Thermal Analysis of a Sensible Heat Thermal Energy Storage System Using Circular-Shaped Slag and Concrete for Medium- to High-Temperature Applications

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Session 2018-20

Supervised by

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THESIS ACCEPTANCE CERTIFICATE

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Abstract

Thermal energy storage (TES) systems are a technique for storing thermal energy in a storage media for later use in industrial processes to balance demand. Decrease dependency on nonrenewable energy reserves while shifting part of the load to renewable energy resources are both necessary and desirable outcomes. The level of nonrenewable energy reserves is diminishing on a constant basis. It is therefore important to store the thermal energy to be utilized later on. Due to the shortage of energy supply, there is a demand in research of thermal energy storage (TES), therefore an agile field in applied energy. The proposed sensible thermal energy storage tank, which is comprised of concrete blocks and heat transfer fluid (HTF) passageway has been used for further evaluation. The introduction of slag and concrete particles into the heat transfer fluid route is done in order to evaluate the performance of the TES system. Ansys fluent has been used for numerical modeling to develop the combined energy balancing technique with enthalpy based methodology for analysis of charging and discharging cycles for a specific period of time. The numerical modeling results shows that during charging and discharging cycles of the thermal energy storage system, the thermal distribution of temperature has varied at various time intervals during the cycle. For the purpose of thermal performance study, two distinct configurations are analyzed by using numerical simulations. Circular slag particles are put in front of the HTF flow in the first configuration, while circular concrete particles are placed in front of the HTF flow in the second configuration. In compared to a TES tank that was filled with slag, the concrete-filled TES tank charged and discharged more swiftly than the former. TES tanks loaded with concrete are more efficient than TES tanks filled with slag, according to the research.

Keywords: thermal energy storage; sensible heat storage; temperature distribution; numerical modeling;

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List of Abbreviations

PV	Photovoltaic
CSP	Concentrated Solar Powerplant
TES	Thermal Energy Storage
LCOE	Levelized Cost of Electricity
PCM	Phase Change Material
GHG	Green House Gases
LTES	Latent Thermal Energy Storage System
STES	Sensible Thermal Energy Storage System
HTF	Heat Transfer Fluid
CFM	Cubic Feet Per Minute

List of Publications

1. **Yasir Saleem**, Jamsheed Sajid, Naveed Ahmed "Thermal analysis of sensible heat thermal energy storage system using circular-shaped slag and concrete for medium to high-temperature applications". In 1st International Conference on Energy, Power and Environment (ICEPE-2021)**.** Presented: 11 November 2021.

CHAPTER 1

Introduction

1.1 Background

Pakistan is a developing nation with a larger demand for energy than available supply. There is an imbalance between demand and supply and has shortfall of 40% [1]. Even developed nations are investing in renewable energy resources harvesting. The amount of conventional energy reserves is dwindling by the day. Furthermore, these fuels are causing harm to the natural climate system. There is a need of promotion of investment in clean energy projects [2]. The use of nonrenewable energy reserves may be reduced by improving technology efficiency and moving some energy load to renewable energy sources [3]. Pakistan's industries are operating at a lesser capacity than intended. Thermal energy waste accounts for a significant quantity of energy. Drying is used in a variety of sectors, including leather, textiles, pharmaceuticals, and food. As a result, thermal energy storage devices may be employed to distribute waste or excess energy (in the form of solar thermal) as required [4]. To utilize waste energy for later use, there is a need for research into various storage systems and storage materials. The main reason is to adopt these systems is unavailability of energy constantly and usage of waste energy.

1.2 Solar Energy Potential in Pakistan

Pakistan is situated in northern side of the equator line and has enormous solar energy potential for both PV and CSP plants. The results obtained from the solar atlas for solar irradiation and PV electricity output show a high potential of solar power throughout the country. An average value of 4.1 kWh/kWp per day is obtained from an installed capacity of 1 KWp. The solar potential is estimated to be over 2900 GW [5].

