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Energy analysis of thermal energy storage in an air-gravel packed bed using sensible heat storage

A project report submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Mechanical Engineering

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ

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الشكر لله الذي جعلنا نَتمم هذا العمل بكل تفاني واجتهاد ، الحمد لله على ما وصلنا اليه

جزيل الشكر والامتنان الى مشرفنا الدكتور محمد مهدي الذي كان عوناً لنا لأنجاز هذا العمل الدؤوب بكل تفاصيلهِ ، فان الكلمات عاجزة عن وصف فضلهِ الكبير .

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مع كامل الشكر والامتنان الى اهالينا الذين كانوا معنا بكل خطوة نسأل الله أن يجزيكم خير الجزاء، ويبارك في أعماركم وأعمالكم، ويجعل ما قدمتموه في ميزان حسناتكم، فأنتم منارات أضاءت لنا درب الحياة.

DEDICATION

الاهداء

(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ)

حمد لله الذي ما تمّ جُهد ولا ختم سعي إلا بفضله، الحمد لله على البلوغ ثمّ الحمد لله على التمام

الى الجسر الوحيد الذي جعلني أصل لمرحلة التخرج هي أمي أغلى ما في الكون

الى من أعجز عن وصفه سندي وملجأي بعد الله

أبي (حفظه الله)

الى من ساندني ودعمني في طيلة مسيرتي هذه

الدكتور الفاضل: محمد مهدي صالح

الى من شهدوا معي متاعب الدراسة وسهر الليالي، من كانوا خير عون لي في دربي .. أخوتي الأعزاء

الى الأصدقاء الأوفياء، الذين ما انفكّوا يومًا عن تقديم العون والمساعدة والدعم لي في أحلك الظروف

الى الذين حصرهم قلمي ولم يحصرهم قلبي

اساتذتي و زملائي اهديهم جميعا, حروفي ..... حبا و وفاءاً

ABSTRACT

Thermal energy storage (TES) is used in renewable energy systems such as concentrated solar power (CSP) to provide heat for dispatchable power production, and thus could be considered a significant component in such systems. In the present work, thermal performance during the charging process in air-gravel thermal energy storage tank was tested experimentally and analyzed. The study focused on determining the temperature profiles, heat losses and the efficiency of the storage during the charging period. Air was used as the working heat transfer fluid with an inlet temperature of 100 ℃ at one flow rate of 0.0001901 m^3/s. Gravel was used as storage materials. The results showed that the total energy stored in the storage packed bed is approximately 992.04 kJ which can be improved by reducing heat losses to the ambient. Heat losses from the storage system is very high which should be decreased.

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CHAPTER ONE

Introduction

Chapter One

Introduction

1.1 Background and motivation

Thermal energy storage (TES) system has received a lot of attentions due to the great potential in balancing the disproportion between the energy supply and demand, which is the major barrier of the development and application of renewable energy, particularly, wind and solar energy. In thermal energy storage (TES), energy is stored by changing the internal energy of materials by changing the temperature as in sensible heat storage [1] or the phase of a material as in latent heat storage [2]. The latent heat thermal energy storage (LHTES) is a crucial technology of the TES due to nearly constant operating temperature, high heat transfer rate and high energy utilization efficiency [3-4]. Thermal energy storage system is essential to make concentrating solar power (CSP) generation competitive for meeting current and future energy needs. Storing energy for future use allows the power plant to operate continuously during periods of intermittent sun, reduces the mismatch between the energy supply and demand by providing load leveling and helps to conserve energy by improving the reliability and performance of CSP plants.

Thermal energy can be stored as either sensible or latent heat [5]. Most of the thermal energy storage systems in operation are based on sensible heat storage. Storing heat in the form of latent heat of fusion of phase change material (PCM) in addition to sensible heat significantly increases the energy storage capacity and reduces size of the TES system [6-7]. In developing thermal storage technologies, the exergetic efficiency is sought to be high to ensure that heat quality is maintained after storage [4]. Previous investigations focused on latent thermal energy storage systems have shown that cascading several PCMs in the order of their decreasing melt temperatures from the hot heat transfer fluid HTF inlet side can result in higher heat transfer rates, as well as improved exergetic efficiency [8].The Packed bed thermal energy storage (PBTES) system is one of the most commonly used LHTES systems, benefited from the large heat transfer area between phase change material (PCM) and heat transfer fluid (HTF), and it is widely used in many scenarios including waste heat recovery and utilization, solar power plants, compressed air energy storage and other thermal systems[9-10]. Investigation the charging process of the PBTES system and the enthalpy-porosity model combined with the surface-to-surface radiation model was used for describing phase change as well as radiative heat transfer. The cascaded PCMs can be utilized in the PBTES system to improve its thermal performance. However, there are limited a few experimental researches reported about the thermal performance of the PBTES with cascaded PCMs [11]. The (PCMs) should first be selected based on their melting temperature. Materials that melt below 15 °C are used for storing coolness in air conditioning applications, while materials that melt above 90 °C are used for absorption refrigeration. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications. These materials represent the class of materials that has been studied most [12]. Recently, packed-bed TES systems filled with high-temperature PCM capsules have been identified as a promising compact and cost- effective TES technology for CSP plants. Capsules filled with phase change material (PCM) have been considered as a better option to be used in packed-bed TES systems. The benefits of PCM include the utilization of latent heat, which may result in a higher energy storage density and a smaller storage volume. Packed-bed TES systems filled with PCM capsules have been extensively studied both experimentally and numerically for low-temperature storage applications such as space and water heating, cooling and air-conditioning etc [13]. Materials to be used for phase change thermal energy storage must have a large latent heat and high thermal conductivity. They should have a melting temperature lying in the practical range of operation, melt congruently with minimum subcooling and be chemically stable, low in cost, non-toxic and non-corrosive. Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and non- organic compounds [12]. Commercial paraffin waxes are cheap with moderate thermal storage densities (200 kJ/kg or150 MJ/m3) and a wide range of melting temperatures. They undergo negligible sub cooling and are chemically inert and stable with no phase segregation. However, they have low thermal conductivity (0.2 W/m C), which limits their applications. Metallic fillers, metal matrix structures, finned tubes and aluminum shavings were used to improve their thermal conductivity [14]. Pure paraffin waxes are very expensive, and therefore, only technical grade paraffins can be used. Commercial paraffin waxes, which melt around 55C, have been studied most [15-18].

