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Analysis of Cooling Applications for Solar Thermal-Energy-Storage System

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Abstract: This paper presents the experimental setup built to study a Thermal-Energy-Storage System (TESS) based on concrete as packed-bed using air heat-transfer fluid. Thermal energy storage using sensible heat storage materials have gained much interest in the renewable energy storage sector due to its relatively low cost, abundant availability and technical development. The objective of this work is to design, fabricate and test a sensible heat thermal-energy-storage system. This work can be actualized in low-temperature cooling. A use of this work on low-temperature cooling is by utilizing silica gel-water adsorption chiller which can be driven by 55°C of heated water. In this examination, two tests have been completed warmth stockpiling components of various porosities and surface area. The parameters such as porosity and surface area influence heat-transfer by conduction and convection. Also, numerical analysis is being carried out to have a detailed analysis of the problem for varying parameters and to compare with experimental results.

Keywords: Concrete, heat-transfer performance, packed-bed, thermal-energy-storage

1 Introduction

Solid sensible heat storage systems have used storage media such as concrete, rocks, geomaterials and cemented saturated porous media to store solar thermal-energy. Thermal Energy can be stored as sensible heat, latent heat, and thermo-chemical heat [12]. In this process, sensible heat can be stored using liquid media such as water or solid media such as rock, building structure, and ceramics. Latent heat can be stored using inorganic PCM such as salt hydrates or metals, Organic PCM such as paraffin or non-paraffin, eutectics, and composite PCMs. Thermo-chemical heat can be stored using sorption materials such as adsorption or absorption materials and chemically reactive materials.

The sensible Thermal Energy Storage System (TESS) uses the energy released or absorbed when the temperature decreases or increases. According to the physical state of the sensible storage medium, they are classified as solid (rocks, ceramics, plastic foams, concrete and others) and liquid media (water, oil, molten salts, etc.). Latent TESS medium can store or release the same amount of heat as the energy involved during the phase change, that is transition from solid to liquid or liquid to solid states.

A packed-bed storage system consists of a storage tank filled with particles of different shape and size of a given solid material and the heat is charged or discharged by the circulation of a heat-transfer fluid through the free space between the filler particles.

In their work, Donald and John had performed analysis, and obtained experimental results, for the transient response of a packed-bed thermal-storage unit [3]. Their study had analyzed various important parameters such as flow distribution, thermal wall effects, wall-energy losses and void fraction distribution. They had presented results for the behaviour of Prandtl number and Reynolds numbers using non-dimensional analysis.

In a review of sustainable thermal-energy-storage technologies on heat storage materials and techniques, Hasnain had presented his work on space and water-heating applications [4,5]. It is highlighted that, to assist the effective and appropriate design of thermal-storage units, there is a need to generate

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experimental data for the thermo-physical properties in the solid and liquid phases of materials.

Ranjit Singh et al. [13], had presented a detailed review of models for predicting the thermal performance of packed-bed energy storage system in solar air heaters. The mathematical models had been discussed for predicting the thermal performance of packed-bed energy storage system for solar air heaters. The types of models for predicting thermal performance of packed-bed are: i) Two-phase model (Schumann model); ii) Intra-particle conduction and dispersion model; iii) Single-phase Model; iv) Equivalence of Two-phase and Single-phase models; v) Cautier and Farber model; vi) Sagara and Nakahara model; vii) Mumma and Marvin model.

Mawire et al. [11], had presented their work on the simulated performance of storage materials for a pebble bed thermal-energy-storage system. They had presented a simplified one-dimensional single phase model for an oil pebble thermal-energy-storage system, and evaluated the thermal performance of three solid and sensible heat pebble materials such as fused silica glass, alumina, and stainless steel. Their results presented the value of the total amount of energy stored for oil-pebble-bed systems by considering thermal stratification.

Arteconi et al. [1], had presented a review article on state of the art of thermal-storage for demand-side management. The disadvantages for thermal energy storage with errors in sizing the system that affects the payback time, failure in the equipment or control system, the inexperience of operators had been highlighted. They had mentioned that concrete can be used as thermal-storage material due to its high specific heat, good mechanical properties, and resistance to thermal loading, low cost, and wide availability.

Tian and Zhao [15], had reviewed solar collectors and thermal-energy-storage in solar thermal applications. The design criteria, material selection, and different heat-transfer enhancement technologies of various thermal-energy-storage systems such as sensible heat storage, latent heat storage, chemical storage and cascaded storage had been studied.

