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Energy Analysis of Simultaneous Charging and Discharging Concrete Bed Storage System

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Strictly as per the compliance and regulations of:

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Adeyanju A.A [α] & Manohar K [σ]

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This is an indication that there was continuity of energy delivered for usage during charging and none charging.

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I. Background of the Study

A thermal energy system can be considered as being made up of charge, storage and usage (discharge) as shown in Figure 1.0.

Thermal energy can be stored by three major methods:

As sensible heat in liquids

As sensible heat in solid materials

As latent heat in phase transition of materials

A thermal storage unit in which particulate material is contained in an insulated vessel is known as a packed bed (pebble bed or rock pile) storage unit. It uses the heat capacity of a bed of loosely packed particulate material to store energy. A fluid, usually air, is circulated through the bed to add or remove energy. The most commonly used solid is rock.

A thermal-storage unit in which particulate materials contained in an insulated vessel is known as packed bed (pebble bed or rock pile) storage unit. It uses the heat capacity of loosely packed particulate materials to store energy. Fluid, usually air, is circulated through the bed to add or remove energy. The most commonly used solids are rocks, concrete, clays and walls (Adeyanju 2009a, Ataer 2006). The materials are invariably in porous form and heat is stored or extracted by the flow of a gas or a liquid through the pores or voids. Typically, the characteristics size of the pieces of rock used varies from 1 to 5cm (Ataer 2006). An approximate rule of thumb for sizing is to use 300 to 500kg of rock per square meter of collector area for space heating applications. Rock bed storages can also be used for much higher temperatures up to 1273K. The difficulties and limitations relative to liquids can be avoided by using solid materials for storing thermal energy as sensible heat. But larger amounts of solids are needed than using water, due to the fact that solids, in general exhibit a lower storing capacity than water. The cost of the storage media per unit energy stored is, however, still acceptable for solids. Direct contact between the solid storage and a heat transfer fluid is necessary to minimize the cost of heat exchange in a solid storage medium (Adeyanju 2009b, Ataer 2006).

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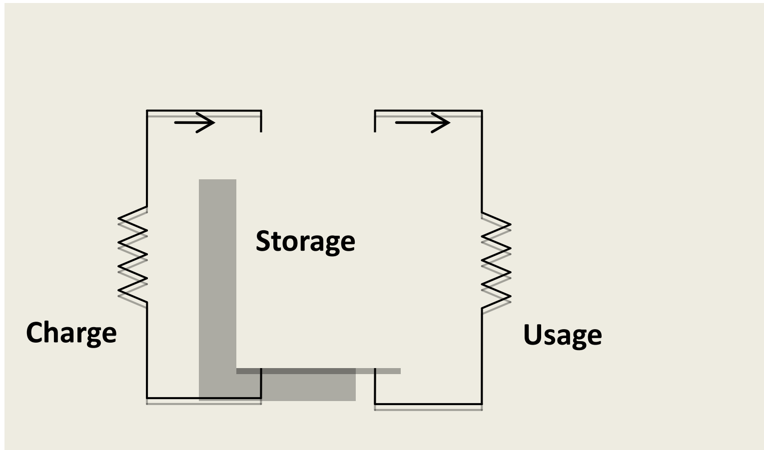

Figure 1.0 : Schematic of thermal energy Storage System

Thermal energy storage is very important to many engineering applications. For example, there is a need for waste heat recovery systems for systems where the waste heat availability and utilization times are different. Similarly, for systems such as solar heat collectors, there needs to be an effective medium in which to store the energy for night usage or even on cloudy days. An effective review on some of the main storage mediums can be found in Hasnainet al. (1998).

As expected, there are two main types – sensible and latent systems. Sensible systems harness the specific heat of materials, which include both liquid and solid materials. Latent systems store thermal energy in the form of a change in phase, and do not require vast temperature differences to store thermal energy, and can be stored in a variety of Phase Change Materials.

The first-law efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the storage to the energy stored into it where mC is the total heat capacity of the storage medium and T, T_o are the maximum and minimum temperatures of the storage during discharging respectively, and T_∞ is the maximum temperature at the end of the charging period.

$$\eta = \frac{mC\left(T - T_O\right)}{mC\left(T_\infty - T_O\right)} \qquad (1)$$

Heat losses to environment between the end of discharging and the beginning of the charging periods, as well as during these processes are neglected. The first law efficiency can have only values less than one.

Two particular problems of thermal energy storage systems are the heat exchanger design and in the case of phase change materials, the method of encapsulation. The heat exchanger should be designed to operate with as low a temperature difference as possible to avoid inefficiencies.

If one tries to get an overview of heat storage systems one would be overwhelmed by the large number of possible technical solutions and the variety of storage systems. Latent heat thermal energy storage systems, using phase change materials to store heat or coolness, have many applications.

The specific application for which a thermal storage system is to be used determines the method to be adopted.

Some of the considerations, which determine the selection of the method of storage and its design, are as follows:

- The temperature range, over which the storage has to operate.
- The capacity of the storage has a significant effect on the operation of the rest of the system. A smaller storage unit operates at a higher mean temperature. This results in a reduced heat transfer equipment output as compared to a system having a larger storage unit.

  The general observation which can be made regarding optimum capacity is that "short-term" storage units, which can meet fluctuations over a period of two or three days, have been generally found to be the most economical for building applications.
- Heat losses from the storage have to be kept to a minimum. Heat losses are particularly important for long-term storage
- The rate of charging and discharging
- Cost of the storage unit: This includes the initial cost of the storage medium, the containers and insulation, and the operating cost.

Other considerations include the suitability of materials used for the container, the means adopted for transferring the heat to and from the storage, and the power requirements for these purposes. A figure of merit that is used occasionally for describing the performance of a storage unit is the storage efficiency, which is defined by Equation (1). The time period over which this ratio is calculated would depend upon the nature of the storage unit. For a short-term storage unit, the time period would be a few days, while for a long-term storage unit it could be a few months or even one year. For a well-designed short-term storage unit, the value of the efficiency should generally exceed 80 percent.