Sensible heat storage in single-tank storage is cheap and easy, but it suffers from the outlet temperature (recovery temperature) dropping during the discharging process [19]. The thermocline can be formed by storing the heat transfer fluid (HTF) in a single tank or by passing the HTF through solid storage media made of materials mentioned above. A common configuration for solid storage is via a packed bed arrangement. The thermocline can be affected by several parameters such mass flow rate, HTF, thermal wall losses and particle size. The influence of different parameters on the thermocline in packed-bed TES has been studied in literature [20-25]. The present study is focusing on studying the thermal performance using sensible heat storage with air as heat transfer fluid and gravel as storage materials.

1.2 Aims and Objectives

The present study to design a storage tank that can be used to store the thermal energy and thus calculate the thermal efficiency (charging efficiency) of the storage tank. Sensible heat storge will be tested by using gravel. Air will be used as heat transfer fluid. The following are the objectives of the study.

1- Design and build a storage tank with the needed component in the laboratory.

2- Studying the thermal performance of the packed bed system.

CHAPTER TWO

Literature Review

Chapter Two

Literature Review

The most commonly used method of thermal energy storage is the sensible heat method. In solar heating systems, water is still used for heat storage in liquid-based systems, while a rock bed is used for air-based systems. In the application of load leveling, heat is usually stored in a refractory bricks storage heater, known as a night storage heater. These units are capable of providing space heating during the day from the stored heat during the night; however, they are heavy and bulky in size [26].

Several approaches have been considered in the literature to improve the heat transfer rates. However, a promising approach is to increase the heat transfer area by incorporating the PCM mixture in small capsules using suitable shell materials. For example, PCM stored in capsule diameters of 10 mm offer surface area of more than 600 square meters per cubic meter of capsules. Research to find suitable materials and process to encapsulate high temperature PCM is underway . The working of a latent thermocline energy storage (LTES) system in a CSP plant fundamentally involves the exchange of heat between a heat transfer fluid (HTF) and the packed bed of spherical PCM capsules during the charging and discharging processes. With increase in porosity, the sensible energy extraction rate increases while the latent energy extraction rate decreases due to the increase in HTF volume and reduction in the number of PCM capsules respectively This leads to a faster decrease in the exit temperature of the HTF following the discharge of pre-existing hot HTF in the tank [27].

Due to the design concept that only sensible heat of the storage medium is exploited within the operating temperature range, and nearly half of total tank volume is unoccupied by the storage medium during the operation, the two-tank TES system carries a high capital cost and generally accounts for about 20% of the overall cost of a CSP plant and is lack of potential to make a cost reduction. As one of key parameters to evaluate the thermal performance of a TES system, capacity factor in a cyclic state of the thermocline TES is much lower than the one of the two-tank TES system, which is an indispensable sacrifice to reduce the number of tank. Even though, the cost of both storage medium and container can be reduced compared to an equal-scale two-tank system [28].

The thermocline-like TES considered are formed by different elements: thermocline packed bed (filler material and HTF), tank foundation and tank walls, which interact with each other through their boundary conditions, which allows linking between different elements of the thermal system. The mathematical model considers the transient behaviour of the thermocline-like packed beds, the tank walls and insulation, taking into account the variable outdoor conditions. A brief mathematical description, focused on the modelling of the packed bed, is presented hereafter. Two different analyses were performed, one centred in evaluating the performance of the TES systems under specific conditions, in which the TES is charged and dis- charged consecutively until reaching a periodic steady state; and another in which the same TES configurations are tested under 17 days of operation in the reference CSP plant.

In the variation of the operating conditions due to the changes in the direct normal irradiation were simulated, and the tank walls and foundation were taken into account [29].

Stratification refers to the layering of fluid temperatures in a TES system, where warmer fluids tend to rise and cooler ones stay lower. In the context of TES, maintaining good stratification is essential for efficient heat storage and retrieval. The addition of PCM capsules was found to improve the extent of stratification, especially as the temperature difference between the inlet HTF (Heat Transfer Fluid) and the PCM's melting temperature increases [30].

The cyclic thermal performance of the PBTES system with cascaded PCMs is first numerically analyzed to optimize the configuration of the cascaded PBTES system and study the heat transfer mechanism. There is no natural convection of the HTF (air) inside the TES tank since the HTF flows downwards in charging process and flows upwards in discharging process. In the present study, the porous medium model is used. The variations of the thermo-physical properties of HTF (air), including density, thermal conductivity and dynamic viscosity, with temperature are considered. We established a concentric-dispersion mathematical model to compute the transient temperature distribution of molten salt, solid granules, and PCM spherical capsules along the bed and at various periods of a hybrid sensible-latent storage system to characterize cyclic behaviours. Two volume fractions of rock/slag pebbles-PCMs have been adopted based on two distinct scenarios, namely hypothetical and average scenarios [31].