Kousksou et al. [9], had presented a detailed study on energy storage, its applications and its challenges of several energy storage technologies. The requirement of various thermal-energy-storage system parameters such as energy and power density; storage capacity; monitoring and control equipment; self-discharge; response time; cost and economies of scale; lifetime; efficiency and operating constraints have been identified. Pebble beds are often used for storage mainly due to the reason of low-cost and solid-storage materials are used for low as well as high-temperature thermal-energy-storage system [6].

As highlighted by Hasnain [4,5], 1-5cm of size was maintained in the rock and pebble for industrial applications to store up to 100°C. Singh et al. [6] had suggested that the cost of heat-transfer can be minimized by having direct contact between solid storage and heat-transfer fluid. In this solid storage material, the temperature cannot be maintained at a constant level as it affects outlet temperature of the collector. They had compared the overall performance of the large-size and small size bed storage system elements and concluded that both give same results. Based on economic feasibility, large-size particle storage system was suggested as a better choice. Fused silica glass, alumina and stainless steel are considered as pebble material by Mawire et al. and they had compared the performance of these materials. They concluded that fused silica glass yields best thermal performance when compared to other materials [13].

Kalidasa Murugavel and their team are performing various experiments on thermal-energy-storage techniques and materials [7,8]. They have presented different experimental results showing better thermal performance when using thermal-energy-storage systems.

Lu and Wang [10] had carried out an experimental performance investigation of small solar air-conditioning systems with different kinds of collectors and chillers. For CPC (Compound Parabolic Concentrating) solar collector and single-effect absorption chiller, the solar COP (Coefficient of Performance) of their system can reach 0.24 in sunny weather conditions. For PTC (Parabolic Trough Collector) solar collectors, the solar COP of the solar cooling system is about 0.5. They had observed that, double-effect LiBr absorption chiller is more attractive because of its higher solar COP and better economy.

Ryan Anderson and their team had presented their experimental results and modeling of energy storage and recovery in a packed-bed of alumina particles [14]. In their model, they had included natural convection losses and varying thermo-physical properties and had studied thermal-energy-storage with air as heat-transfer fluid in a packed-bed of alumina [2,16].

2 Sensible Heat Thermal Energy Storage Materials

Salomoni et al. [16], had carried out the development of an appropriate concrete mixing to optimize its chemical-physical properties, durability, and performance at temperatures between 80 and 300°C. The SolTeCa project involves a concentrated solar power plant integrated with the thermal design of a storage module. For TES application, the material used is of low cost with good thermal capacity, stability, and durability under service temperatures. In Table. 1, the properties of solid thermal-energy-storage materials are presented.

Claudio and their team had carried out their work on finite element method modeling of sensible heat thermal energy storage with innovative concretes and comparative analysis with literature benchmarks [2]. Their work focused on sensible heat thermal-energy-storage systems using solid media and numerical simulation of their transient behavior using the finite element method. They had considered various aspects such as high-temperature thermal properties at the repeated storage-element geometry and the storage cycle adopted in their mathematical model and simulation approach. The undesired cyclic thermal stresses in the storage materials in a real module are due to thermal gradients, and they must be avoided to prevent the decrease of thermo-mechanical properties. In Table. 2, the properties of different concrete materials used for storing thermal-energy are given.

Fig. 1: Experimental Setup of Thermal Energy Storage System [TESS]

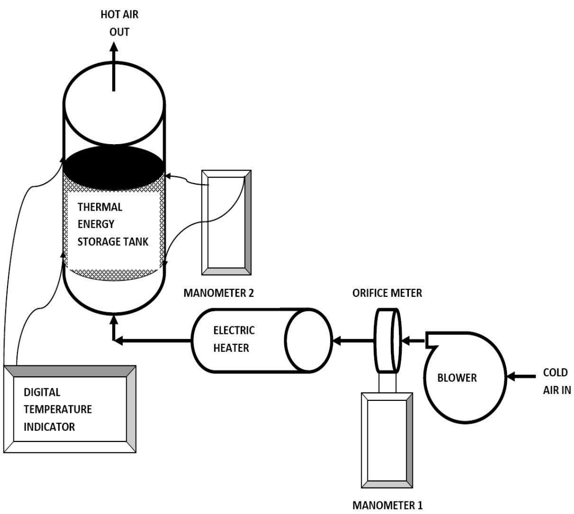


Fig. 2: Schematic diagram of Thermal Energy Storage System

The experimental setup of the thermal-energy-storage system is presented in Fig. 1. Atmospheric air is passed through a blower and gets heated using an electric heater. This heat is absorbed by the concrete stored in the packed-bed storage tank. The stored heat can be used for cooling applications which are the research objective of this work. In Fig. 2, the layout of thermal-energy-storage system with the main components is presented. In Fig. 3, the thermal-energy-storage elements in the form of cylindrical sectors are presented. These thermal-energy-storage elements have more surface area for absorbing, and releasing more amount of heat in the form of convection and conduction.