Table 1.0 : Overview of Thermal Energy Storage Methods

Type of Thermal Energy Storage	Functional Principle	Phases	Examples
Sensible Heat	Temperature change of themedium with highest possible heat capacity	Liquid Solid	Hot water, organic liquids, molten salts, liquid metals
Latent Heat	Essentially heat of phase change	Liquid – Solid Solid - Solid	Nitrides, Chlorides,Hydroxides,Carbonates,Fluorides,Euctectics and Hydroxides

In latent heat storage the principle is that when heat is applied to the material it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapour as latent heat of vaporization. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapor to liquid.

The latent heat of transformation from one solid phase into another is small. Solid-vapor and liquid-vapor transitions have large amounts of heat of transformation, but large changes in volume make the system complex and impractical. The solid-liquid transformations involve relatively small changes in volume. Such materials are available in a range of transition temperatures.

Heat storage through phase change has the advantage of compactness, since the latent heat of fusion of most materials is very much larger than their enthalpy change for 1 K or even 0 K. For example, the ratio of latent heat to specific heat of water is 80, which means that the energy required to melt one kilogram of ice is 80 times more than that required to raise the temperature of one kilogram of water one degree Celsius.

Any latent heat thermal energy storage system should have at least the following three components: a suitable phase change material (PCM) in the desired temperature range, a containment for the storage substance, and a suitable heat carrying fluid for transferring the heat effectively from the heat source to the heat storage.

Furthermore, the PCMs undergo solidification and therefore cannot generally be used as heat transfer media in a solar collector or the load. Many PCMs have poor thermal conductivity and therefore require large heat exchange area. Others are corrosive and require special containers. Latent heat storage materials are more expensive than the sensible heat storage media generally employed, like water and rocks. These increase the system cost. Due to its high cost, latent heat storage is more likely to find application when:

1. High energy density or high volumetric energy capacity is desired, e.g., in habitat where space is at a premium, or in transportation where either volume or weight must be kept to a minimum.
2. The load is such that energy is required at a constant temperature or within a small range of temperatures, or
3. The storage size is small. Smaller storage has higher surface area to volume ratio and therefore cost of packing is high. Compactness is then very important in order to limit the containment costs. Similarly, heat losses are also more or less proportional to the surface area. Compactness is also an important factor to limit the heat losses in storages of small capacities.

Latent TES systems have become much more viable for a high volumetric heat capacity. Usually, latent systems can store much more thermal energy for a given volume, require less of a temperature gradient, and can be used for both hot and cold thermal energy storage, depending on the material.

A comprehensive review of the various types of systems can be found in Sharma and Sagara (2007) where various applications and PCM innovations are discussed. Briefly, some of these applications include space heating and cooling, solar cooking, greenhouse upkeep, solar water heating and waste recovery systems. However, it is the design, control and analysis of these systems which researchers are most concerned with.

As examples, a solar water heating system utilizing encapsulated PCM, an ice-on-coil laboratory unit and an encapsulated ice industrial refrigeration system are presented, as well as past and present methods for system optimization.

Latent solar-water heating systems are a perfect example of the advantage of thermal energy stored in

PCMs. Nallusamy *et al*. (2006) study the performance of a solar collector, coupled with a storage tank filled with encapsulated PCMs, which in this case is paraffin. Water is used as the heat transfer fluid, and the inlet temperature to the storage tank was varied to study the effects of bed porosity and flow rate on overall system performance. It was found that the latent storage system drastically reduced the size of the solar heat storage system, and that these systems are best used for intermittent usage where the latent heat can be best used.

Lee and Jones (1996) studied an ice-on-coil TES unit perfect for residential and light commercial conditions. The chiller, a vapor compression refrigeration cycle using Refrigerant R22, freezes the water inside the evaporator tubes during charging, for the purpose of extraction during peak energy times. The unit was tested varying both evaporator and condenser temperatures, and parameters such as the ice-building rate, the compressor power, cooling rate, heating rate, energy efficiency ratio and power consumption factor are studied. The results indicate that, among other things, the energy efficiency increased with a decreased condenser temperature. The energy efficiency is also readily calculable and heat transfer rates are easily obtainable, which is an encouraging aspect of many TES systems when attempting to minimize energy losses.

An encapsulated ice refrigeration system is studied in Cheralathanet al. (2007). Henze (2003) presents an overview of the control for central cooling plants with ice TES. The control algorithms target the minimization of energy usage and minimizing demand costs, to name a few. Fully optimal control, based on full system knowledge, is also introduced. The main arguments here state that depending on the specific objectives of the system, a control algorithm can be utilized which optimizes the objectives in a concise manner. Henze (2005) furthers this by investigating the relationships between cost savings and energy consumption associated with the conventional control of typical TES systems. Items accounted for in these optimizations include varying fan power consumption, as well as chiller and storage coefficient of performance.

The results indicate that buildings can be operated in such a manner as to reduce overall costs, with only a small increase in total energy consumption.

Another interesting application of PCMs is the regulation of indoor temperatures when rapid changes occur in the surrounding outdoor temperature. Khudhair and Farid (2004) discuss, among other latent TES applications, the advantages of PCMs installed in concrete, gypsum, wallboards, ceilings and floors to limit the effects of outdoor temperature swings on indoor temperatures. These PCMs can act as a heat source while solidifying during cooler indoor temperatures, or a heat sink when melting during warmer indoor temperatures, by having a fusion point close to that of room temperature. Latent TES by means of solar energy and peak load shifting by running a refrigeration cycle are also discussed, as are many other advantages and typical drawbacks of these systems.

It has been conventional, as has been done in the above works, to use energy consumption, energy efficiency and cost minimization as the main benchmarks in determining optimal system configurations. However, in recent years, a new approach has been exercised which simultaneously reduces both energy and cost inputs. These exergy analyses have been the preferred method of late to better analyze the performance of these systems, as well as the location and severity of energy losses. Dincer and Rosen (2002) discuss the usefulness of exergy analysis in the performance and optimization of various TES systems. During exergetic analyses of aquifer, stratified storage and cold TES systems, appropriate efficiency measures are introduced, is the increasing importance of temperature, especially during cold TES.

Rosen et al. (1999) provide detailed exergy analyses of many types of cold TES systems. They consider full cycles of charging, storage and discharging in both sensible and latent systems. The results indicate that exergy clearly provides a more realistic and accurate measure of the performance of a cold TES system, since it treats “cold” as a valuable commodity. This is in contrast to the energy analysis, which treats cold as an undesirable commodity. In addition, it was summarized that the exergy analysis is substantially more useful than the energy analysis. Furthering this study, Rosen et al. (2000) examine an industrial sized encapsulated ice TES unit during full charging, discharging and storage cycles. The results indicate that in addition to energy analyses being incomplete for cold TES, they also achieve misleadingly high efficiency values.