Three working modes are investigated in this study, which are the single charging process, the single discharging process and the multiple charging/discharging cyclic process. During the single charging process, hot molten salt flows into the cold tank through the top port, and flows downside through the packed-bed region re- leasing heat to the packed PCM capsules. The solid PCM in capsules melts to liquid phase after absorbing enough heat from the hot molten salt, and thus heat is stored in the PCM capsules. While during the single discharging process, cold molten salt flows reversely from the bottom to the top and is heated by the hot PCM capsules, in which liquid PCM is solidified after releasing heat. The cyclic process includes multiple consecutive charging/discharging cycles, during which hot molten salt flows into the cold tank through the top port during charging processes while cold molten salt flows into the hot tank through the bottom port during discharging processes [32].

The effect of the various design and operating parameters on the performance of the EPCM-TES system is studied by varying one parameter at a time with the rest of the parameters at the default value. Since a thermal storage system installed in a CSP plant is subjected to repeated charging and discharging processes, the dynamic behavior of the EPCM-TES system is analyzed in the present study. Initially, the tank is kept in a fully discharged state and charging takes place as hot HTF flows into the tank from the top until the temperature of the HTF flowing out of the storage system reaches a certain maximum charging cut-off temperature. An EPCM-TES model accounting for axial variation of temperature in the HTF and radial temperature variation in the PCM at any axial position is solved and the effects of various nondimensional design and operating parameters on the dynamic performance of the storage system are analyzed. Important results pertaining to the analysis [33].

gravity-assisted heat pipes effectively transfer heat when the hot medium is below the cold medium. All stages of heat transfer during charging including (i) preheating of solid PCM that is initially below its melting temperature, (ii) melting, and (iii) further heating of completely molten PCM are considered. During discharg- ing, heat transfer associated with (i) cooling of superheated PCM, (ii) solidification, and (iii) cooling of subcooled PCM is accounted for. Storage utilizing single PCMs is also considered, and the single-PCM performance is compared with that of the cascaded LHTES system. Heat transfer between the HTF and PCM is determined by application of a thermal network model based upon the following assumptions. All PCM properties are assumed to be constant in both the liquid and solid phases, and PCM phase change occurs at a fixed temperature. LHTES) utilizing phase change materials (PCMs) relative to sensible heat storage include a higher energy density and the potential to minimize the temperature difference in the storage media. However, the low thermal conductivities of typical PCMs have precluded their use in large scale applications [34].

The utilization of renewable energy is widely considered as an efficient solution to the global environmental pollution caused by the overuse of fossil fuel. the related research on solar thermal. utilization has been rapidly developed Because of the unstable and intermittent nature, the integration of thermal energy storage (TES) system in the concentrating, solar power (CSP) systems play an important role to improve the stability of the power generation system and the energy utilization efficiency. TES can be divided into the two-tank heat storage system and the single-tank heat storage system. The two tank heat storage system is most widely adopted in the commercial market but its disadvantages include high consumption of molten salt, large plot area and more investment costs. The thermal storage mediums normally are sensible thermal storage materials including quartz sand, rock, ceramic [35].

CHAPTER THREE

Experimental Work

Chapter Three

Experimental Work

3.1 Introduction

This chapter details the properties of the experimental storage vessel, flow loop setup, and experimental conditions. A numerical model is also introduced, which is utilized to verify the performance of the experimental setup at baseline conditions. Finally, the thermal efficiency equations are presented for the charge cycle.

3.2 Components of the experimental system

This section explains the design of the experimental storage tank, the heater used to provide the desired temperature, air blower and the inlet/outlet pipes used to connect the entire system and achieve charge process.

3.3 The storage packed bed (cylindrical storage vessel) design

The apparatus used in the present work shown in **Figure 1** was designed and built in the heat transfer laboratory (College of Engineering- University of Misan). The storage packed bed is a vertical cylindrical vessel made of stainless steel 304 which is characterized by its high durability and resistance to high and low temperatures. The outer and inner diameters are 8 inch (20.32cm) and 7.68 inch (19.52cm) respectively (8″ NPS schedule 10 with 0.157″wall thickness). The connections at the inlet and outlet of the vessel are torispherical flanges. The length of the cylindrical vessel is 80 cm. The storage packed bed length is 60 cm. The inlet side at the top and outlet side at the bottom. To obtain uniform flow through the vessel, distributers were used at a distance 10cm from the inlet and outlet of the storage tank. The distributor also prevents the storage materials from falling in the inlet and outlet pipes. External insulation (Fiber glass) is used with 1 cm thickness to insulate the storage tank from the environment. The inlet and outlet of the vessel is ½ inch (1.27 cm) FNPT (Female National Pipe Thread). At the surface of the cylindrical vessel seven holes were drilled of ¼ inch (0.635 cm) FNPT along the axial length to insert a K-type thermocouples to read the temperature variation inside the storage vessel. Seven thermocouples were used starting at $x = 0\ cm\ to\ x = 60\ cm.$ The sensing points are evenly spaced at 10cm (TI1− TI7). The radial location of the seven sensing points inside the storage bed is $r = 0\ cm$. In addition, two thermocouples are used to record the temperature at the inlet and outlet of the storage tank. The error associated with the thermocouples is ± 2.2℃ as specified by producer. Digital Thermal Camera was used to record the temperature at the surface of the insulation. All thermocouples are connected to a data acquisition system to read and record the temperature data every five minutes.