3 Material properties of packed-bed TESS

Sensible thermal-energy-storage systems store energy by converting the temperature of the storage medium, which can be water, soil, rock and pebbles. Liquid storage media are often water and thermal oil, and solid storage media are rocks, bricks, concrete, and iron, dry and wet earth. Sensible thermal-energy-storage systems are capable of storing thermal-energy at high temperature without phase change except for water. Rock, marble, ceramics, and pebble materials act as a thermal-storage material for sensible heat storage, especially suitable for air as a heat-transfer fluid in the solar application. The major merits of this are: (1) Easy to eliminate the chemical instability, (2) Ambient level pressure is sufficient, (3) No need of heat-transfer medium between heat-transfer fluid and storage material.

In Table.3, the thermo-physical properties of packed-bed TESS are given and in Table. 4, the variable parameters of Packed Bed are provided. In Fig. 3, the mould for preparing cylindrical sector elements is shown and in Fig. 4, the cylindrical sector concrete blocks are shown. The arrangement of concrete bricks for experiment 1 and 2 is shown in Fig. 5 and Fig. 6. In experiment 1, the concrete blocks are placed adjacent to each other like bricks. In experiment 2, the concrete blocks are placed with increased porosity and decreased thermal-energy-storage elements

Fig. 3: Mould for preparing cylindrical sector elements

Table 1: Properties of solid storage media [16]

Storing medium	Temperature		Average Density	Average heat	Average heat	Volume specific
	Cold(°C)	Hot(°C)	(kg/m^2)	conductivity(W/mK)	capacity(kJ/kgK)	heat capacity (kWh_t/m^3)
Sand-rock-mineral oil	200	300	1700	1.0	60	60
Reinforced concrete	200	400	2200	1.5	100	100
Nacl(solid)	200	500	2160	7.0	150	150
Cast iron	200	400	7200	37.0	160	160
Cast steel	200	700	7800	40.0	450	450
Sllica fire bricks	200	700	1820	1.5	150	150
Magnesia fire bricks	200	1200	3000	5.0	600	600

Table 2: Properties of different concrete materials [2]

Material	Density Kg/m^3	Specific heat capacity $(J/(kgK))$	Thermal conductivity $(W/(mK))$	Thermal diffusivity $\times 10^7 (m^2/s)$	Volume heat capacity $(kWh/(m^3))$
plain concrete	2451	810	1.02	5.14	0.551
High-temprature concrete	2750	916	1.00	3.97	0.700
Castable	3500	866	1.35	4.45	0.842
Graphite concrete	2680	950	2.43	9.54	0.707
Fiber-remforced concrete	2440	630	1.16	7.55	0.427

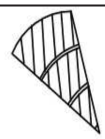
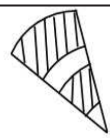
Table 3: Thermo-physical properties of packed-bed TESS

Properties	Air	Concrete
Density, $\rho[kg/m^3]$	1.05	2300
Thermal Conductivity, k[W/mK]	0.03291	1.4
Specific Heat, c[J/(kgK)]	934	880

Fig. 4: Cylindrical sector concrete blocks

Fig. 5: Concrete bricks for Experiment 1

Table 4: Variable parameters of packed-bed

Description	Experiment 1 Value	Experiment 2 Value
Cross section of packed-bed		
Volume of packed-bed, m^3	0.211	0.141
Surface Area of packed-bed, m^2	15	14.231
Porosity,ε	0.1	0.3

4 Mathematical model of packed-bed TESS

In a sensible heat storage process, the amount of heat energy [Q], is given in Eq. (1) which depends on the specific heat of the material [C_p], the temperature change [ΔT], and the mass [m] of the material.

$$Q = mC_p\Delta T \tag{1}$$

Fig. 6: Concrete bricks for Experiment 2

Table 5: Fixed parameters of packed-bed

Description	Parameter	Value
Volume of packed-bed, m^3	V_b	0.45
Length of packed-bed, m	L	0.75
Number of bed elements	N	10
Initial bed temperature,°C,	T_{bi}	25
Dynamic viscosity of air, kg/s-m	m_a	1.865 $\times 10^{-5}$
Density of air, kg/m^3	r_a	1.1
Inlet air temperature to bed,°C	T_{ai}or T_{bi}	40
Ambient temperature,°C	T_∞	25