For the system in question, the overall energy efficiency was 99.5%, while the exergy efficiency was calculated to be 50.9%. This solidifies the fact that exergy analyses allow for a more complete diagnostic of cold TES systems and the locations of their shortfalls.

This study utilized spherical shaped concrete imbedded with copper tube as the storage medium. Thermal storage in concrete relies on sensible heat storage where the stored thermal energy is defined by the heat capacity of the concrete and the temperature difference between the charged and the discharged states.

II. Methodology

a) Test and Equipment

The schematic diagram of experimental set up is shown in Figure 2.0. A photograph of the components is presented in Figure 3.0.

For indoor experimentation, air duct with an electric heater was used (Singh, Saini and Saini, 2005). The size of the duct was 3 x 0.5 x 0.0254m. The packed bed storage system consists of packed spherical shaped concrete imbedded with copper tubes, inlet plenum chamber and outlet plenum chamber. The copper tube was of type L and of 0.00635m standard size. The outside diameter of the copper tube was 0.02223m, the inside diameter was 0.01994m, wall thickness of 0.01143m, length 1.32m, number of copper tubes was 4 of two passes with radius 0.115m. The spherical shaped concrete was made of ratio 1:1.2:1.1 of cement, sand and gravel, respectively.

The entry and exit lengths were 0.65 and 0.96m respectively, including the inlet plenum and outlet plenum height of 0.3 m each. The heating section was 2 x 0.5 x 0.0254 m. Electric heater having size of 2 x 0.5 m was fabricated by combining series and parallel loops of heating wire wound on an asbestos sheet. In order to minimize the heat losses, the backside of the heater was insulated with fiber glass.

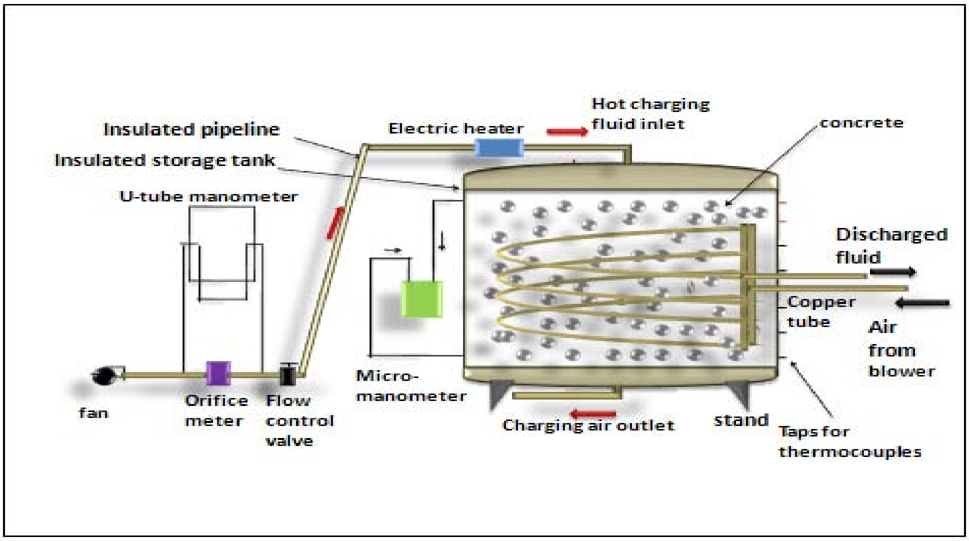

Figure 2.0 : A diagrammatic sketch of simultaneous charging and discharging packed bed energy storage system components

The heater was fixed on the top of the duct between entry and exit lengths. Electric supply to heater was controlled by a variac.

Air duct was well insulated from outside. A centrifugal blower was used to force hot air from air duct to storage tank through a 0.051m diameter orifice. The blower motor range is from 1-5 horsepower and maximum blower revolution per minute is 3800.

Flow was varied by controlling the blower speed using the variable transformer which could supply any voltage from 0 to the rated voltage of 120 V. This blower produced a flow of 0.047m^3/s at a pressure of 13699.9 N/m^2 at standard conditions.

A 3m long pipe of 0.15m inside diameter made of plastic connected with a 0.53m long barrel pipe made of galvanized steel was used between the blower and the electric heater. The length of the pipe was important to provide a fully developed air velocity distribution inside the pipe in order to accurately measure the air flow rates with an orifice meter.

Storage tank having 0.70 m diameter was made of MS sheet of 3.00 mm thickness. The tank was 1.07 m high, including lower and upper plenums of height 0.25 m each resulting to packed bed height of 0.47 m. Tank was insulated with fiber glass to minimize the heat losses. It was mounted in hanging condition on a rigid stand made of MS angles, with the tilting provision to make it trouble-free for attaching and detaching the union joint in the pipe line at entry to the bed and also for easy loading and unloading of storage material. To make air supply from air duct to storage tank, a pipeline of 0.082 m diameter, well insulated with fiber glass, was used. A flange with 0.64m inside diameter and 0.7m outside diameter was installed with the tank cover. Silicone rubber was used for sealing the joint connections in order to avoid air leakage.

Global Journal of Researches in Engineering (A) Volume XVI Issue I Version I Year 2016

Figure 3.0 : A photograph of simultaneous charging and discharging packed bed energy storage system components before and after insulation

An arrangement was provided in order to ensure uniform distribution of air into the bed. A circular MS sheet of 3.00 mm thickness with number of holes was placed on MS angles inside the tank to support the storage material above the lower plenum. All joints of the experimental apparatus were sealed properly to avoid any air leakage. Hole was drilled at different cross sections of the tank in order to insert the thermocouple wires. An air velocity meter was used for the measuring of air flow rate in the pipeline. This meter simultaneously measure and data log the air parameters using a single probe with multiple sensors. The model measure velocity, temperature and calculate flow. It has a telescopic articulated probe.

Figure 4.0 : A photograph of spherical shaped concretes and those imbedded with copper tube

An orifice meters with a U-tube manometer was installed along the pipeline for pressure drop measurement.