Figure 1: The schematic of the cylindrical storage packed bed used in the present study.

3.4 Heater, blower, insulation and charging configuration

An electric heater is used to heat up the air coming from the blower and thus provides the required heat energy which is shown in **Figure 2** (on the left). Control unit (**Figure 2**, on the right) is used to control the outlet temperature from the heart and thus provides the desired temperature. The maximum outlet temperature that the heater can provide is approximately 350°C.

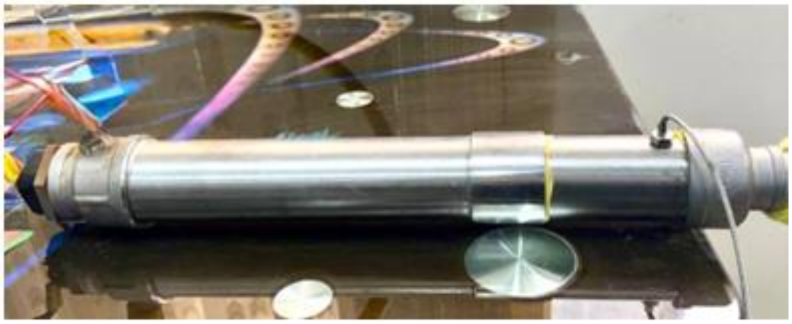


Figure 2The electric heater (on the left) used to provide the desired inlet temperature. The temperature controller (on the right) used to control the outlet temperature from the heater.

A commercially available blower (Figure 3, on the left) with power of 0.37 kW is used to provide the required cold air which is then heated by the electric heater mentioned above. On flow is used in the experimental work which is 0.0001901 m^3/s. Digital Anemometer (Figure 3, on the right) was used to measure the outlet velocity from the system and based on the pipe area, the volumetric flow rate is determined.

Figure 3: Air blower used to provide cold air to the storage system on the left. Digital Anemometer (on the right) used to measure the outlet velocity from the system

In order to reduce the heat losses to the environment, external insulation was used as can be seen in **Figure 4**. Commercial glass wool was used to insulate the tank and pipes. The thermal conductivity of the insulation is 0.03 (W/m. K) and the thickness of the insulation is 1 cm.

Figure 4:The storage vessel showing the external insulation used to reduce heat losses to the ambient.

Figure 5 shows the storage tank with the connected pipes used to provide the hot air during the charging process. During the charging process, hot air is entered the storage packed bed from the top of the vessel to deposit heat into the storage materials (gravel). After depositing the hot energy in the packed bed, the air leaves as cold air from the bottom of the vessel and is then vented to outside of the lab room. A couple of open gate valves are connected on the direction of the hot air to control the flow and let the air goes in the right direction during the charging process. The diameter of the used pipes is ½ inch in the entire system. Gravel was used as storage material with one size (X mm) which can be seen in **Figure 6**. Air at room temperature was used as working fluid which was provided using a blower. The air

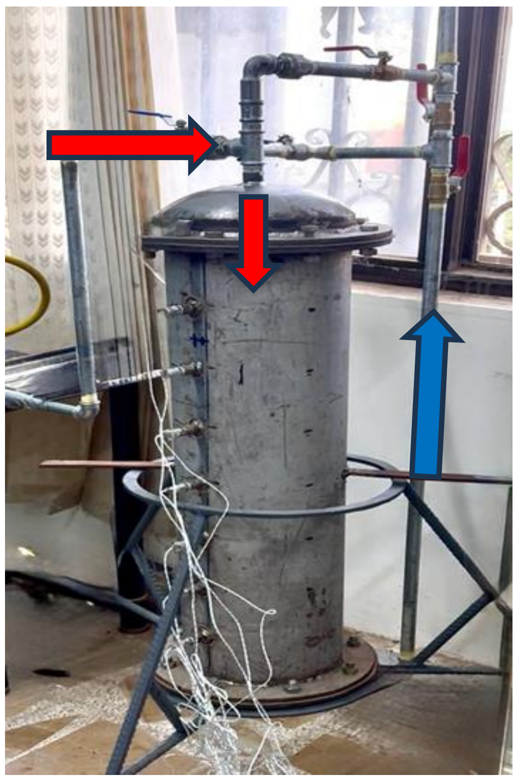


Figure 5:The storage packed bed showing the direction of hot air during the charging process. Red arrow is the hot air etering the storage packed bed. Blue arrow is the cold air leaving the storage packed bed

was heated using the electrical heater to provide the inlet temperature, 100℃.

The properties of the entire system are provided in **Table 1**.

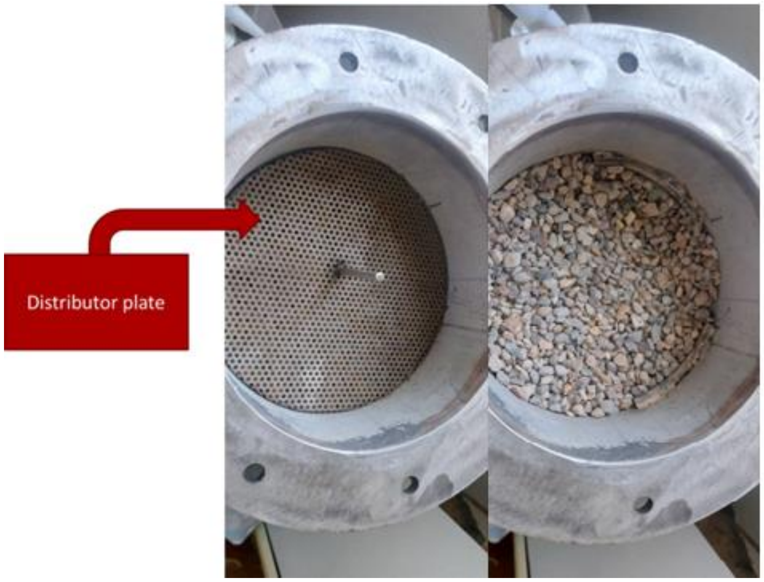


Figure 6:The storage packed bed filled with storage materials (gravel). A screen was used to provide uniform flow inside the storage tank.