5 Results and Discussion

In this experimental investigation, concrete is used as heat storage material and air as the heat-transfer fluid. The results of charging and discharging at the inlet location of the thermal-energy-storage tank are presented in Fig.2. Various experimental analyses can be carried out in this setup under laboratory conditions. The axial temperature variation has been observed, and the radial temperature is assumed to be uniform. In Table. 5, the fixed parameters of packed-bed storage system are presented.

5.1 Charging heat-transfer performance

In Fig. 7, the temperature variations during charging are shown for experiments 1 and 2. The temperature of the packed-bed is increased from atmospheric temperature to 85°C. Concrete as the packed-bed thermal-energy-storage material can withstand many thermal cycles without degradation of mechanical and thermal properties. Even high-temperature applications are using concrete as heat storage material.

5.2 Discharging heat-transfer performance

In Fig. 8, the temperature variations during discharging are presented for experiments 1 and 2

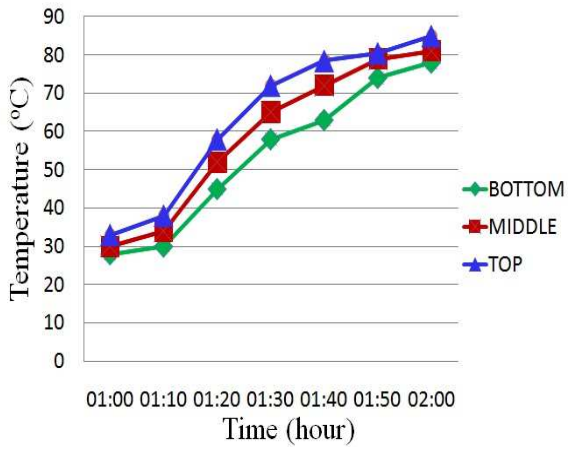


Fig. 7: Temperature variation during charging in experiment 1

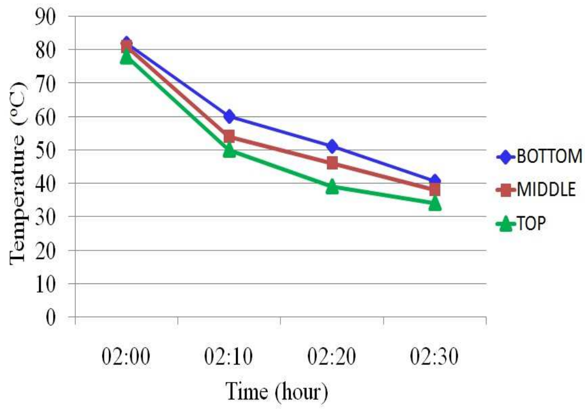


Fig. 8: Temperature variation during discharging in experiment 1

5.3 Storing heat-transfer performance

The charged heat can be stored for a longer duration with better insulation material. As the focus is on low-temperature will be more. This novel method of thermal-energy-storage has been adapted due to its high volumetric thermal-energy-storage capacity.

5.4 Effect of enhanced heat conduction and convection

As the surface area of the heat storage elements is more in the cylindrical sector elements the heat conduction and convection will be more. This novel method of thermal-energy-storage has been adapted due to its high volumetric thermal-energy-storage capacity.

5.5 Effect of pressure drop in packed-bed

The heat-transfer in the packed-bed storage media depends upon the pressure drop in the packed-bed. Two test cases with different porosities have been experimented.

6 Conclusion

In this work, the design, fabrication and experimental analysis of a sensible heat thermal-energy-storage system have been carried out. This work can be adapted for an application on low-temperature cooling using silica gel-water adsorption chiller which can be driven by 55°C of hot water. The focus is towards better thermal conductive and convective properties for heat-transfer in the packed-bed. This work has demonstrated the high potential of this concrete material to obtain an efficient and cost-effective thermal-energy-storage solution. In this method, easily available and economical thermal-energy-storage material concrete has been used. The heat storage elements have been made as cylindrical sector elements to have more area for heat conduction and convection. This work is a low-cost solar thermal-energy-storage system with an application as a solar thermal integrated cooling system. Numerical analysis is also carried out to perform various simulations and compared with experimental observations.

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