A control valve was provided in the pipeline for adjusting the flow rate of air. Micro-manometer was attached with the taps at top and bottom of the bed for measuring pressure drop through the bed. Temperatures of air and solid at different points along different cross sections in the bed were measured with thermocouples.

The temperature of the flowing air through the packed bed, the surface and core of the spherical shaped concrete, the concrete/copper tube contact and also the surface of the copper tube together with air flowing inside the copper tube were measured at interval of ten minutes at several locations. These temperatures were measured by means of thermocouples. At each location, a thermocouple was positioned at the center of the horizontal plane of the packed bed for measuring the air temperature, the surface and the center of the concrete material and copper tube. Air temperatures were also measured at the inlet and outlet of the storage tank and also at the inlet and outlet of the copper tube through the thermocouples.

The thermocouples were then connected to three data loggers which have its software installed on the computer for the temperature readings. The data loggers have 8-channel each. Input from thermocouples of types B, E, J, K, R, N, S, or T could be recorded using the instrument. Each of the 8-channels are independent of each other, and can be independently enabled or disabled. Type J thermocouples were used for all tests performed. This Pico instrument was capable of 0.1°C resolution with readings displayed in °C and capable of continuously recording and exporting data to a remote computer.

A centrifugal fan with a control valve was installed to provide air at varied flow rates through the copper tube in the storage tank.

b) Test Procedures

The experimentation involved testing of the thermal performance of energy stored in a packed bed storage system in which the inlet air temperature to the packed bed were generated from the discharge air temperatures of a simulated air type flat plate solar collector. The second phase of the experiment involved studying the pressure drop, energy loss, air passage through the packed bed and the fan energy used for optimization of the packed bed storage system.

Before a test was conducted on the packed bed which contains partly spherical shaped concrete of a specific size and the spherical shaped concrete imbedded with a copper tube of same size. The spherical shaped concrete of three different sizes with diameters 0.065m, 0.08m and 0.11m were casted and several of its physical properties such as weight, density and compressive strength were determined. The void fraction (ε) was calculated using the relationship between porosity and concrete bulk density (ρ_b) which is given by the following equation:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_c} \tag{2}$$

The bulk density of the spherical shaped concrete was determined from the volume of the storage section of the packed bed and the weight of the concrete filling the volume.

Tests were carried out with spherical shaped concrete of diameter 0.11, 0.08 and 0.065m, respectively. The spherical shaped concrete imbedded with copper tube was then dropped into the storage section of the tank and the remaining concrete without copper tube was dropped and arranged in the storage tank to maintain space volume between particles within very close limits. Moreover, different porosity could be obtained.

Before packing of storage material, thermocouples were fixed in small sized grooves in material particles. During packing these were placed at different points in different cross sections of the bed along with thermocouples for measurement of air temperature at the same points.

At each location, a thermocouple was positioned at the center of the horizontal plane of the packed bed for measuring the air temperature, the surface and the center of the concrete material and copper tube. Holes were drilled at different locations across the height of the storage tank where twenty two thermocouples were inserted. Four thermocouples were inserted to measure the air temperature within the void of the packed bed at different height of the tank. Four thermocouples each were also inserted to measure the surface and internal temperature of the spherical shaped concrete and another four each for the copper tube surface and internal air temperature at different height.

One thermocouple each was also inserted at the entry and exit of the copper tube and at the entry and exit of the storage tank respectively.

Three runs of air flow rates were conducted for the 0.11, 0.08 and 0.065m diameter spherical shaped concrete at the normal drop. The designed air flow rates were 0.0094m^3/s, 0.013m^3/s, and 0.019m^3/s per square meter of total cross sectional area of the storage tank.

The corresponding superficial velocities were approximately 0.1m/s, 0.15m/s and 0.20m/s.

As soon as the air enters the storage tank into the packed bed, temperature measurements of air, concrete surfaces, copper tube surfaces, concrete core and inside of the copper tube were recorded at four levels via a data logger connected with the computer. These four levels were located at different heights above the base, 117.5cm, 235cm, 352.5cm, and 470cm.

Temperatures were measured at the storage tank inlet and outlet and copper tube inlet and outlet via a data logger connected to a computer. The measurements were taken automatically at an interval of 10 minutes for between 10 to 12 hours.

In order to test the storage capacity of the spherical shaped concrete and the copper tube, the measurements were also taken during the night period when the simulated heat was no longer in supply to the packed bed.

Upon analysis of all measuring equipment, the error calculated for these experiments was found to be ±5%.

The second phase of the experimentations involves studying the air resistance through packed bed and the blower and also through the copper tube. The pressure drop measurements were taken at varying air flow rates of 0.0094, 0.012, 0.014, 0.017, 0.019, 0.021, 0.024, 0.026, 0.028, and 0.031m^3/s.

The pressure drops were taken for spherical shaped concrete of diameter 0.11, 0.08 and 0.065m.

The following measurements were taken:

Pressure drops of air across the pipe (barrel) leading to storage tank inlet

Pressure drops of air across the pipe entry the copper tube inlet

Pressure drops of air across the packed bed

From this experimentation blower characteristics performance and the power used for the operation were established. The volume flow rate handled by the blower expressed the inlet conditions. The blower total pressure is expressed as follows:

Blower total pressure = Outlet blower total pressure –Inlet blower total pressure (3)

The blower total pressure calculated from equation (3) represents the pressure drop across the blower.

The blower efficiency can also be expressed as follows:

$$\eta_{blower} = \frac{\text{power output}}{\text{power input}} \quad (4)$$

III. Results and Discussion

This is the results of the experimentation which involved the determination of the thermal performance of packed bed energy storage system using a heater.

The ambient air temperature; fan inlet and outlet temperature; pressure drop across blower, barrel and pipe; and blower power input at air flow rates of $0.0094m^3/s$, $0.013m^3/s$, and $0.019m^3/s$ for spherical shaped concrete of size 0.065, 0.08 and 0.11m, respectively, were shown in Tables 2.0 to 4.0.