Table 1: Thermophysical properties of the storage tank, storage materials and insulation [36, 37]

Property	Value	Unit
Stainless steel 304		
Density	7930	Kg/m3
Thermal conductivity	16.2	W/m K
Heat capacity at constant pressure	500	J/kg K
Gravel		
Density	1460-1920	kg/m^3
Thermal conductivity	1.5	W/m K
Heat capacity at constant pressure	840	J/kg K
Insulation		
Density	20	Kg/m3
Thermal conductivity	0.03	W/m K
Heat capacity at constant pressure	840	J/kg K

3.5 Experimental procedure, calibration, test method and collecting data

The bed is filled with the storage materials (gravel). The gravel used had an average diameter of (10 mm), and a porosity of 0.4 [36]. Small-sized gravel was used because it has a larger surface area relative to its volume, enabling it to absorb heat more quickly. Smaller sizes also conduct heat more evenly, increasing short-term storage efficiency. However, pressure drop increases with small sizes leading to a reduction in net efficiency from the storage system. After the bed was filled with storage materials, the packed bed is closed with the torispherical flanges. Then, the entire system is connected (blower, heater, inlet and outlet pipes). The outlet of the blower is connected to the inlet of the heater and the outlet of the heater is connected to the inlet of the storage tank. The pipes from the outlet of the heater to the inlet of the storage tank is insulated to minimize the heat losses to the ambient. The thermocouples were connected to a data logger to record the temperature inside the storage vessel during the charging process. The system is ready to collect the required data points. However, the inlet temperature should be constant during the charging process to provide constant energy during this period. Therefore, calibration is needed. The calibration was done by setting the heater temperature higher than the inlet temperature and data was collected for several hours until the systems reached steady state. As an example, **Table 2** and **Figure 7** show the calibration process that have been achieved in the lab to get inlet temperature of 100℃.

Table 2: Inlet temperature calibration.

Heater temperature (°C)	Temperature before the inlet of the bed (°C)	Temperature at $x = 0$ (°C)	Time
120	80.1	26.8	1:00 PM
120	92.9	59.1	1:15 PM
130	102.6	82.4	2:00 PM
140	116	96	2:45 PM
145	118	98	3:10 PM
150	120	102	3:20 PM
144	114	100.3	4:10 PM

Figure 7:Images from data logger showing the temperature from two sensing points. Sensing point 1 (01) between the outlet of the heater and the inlet of the storage tank. Sensing point 2 (02) at x = 0 inside the storage tank.

Charging process was tested only by running the experiment for four hours during the charging cycle. Charging represents half of the cycle and discharge process represent the second half of the cycle. The charging process was stopped when the outlet temperature from the bed exceeded the room temperature which was approximately 28°C. The bed was heated for four hours and the temperature was recorded during the entire charge time. The temperature data points were exported to excel file which then analyzed and plotted as will be seen in chapter four.

3.6 Energy and charging efficiency

Based on the first law of thermodynamics (steady-flow thermal energy equation), Eqn. 1 determines the energy stored in the bed domain [38].

$$Q_{bed} = \int_{T_o}^{T_{bed}} mCp_{\mathbf{Gravel}}(T)dT \qquad (1)$$

where T_o and T_{bed} are the initial and averaged bed temperature, m is the mass of gravel, and $Cp_{\mathbf{Gravel}}$ is the heat capacity of the alumina beads. [39]. The total energy delivered to the system is defined in Eqn. 2:

$$Q_{supplied} = \dot{m}Cp_{air} \int_0^{t_s} (T_{hot} - T_o) dt \qquad (2)$$

where $\dot{m}$ is the mass flow rate, Cp_{air} is the specific heat capacity of the air (constant here), T_{hot} is the inlet temperature ($T_{hot} = 100°C$ which is approximatly $\approx 96°C$), T_o is the ambient temperature, and t_s is the storage time.

Eqn. 3 calculates the charging efficiency, which is the ratio of energy stored in the bed to energy supplied to the storage bed.

$$\zeta_{charging} = \frac{Q_{bed}}{Q_{supplied}} \qquad (3)$$

CHAPTER FOUR

Results and Discussions

Chapter Four

Results and Discussion

4.1 Introduction

In this chapter the results of temperature distribution inside the storage packed bed, heat losses to the ambient and charging efficiency from the experimental work will be presented and discussed.

