time is also increasing. When air is provided at mass transfer of 0.387 kg/s the charging and discharge period shows mean rate. Lastly passing the hot air is at various temperatures i.e., 30°c, 35°c, 40°c, and 45°c at the transfer gradient of 0.486kg/s, the charge time decreases, and the discharge time also decreases. So for ideal performance of setup, when 0.285kg/m^2-s is the discharge period and 0.486 kg/s is charging time taken for ideal charge and discharge process .The current project can be implemented in control volume heating and radiation drying process in high altitudes as well as in low altitudes, the model that has been demonstrated in current analysis can be later exploit for estimation of thermal and accumulation action of (multiuse/composite) substances and phase changing substances etc.

The key points obtained in the experiment are as follows: -

- In the [PEC] with the higher flow gradient, the charging period expands and with the lower flow gradient the discharging period also expands.
- Charging time diminishes with lower flow rate and time of discharge diminishes with higher flow rate.
- With the increase dimension of particle in [PEC], the charge period increases, and time of discharge diminishes.
- Pressure drop decreases with the increase size of particle of packed bed.
- For ideal charging rate of 0.486kg/m^2-s the ideal duration of charge is 0.8, 0.916, 0.95, and 1.05 Hrs for the various temperatures like 30°c, 35°c, 40°c, and 45°c.
- For ideal charging flow rate of 0.285kg/m^2-s the ideal charging time observed as 0.75, 0.834, 2.25, and 2.34 Hrs for the various temperatures like 30°c, 35°c, 40°c, and 45°c.
- The working parameters for charging – discharging a unit bed between the temperature raging 30°c - 35°c requisite the charging gradient 0.486kg/s, discharge gradient 0.285kg/s with time of charge 0.75-0.834 Hrs and discharge period between 2.2-2.35 Hrs, but the working guidelines for charge and discharge is 3 to 4 [PEC] are required for space heating.The length of [PEC] taken is 1.6 m which is filled with Nylon-6 material of 1cm diameter particle, time of charge is 3 – 3.5 hour and time of

discharge is 7.5 – 8 in night time with the charging gradient of 0.486kg/s, discharging rate 0.285kg/s.

- The working parameters of charging – discharging a unit bed between the temperature of 40°C - 45°C requisite the charging rate 0.486kg/m^2-s, discharging rate 0.285kg/m^2-s with time of charge 45 - 50 min and time of discharge between 132-141 min, but the working guidelines to charge and discharge 3 to 4 [PEC] are required for space heating application.
  The bed length taken is 1.6 m which is filled with Nylon-6 material of 1cm diameter particle, time of charge is 3 – 3.5 hour and time of discharge is 7.5 – 8 in night time with the charging rate of 0.486 kg/s , discharging rate 0.285 kg/s.

References

[1] TEW Schumann, Heat transfer: a liquid flowing through a porous prism, Heat Transfer (1929) 405–416.

[2] E Barbour et al., Adiabatic compressed air energy storage with packed bed thermal energy storage, Appl. Energy 155 (2015) 804–815.

[3] MNAHawlader et al., Encapsulated phase change materials for thermal energy storage: experiments and simulation, Int. J. Energy Res. 26 (2) (2002)159–171.

[4] MHänchen et al., High-temperature thermal storage using a packed bed of rocks - heat transfer analysis and experimental validation, Appl. Therm. Eng.31 (10) (2011) 1798–1806.

[5] Becattini, Viola, et al. ‘‘Experimental investigation of the thermal and mechanical stability of rocks for high-temperature thermal-energy storage."Applied Energy, vol. 203, 2017, pp. 373–389.

[6] J. Frijns et al., The potential of (waste)water as energy carrier, Energy Conversation Manager 65 (2013) 357–363.

[7] A. Gutierrez et al., Advances in the valorization of waste and by-product materials as thermal energy storage (TES) materials, Renew. Sustain. Energy Rev. 59 (2016) 763–783.

[8] H.P. Garg, S.C. Mullick, A.K. Bhargava Solar thermal energy storage. D. Reidel Publishing Co; 1985.

[9] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storagewith phase changematerials and applications, J. Renew. Sustain. Energ. Rev. 13(2) (2009) 318–345.

[10] Parfait Tatsidjodoung, Nolwenn Le Pierres, Lingai Luo, 2012, A review ofpotential materials forthermal energy storage in building applications,Renewable and Sustainable Energy Reviews, Elsevier, Vol.18, pp. 327-349.

[11] CCFurnas, Heat transfer from a gas stream to a bed of broken solids, Ind. Eng.Chem. J. (1930) 721–731.

[12] JB Wagstaff, E.A. Nirmaier, Air flow in beds of granular solids, Ind. Eng. Chem.47 (1955) 1129–1135.

[13] PJ Hughes, S.A. Klein, D.J. Close, Packed bed thermal storage models for solarair heating and coolingsystems. Transactions of the ASME, J. Heat Transfer 98(2) (1976) 336–338.