Table 2.0 : Average values of Air Flow Measurements for the Spherical shaped Concrete of size 0.11m diameter

Air flow rate m^3/s	Ambient air temp. (°C)	Fan inlet air temp. (°C)	Fan outlet air temp. (°C)	Pressure drop across barrel orifice (N/m^2)	Pressure drop across pipe orifice (N/m^2)	Atmospheric pressure (N/m^2)	Pressure drop across blower (N/m^2)	Blower power input (watt)
0.0094	24.30	24.40	26.40	89.7	9.96	101320.7	122.5	490
0.013	24.30	24.20	26.60	176.9	19.9	101320.7	220.7	510
0.019	24.40	24.20	27.00	331.3	34.87	101320.7	392.3	530

The energy analysis of the simultaneous charging and discharging storage system at airflow rates of 0.0094, 0.013, and $0.019m^3/s$ for spherical shaped concrete of size 0.11m, 0.08m and 0.065m, respectively, were shown in Tables 5.0 to 7.0.

It can be seen from Figures 5.0, 6.0, 7.0 and 8.0 that at airflow rates of 0.0094 m^3/s; 494.95, 504.50 and 526.80 watts of energy were supplied to charge the packed bed contain spherical shaped concrete of diameter 0.11m, 0.08m and 0.065m, respectively. 201.60, 118.62 and 77.82 watts of energy were stored in the packed bed contain spherical shaped concrete of diameter 0.11m, 0.08m and 0.065m, respectively, while 132.90, 217.78 and 255.78 watts of thermal energy were conducted through the concrete imbedded with copper tube making a total energy in packed bed to be 334.52, 336 and 333.6 and the storage efficiency to be 40.7, 23.5 and 14.8%, respectively.

298.25, 304.3 and 296.49 watts of energy were delivered from copper tube for usage through a simultaneous charging and discharging arrangement per packed bed contain spherical shaped concrete of diameter 0.11m, 0.08m and 0.065m, respectively.

Table 3.0 : Average values of Air Flow Measurements for the Spherical shaped Concrete of size 0.08m diameter

	Ambient air temp. (°C)	Fan inlet air temp. (°C)	Fan outlet air temp. (°C)	Pressure drop across barrel orifice (N/m^2)	Pressure drop across pipe orifice (N/m^2)	Atmospheric pressure (N/m^2)	Pressure drop across blower (N/m^2)	Blower power input (watt)

Air flow rate m^3/s								
0.0094	24.00	24.20	26.00	92.16	12.46	101320.8	122.59	490
0.013	24.00	24.15	26.20	176.85	22.42	101320.8	220.66	510
0.019	24.20	24.40	27.50	323.82	34.87	101320.8	380.51	530

Likewise, an amount of 663.4, 675.14 and 712.1 watts of energy were supplied to charge the packed bed contain spherical shaped concrete of diameter 0.11m, 0.08m and 0.065m, respectively at airflow rates of $0.013m^3/s$; 401.40, 346.4 and 249.67 watts of energy were stored while 127.58, 192.74, and 247.6 watts of thermal energy were conducted through the concrete imbedded with copper tube making a total energy in the packed bed to be 529, 512.97 and 497.27 and the storage efficiency to be 60.5, 51.3 and 35.06%, respectively.

Table 4.0 : Average values of Air Flow Measurements for the Spherical shaped Concrete of size 0.065m diameter

	Ambient air temp. (°C)	Fan inlet air temp. (°C)	Fan outlet air temp. (°C)	Pressure drop across barrel orifice. N/m^2	Pressure drop across pipe orifice (N/m^2)	Atmospheric pressure (N/m^2)	Pressure drop across blower (N/m^2)	Blower power input (watt)
Air flow rate m^3/s								
0.0094	23.30	24.80	27.20	87.18	9.96	101862.6	124.60	490
0.013	23.40	24.65	26.90	174.36	22.42	101320.7	245.18	510
0.019	23.60	24.90	28.00	328.80	34.87	101930.3	392.28	530

406, 423.65 and 412.7 watts of energy were delivered from copper tube for usage through a simultaneous charging and discharging arrangement per packed bed contain spherical shaped concrete size of diameter 0.11m, 0.08m and 0.065m, respectively.

934, 944.71 and 1005.73 watts of energy were supplied to charge the packed bed contain spherical shaped concrete of diameter 0.11m, 0.08m and 0.065m, respectively at airflow rates of $0.019m^3/s$; 536.85, 473.90 and 405.55 watts of energy were stored while 125.55, 187.70 and 244.55 watts of thermal energy were conducted through the concrete imbedded with copper tube making a total energy in the packed bed to be 662.4, 661.6 and 650.1 and the storage efficiency to be 57.5, 50.2 and 40.3%, respectively.

Table 5.0 : Energy analysis for the 0.11m spherical shaped concrete storage system at airflow rates of 0.0094, 0.013, and $0.019m^3/s$

	Energy input to bed (W)	Energy output of bed (W)	Energy conducted through copper tube/ concrete (W)X	Energy store (W) Y	Total Energy in bed (W) X+Y	Energy input to copper tube (W)	Energy delivered from copper tube for usage (W)	Storage Efficiency (%)
Air flow rate m^3/s								
0.0094	494.95	160.43	132.90	201.6	334.52	39.40	298.25	40.7
0.013	663.40	134.40	127.58	401.40	529.00	76.50	406.00	60.5
0.019	934.13	271.60	125.55	536.85	662.40	73.14	388.80	57.5

388.8, 525.9 and 510.2 watts of energy were delivered from copper tube for usage through a simultaneous charging and discharging arrangement per packed bed contain spherical shaped concrete size of diameter 0.11m, 0.08m and 0.065m, respectively.

These analyses indicated that it is possible to charge a packed bed, store thermal energy and discharge the energy simultaneously.