4.2 Temperature distribution vs. Time

Figure 8 shows the temperature profiles during the charging process from the seven sensing points located at $r = 0$ cm and a long the axial length of the storage packed bed ($x = 0$ to $x = 60$ cm). Initially, the bed at room temperature (~ 25℃) as can be seen from all sensing points. Then, the temperature inside the bed increases due to the starting of charging period where heat transfer fluid (hot air) enters the bed from the top and leaves from the bottom after depositing the heat into the storage materials (gravel). The inlet temperature is 100℃. However, the inlet temperature is ~ 97.5℃ which means calibration should be checked a second time. The charge time is 260 minutes. The charging process stops when the outlet temperature exceeds the room temperature. In the present study, the charge period stops when the outlet temperature starts to be 30℃ which considered as the cut off temperature. In addition, heat losses from the storage packed bed is high leading to a reduction in the bed temperature as will be seen in the next sections.

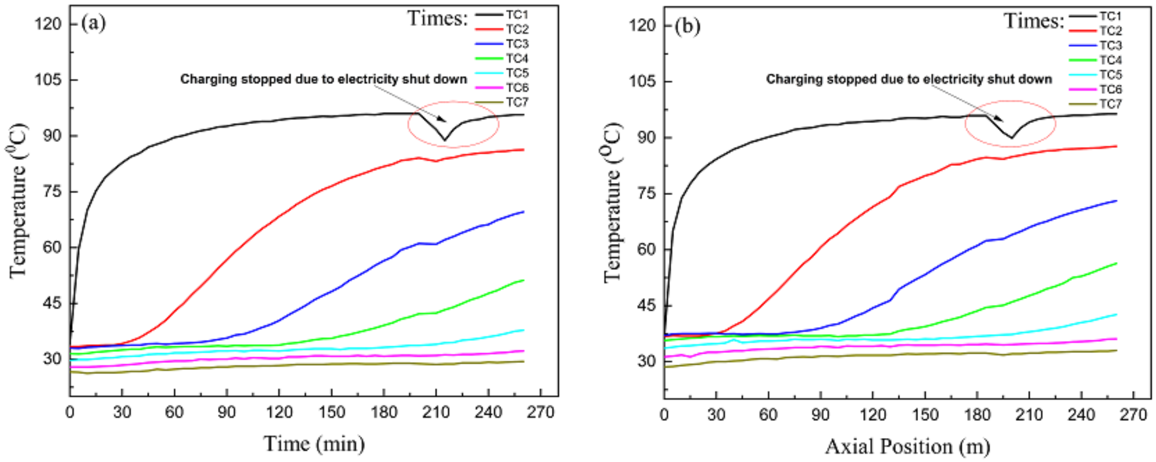


Figure 8:Experimental temperature profiles during the charging process for four hours from seven sensing points. a) Trail 1 and b) Trail 2.

4.3 Temperature distribution inside the storage packed bed

Figure 9 shows the temperature distribution inside the storage bed along the axial length at several time intervales. Initially, the bed at low temperature. Then the temperature inside the bed increases with the increase of time during the storage process where the hot air passes through the bed and deposits hot energy into the gravel materials. As can be seen the bed is at high temperature at $x = 0\ to\ x = 20\ cm$. At $x = 40\ to\ 60\ cm$, the bed at low temperature during the entire charging period. The temperature gradient along the length of the packed bed can be seen clearly in the graphs. The temperature front spreads through the bed due to thermal dispersion effects and the heat losses to the environment. The heat losses increase with time, and at the end of charging the inlet of the vessel has more stored energy (higher temperature) than the exit of the vessel due to these losses. [39-41]. These losses affect the thermal front inside the bed and the amount of energy stored into the storage packed bed and thus affects the thermal/charging efficiency. At time intervale of 210 min, the shut down in the electricity led to the reduction in temperature at sensing point TC1 ($x = 0\ cm$) for about 5-10 minutes.

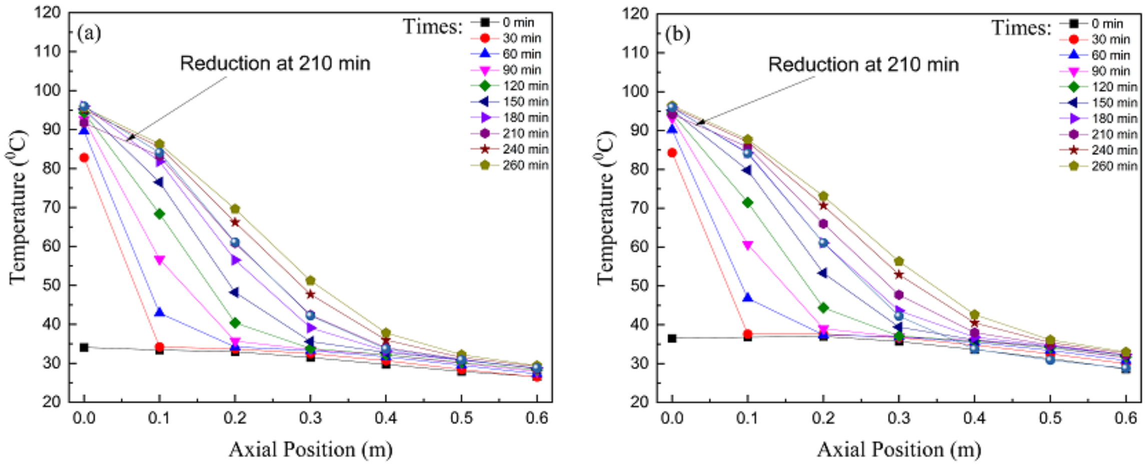
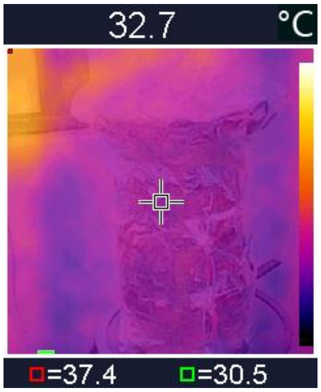