[14] FW Schmidt, J. Szego, Transient response of solid sensible heat thermalstorage unit's using singlefluid. Transactions of ASME, J. Heat Transfer 98 (3)(1976) 471–477.

[15] Riaz, M. 1977. Transient analysis of packed bed thermal storage systems. SolarEnergy Journal 21:123-128.

[16] Balakrishnan, 1979. Heat transfer in packed bed systems - A critical review.IndEngChem (Process Des Dev). 18(1): 30-40.

[17] Puri, VM 1979. Status and prospects of local solar heating and coolingsystems, Energy Journal, Vol. 4, pp. 769-774.

[18] HP Garg, B Bandyopadhyay, V.K. Sharma, Investigation of rock bed solarcollector cum storage system, Energy Con. & Mgmt. 21 (1981) 275–282.

[19] P Chandra, DH Willits, Pressure drop and heat transfer characteristics of airrock bed thermal storage systems, Sol. Energy 26 (6) (1981) 547–553.

[20] AESaez, BJ McCoy, Dynamic response of a packed bed thermal storagesystem-A model

for solar air heating, Solar Energy J. 29 (1982) 201–206.

[21] AShitzer and M. Levy 1983. Transient behavior of a rock bed thermal storagesystem subjected to variable inlet air temperature: analysis and design. SolarEnergyEng (ASME Trans). 105: 200-6.

[22] Adnan M Waked, 1985, Solar energy storage in rocks, Solar & WindTechnology, Vol. 3, No. 1, pp. 27-31.

[23] H Salt and KJ Mahoney, An active charge, passive discharge floor spaceheating system, Solar Energy Vol. 38, No. 1, pp. 25-31.

[24] MMSorour 1988. Performance of small sensible heat energy storage unit.Energy Convers Manage J. 28(3): 211-7.

[25] SL Aly and AI El-Sharkawy 1990. Effect of storage medium on thermalproperties of packed bed. Heat Recovery Syst CHP. 10(5/6): 509-17.

[26] KSagara, N Nakahara, Thermal performance and pressure drop of rock bedswith large storage materials, Sol. Energy 47 (3) (1991) 157–163.

[27] Giorgio G De, SFumagalli, GRizzi, VK. Sharma, Design, development andexperimental performance of solar collector-storage system for space heatingapplications, Energy Convers. Mgmt 31 (1) (1991) 75–93.

[28] VK Sharma, GRizzi, HP Garg, Design and development of an augmentedintegrated solar collectorwith rock storage system for heating applications,Energy Convers. Mgmt. 31 (4) (1991) 369–377.

[29] SA Mahmoud, Experimental study of a solar space heating model usingJordanian rocks for storage, Energy Convers. Mgmt. 33 (9) (1992) 833–842.

[30] TM Sanderson, G.T. Cunningham, Packed bed thermal storage system, Appl.Energy 51 (1995) (1995) 51–67.

[31] C Choudhary, PM Chauhan, HP Garg, Economic design of a rock bed storagedevice for storing solar thermal energy, Sol. Energy 55 (1) (1995) 29–37.

[32] MA Al-Nimr, M K Abu-Qudais, MDMashaqi, Dynamic behavior of a packedbed energy storage system, Energy Convers Manage. 37 (1) (1996) 23–30.

[33] A Hamdan Mohammed 1998. Investigation of an in-expensive solar collectorstorage system. Energy Convers Manage. 39(5-6): 415-20.

[34] ECNsofor, A Adebiyi George, Measurements of the gas particle convectiveheat transfer coefficient in a packed bed for high temperature energy storage,Exp. Thermal Fluid Sci. 24 (2001) 1–9.

[35] Chen Wei, Wei Liu, Numerical and experimental analysis of convection heattransfer in passive solarheating room with greenhouse and heat storage, Sol.Energy 76 (2004) (2003) 623–633.

[36] PTatsidjodoung, Pierres Le Nolwenn, L Luo, A review of potential materialsfor thermal energy storage in building applications, Renew. Sustain. EnergyRev. 18 (2013) (2012) 327–349.

[37] Panwar, K, Murthy, D, S, "Analysis of thermal characteristics of the ball packed thermal regenerator", Procedia Engineering, 127, 1118-1125.

[38] Panwar, K, Murthy, D, S, "Design and evaluation of pebble bed regenerator with small particles" Materials Today, Proceeding, 3(10), 3784-3791.

[39] Bisht, N, Gope, P, C, Panwar, K, " Influence of crack offset distance on the interaction of multiple cracks on the same side in a rectangular plate", Frattura ed Integrità Strutturale" 9 (32), 1-12.

[40] Panwar, K, Kesarwani, A, "Unsteady CFD Analysis of Regenerator", International Journal of Scientific & Engineering Research, 7(12), 277-280.

[41] Singh, I., Bajpai, P. K., & Panwar, K. "Advances in Materials Engineering and Manufacturing Processes".