Table 6.0 : Energy analysis for the 0.08m spherical shaped concrete storage system at airflow rates of 0.0094, 0.013, and 0.019m^3/s

Air flow rate m^3/s	Energy input to bed (W)	Energy output of bed (W)	Energy conducted through copper tube/ concrete(W)X	Energy store (W) Y	Total Energy in bed (W) X+Y	Energy input to copper tube (W)	Energy delivered from copper tube for usage (W)	Storage Efficiency (%)
0.0094	504.50	168.00	217.78	118.62	336.00	32.31	304.30	23.5
0.013	675.14	162.16	192.74	346.41	512.97	61.14	423.65	51.3
0.019	944.71	283.10	187.70	473.90	661.60	115.40	525.90	50.2

Table 7.0 : Energy analysis for the 0.065m spherical shaped concrete storage system at airflow rates of 0.0094, 0.013, and 0.019m^3/s

Air flow rate m^3/s	Energy input to bed (W)	Energy output of bed (W)	Energy conducted through copper tube/ concrete(W)X	Energy store (W) Y	Total Energy in bed (W) X+Y	Energy input to copper tube (W)	Energy delivered from copper tube for usage (W)	Storage Efficiency (%)
0.0094	526.80	193.25	255.78	77.82	333.60	21.07	296.49	14.8
0.013	712.10	214.83	247.60	249.67	497.27	60.52	412.70	35.1
0.019	1005.73	355.6	244.55	405.55	650.10	128.22	510.20	40.3

The energy analysis for discharging only (when no energy is supplied during night time) indicates that energy delivered from copper tube for usage at airflow rates of 0.0094m^3/s were 236.7, 233.7 and 225.9 watts for spherical shaped concrete size of diameter 0.11m, 0.08m and 0.065m, respectively while that of airflow rates of 0.013m^3/s were 257.5, 296.3 and 285.4 watts for spherical shaped concrete size of diameter 0.11m, 0.08m and 0.065m, respectively whereas at airflow rates of 0.019m^3/s it was 298.5, 293 and 277.1watts.

This is an indication that there was continuity of energy delivered for usage during charging and none charging.

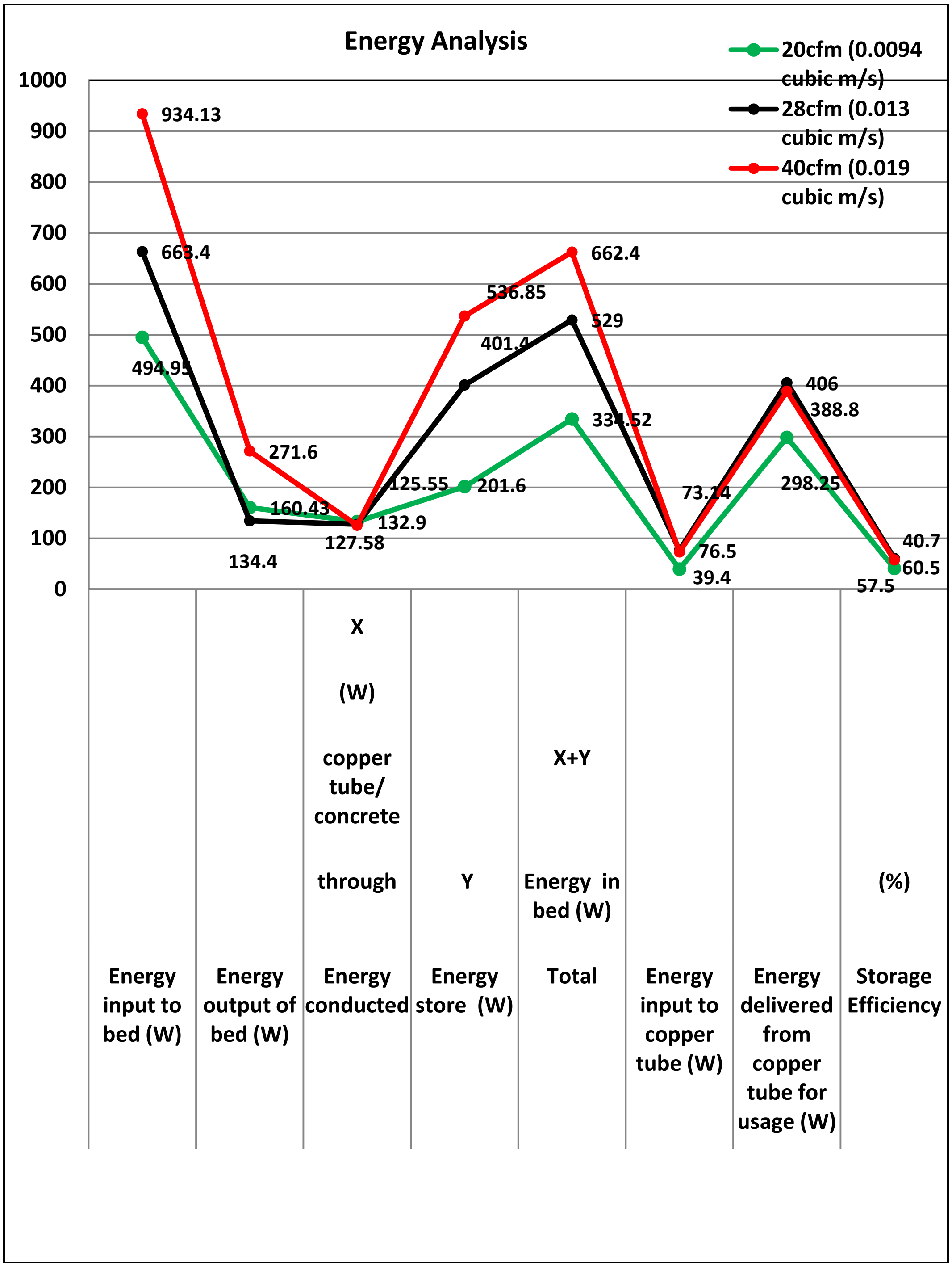

Figure 5.0 : Energy analysis of simultaneous charging and discharging packed bed storage system at airflow rate of 0.0094, 0.013, and 0.019m^3/s for 0.11m diameter spherical shaped concrete