Figure 9: Experimental temperature profiles during the charging process along the axial length at different time intervales. a) Trail 1 and b) Trail 2

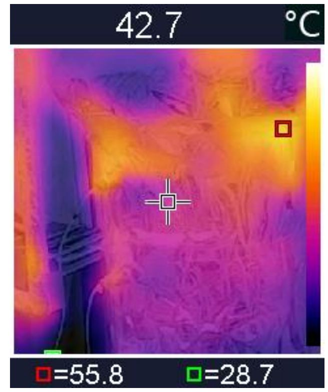
4.4 Heat losses to the environment

Heat losses to the ambient have significant influence on the stored energy in the storage packed bed. Heat losses occur due to conduction through steel wall and insulation and by convection to the ambient. Commercial glass wool was used to insulate the packed bed from the ambient and prevent heat losses. However, significant impact of heat losses was noticed during the charging process as can be seen in **Figure 10,** where a thermal digital camera was used to take images during the charging process at several time intervales. As can be seen the amount of heat losses to the ambient is very high due to the high temperature at the surface. At the inlet of the bed domain x = 0 cm the temperature of the surface reaches about 44.7°C which indicates that heat losses to ambient is very high and thus reducing the energy stored in the bed and thus charging efficiency as will be seen next.

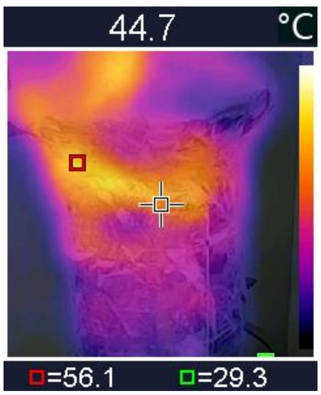


$t = 0\ x = 0\ cm$

$t = 60\ min\ x = 0\ cm$



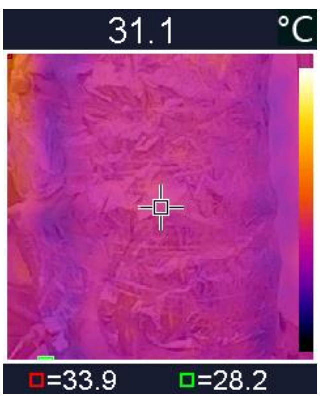
$t = 120\ min\ x = 0\ cm$



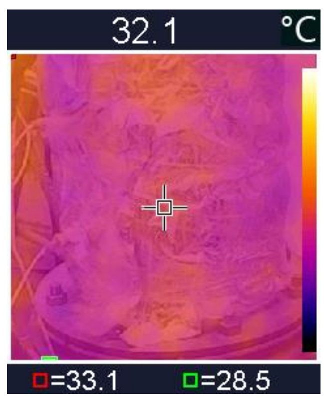
$t = 180\ min\ x = 0$

$t = 0\ min,\ x = 60\ cm$

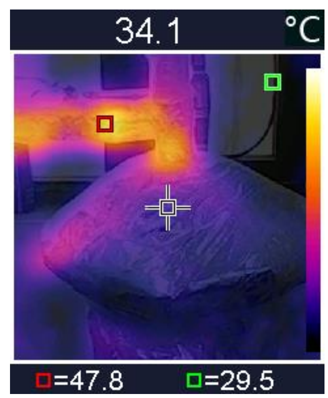
$t = 60\ min, \quad x = 60\ cm$



$t = 120\ min, \quad x = 60\ cm$



$t = 180\ min, \quad x = 60\ cm$



$t = 0\ min, Bed\ inlet$

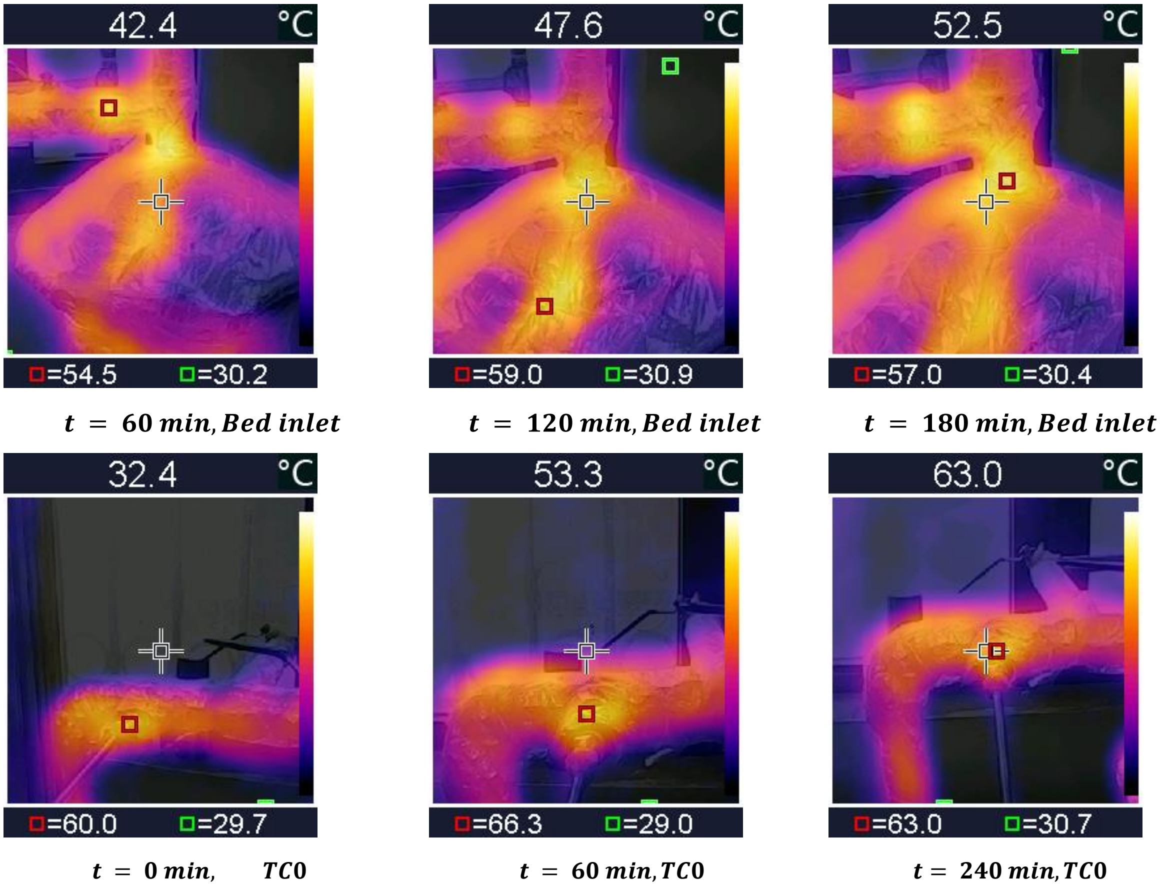


Figure 10 :Temperature of the surface of the insulation wall (storage bed and pipes) showing the amount of heat losses to the ambient. Note: TC0 is the sensing point at about 20 cm before the inlet of the bed.