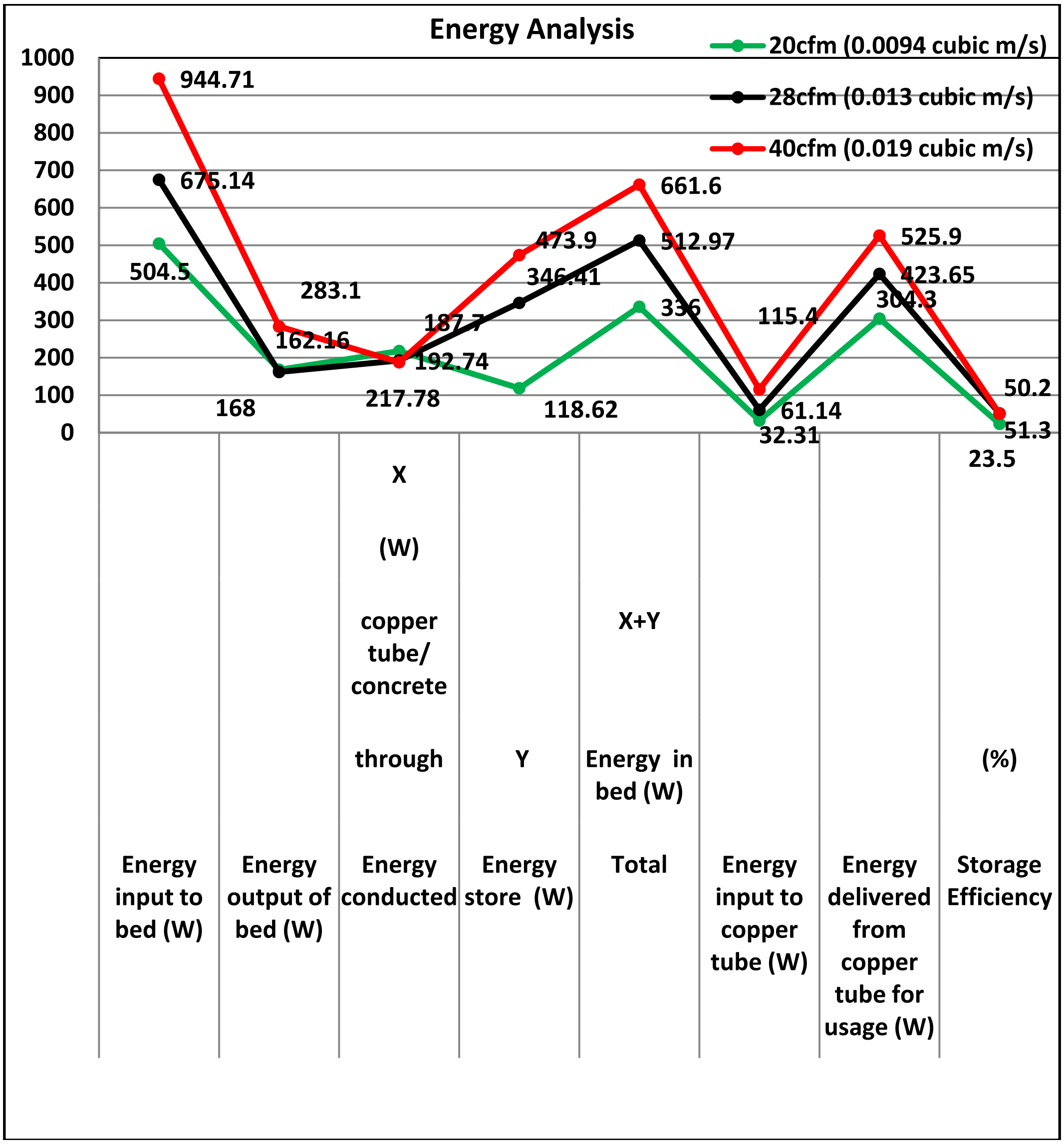

Figure 6.0 : Energy analysis of simultaneous charging and discharging packed bed storage system at airflow rate of 0.0094, 0.013, and 0.019m^3/s for 0.08m diameter spherical shaped concrete

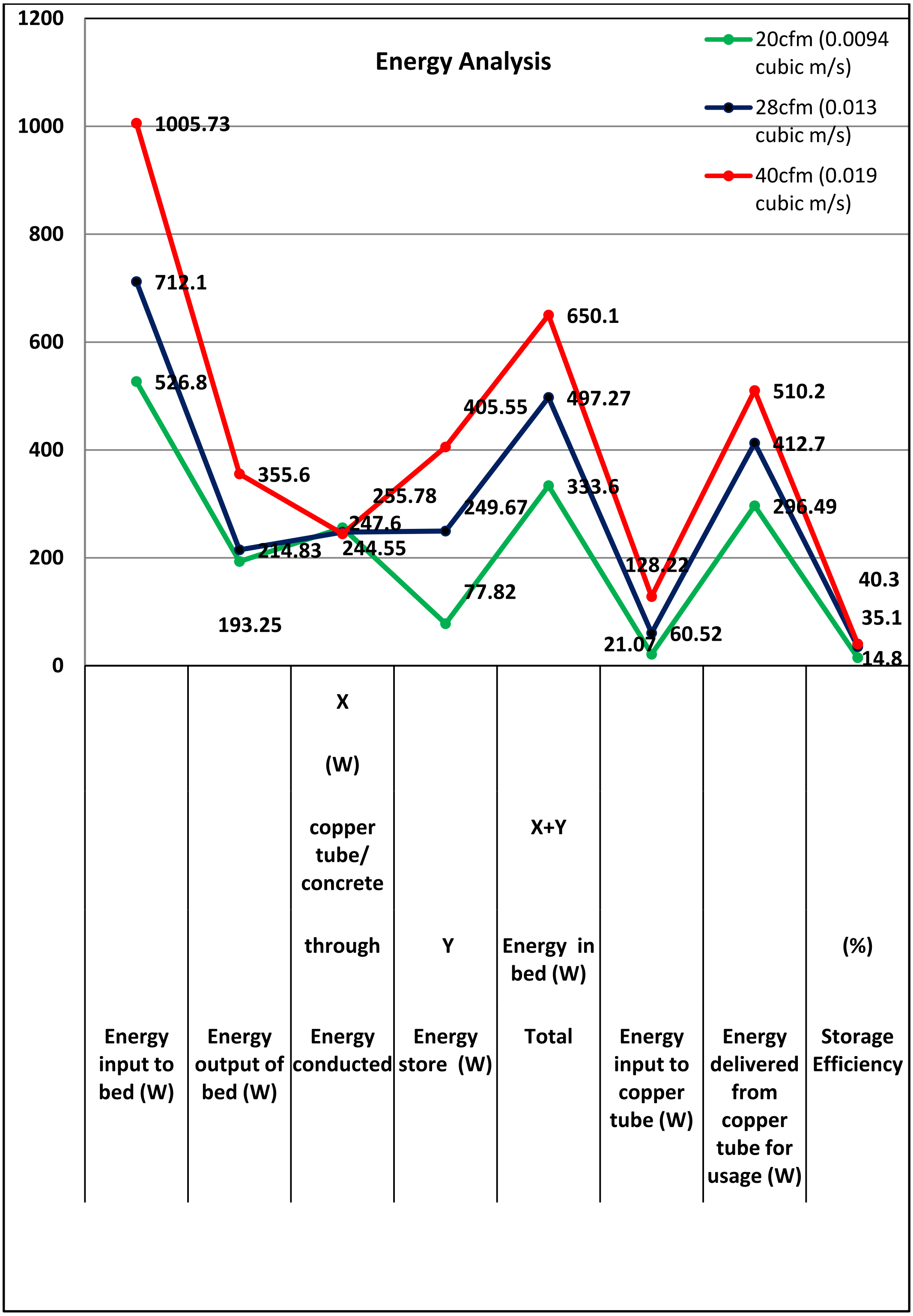

Figure 7.0 : Energy analysis of simultaneous charging and discharging packed bed storage system at airflow rate of 0.0094, 0.013, and 0.019m^3/s for 0.065m diameter spherical shaped concrete

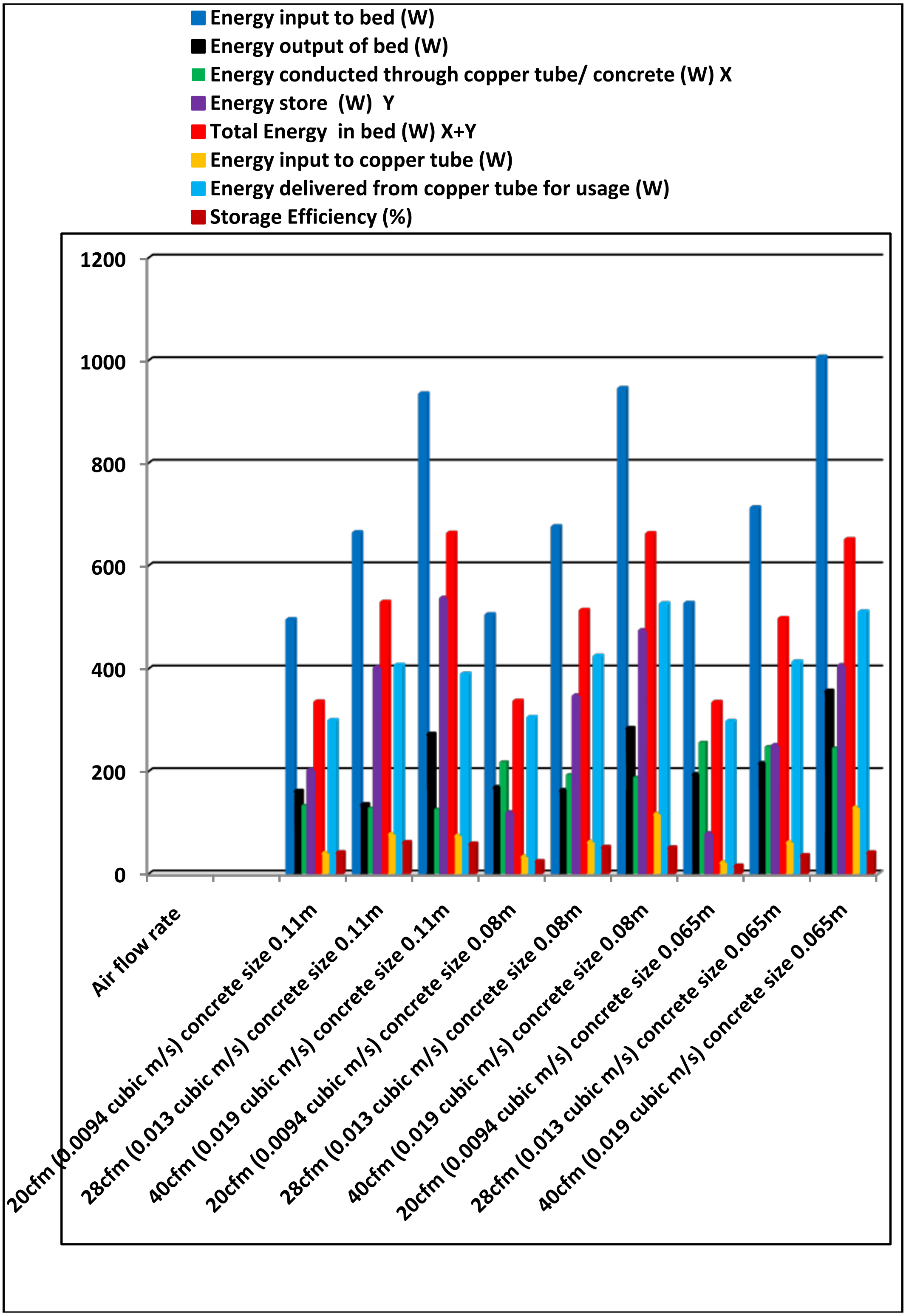

Figure 8.0 : Energy Analysis of Simultaneous Charging and Discharging Packed Bed Storage System for Spherical Shaped Concrete of diameter 0.065, 0.08, 0.11m and Air Flow Rate 0.0094, 0.013, and 0.019m^3/s

IV. Conclusion

Packed bed in a solar heating system does not operate with constant inlet temperature, during the day the variable solar radiation, ambient temperature, collector inlet temperature, load requirements, and other time-dependent conditions result in a variable collector outlet temperature and sinusoidal temperature discharged from the bed. This study further looks into converting this ntermittent solar radiation into continuous form.

Experiments were conducted on conventionally used thermal storage materials and concrete. Precast concrete showed to have superior thermal storage properties than natural stones. Research and laboratory testing on concrete showed that a mix 1: 1.2: 1.1 of cement, sharp-sand and limestone, respectively, plus 20g of 5cm length steel fibers exhibited a high thermal conductivity of 2.46 W/mK and storage capacity of 3.24 x 10^6 J/m^3 K.

Further experimental studies were carried out to investigate the thermal performance of simultaneous charging and discharging packed bed energy storage system and it was discovered that the energy analysis shows a positive results (i.e. energy input = energy output + storage)

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