4.5 Energy stored in the storage packed bed

Figure 11 shows energy stored in the storage packed bed during the charging process. The total energy was calculated by volume averaging the bed domain temperature at each time point during the charging process. The final total energy is 992.04.9 kJ. Dividing the total energy delivered by the HTF over that time yields thermal energy efficiency during the charging process. The energy stored in the bed can be increased and thus the thermal efficiency during the charging process by reducing the heat losses to the ambient.

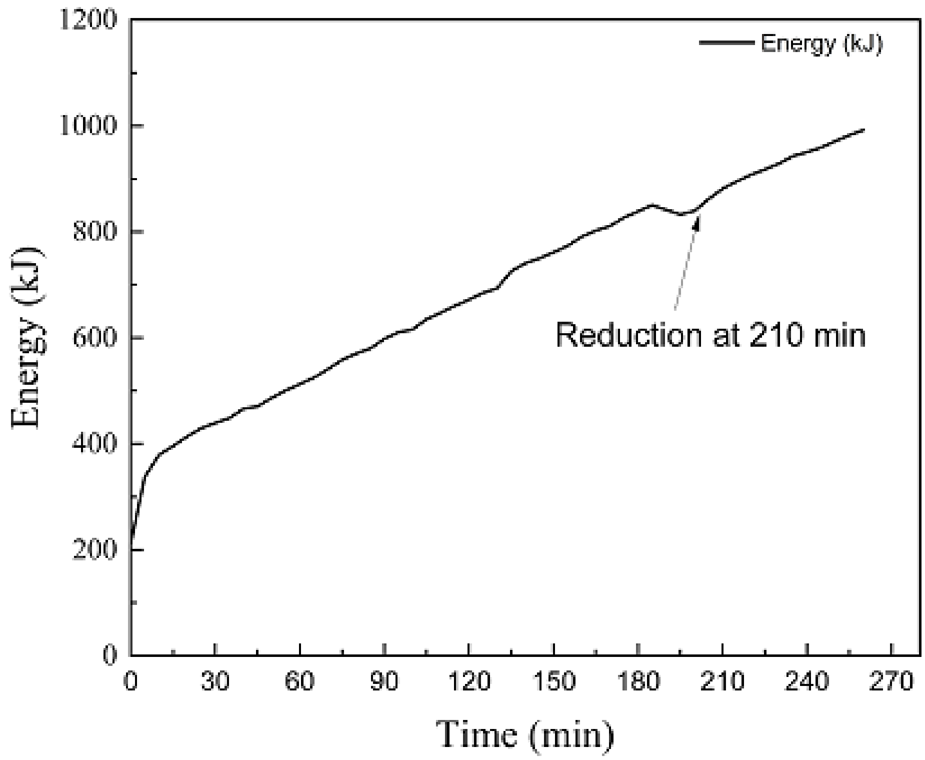


Figure 11: Thermal energy stored in the bed over time during the charging process.

CHAPTER FIVE

Conclusions and Recommendations

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

Thermal energy storage is an air-gravel storage packed bed was studied experimentally. Air was used as HTF with an inlet temperature of ~97 ℃ and gravel was used as storage materials. The analysis was done during the charging process focusing on temperature profiles in the storage tank, heat losses and energy stored. It was found that the total energy stored in the packed bed is approximately 992.04 kJ. Heat losses from the storage system is very high and should be reduced to improve the thermal performance of the storage system.

5.2 Recommendations

1. Study the discharge process and then calculated the net thermal efficiency.

2. Utilize phase change materials (PCMs) at the inlet, outlet, or in the middle of the tank to enhance system efficiency and compare the thermal performance to the current findings

3. Use better insulation materials with lower thermal conductivity for insulating the pipes and the packed bed. Or increase the thickness of the current insulation.

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