1.3 Industries in Pakistan

Industries in Pakistan involve different processes in which high temperatures are used. High temperature fluids are used for drying purposes in various industries such as food, leather and pharmaceutical industries [6]. After their objective some heat energy is remained which can be recovered through thermal energy storage systems. Before entrance of boiler heat transfer fluid can be used for thermal energy storage for later usage. Almost 800 tanneries are working in Pakistan and producing waste. Waste heat energy up to 60 percent of recovered is surplus for drying purpose can be used for on site boiler or thermal energy storage systems [7]. All Industries are moving towards sustainability to strengthen their asset. They are implementing gasification process to use solid waste [8]. Thermal energy storage systems are also integrated with these processes to enhance efficiency.

1.4 Thermal Energy Storage

Due to the shortage of energy supply, there is a demand in research of thermal energy storage (TES), therefore an agile field in applied energy. It can be used in solar power plants and various industrial processes for better efficiencies and minimized the LCOE (levelized cost of electricity). A technology with sensible storage materials is matured and implemented practically[9]. Technology includes the energy efficiency and conservation through shifting load from peak hours to off peak hours and minimized the expenditures. Similarly, in the scenario of solar energy this technology saves abundant thermal energy at day time for later usage [10]. The main trump card for this system is to fuse with existing system and save the cost of again fitting. Below figure shows the basic working principle of thermal energy storage system.

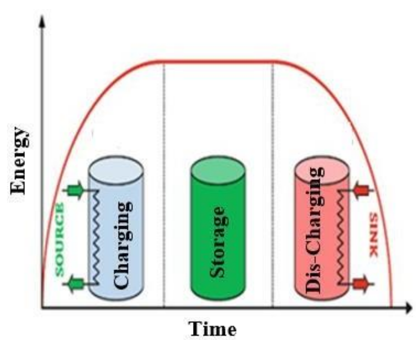

Figure 1-1 Schematic of simple TES [4]

A rudimentary TES system is depicted in the diagram above. During the charging phase, the system is charged using a source. Solar thermal, electric, or natural gas can all be used as a source.

The energy is held in a storage tank when the system is fully charged and transferred to the load/sink when needed, as shown in the graph.

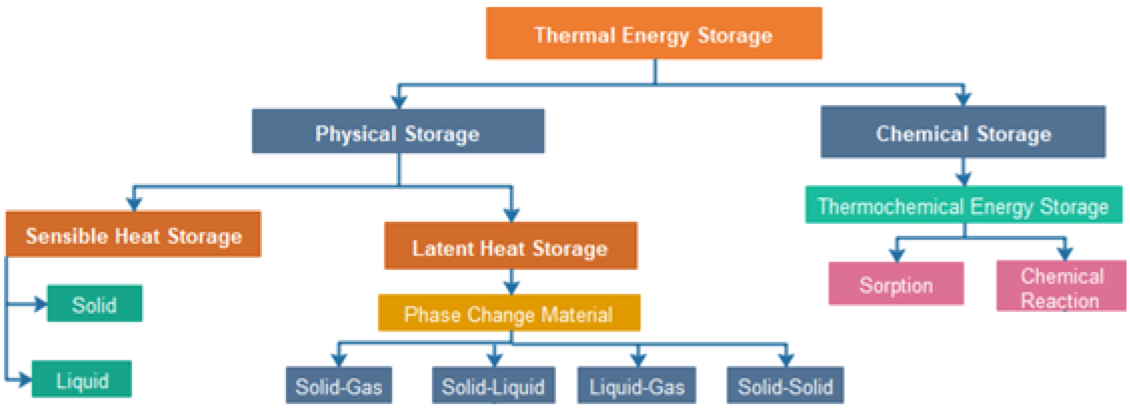

Figure 1-2 Classification of Thermal Energy Storage Systems [10]

TES systems are further classified into a variety of categories according on the uses or storage material employed. The various types of thermal storage are depicted in the diagram below. TES systems can be generically divided into two kinds. The first is known as physical storage, which does not entail any chemical changes to the substance, and the second is known as chemical or thermochemical storage, which involves chemical changes to the substance over each temperature cycle, reducing the system's durability. Sensible (which does not change phase during the heat cycle) and Latent (which does change phase during the thermal cycle) physical storage are the two basic categories (which changes phase during the thermal cycle, solid-liquid, liquid-gas etc.).

1.5 Selection of TES System

Due to the presence of various TES systems, suitable TES system is chosen. Different factors play role in the selection of TES system including durability, commercial workable, temperature, storage density, capacity, efficiency, cost, and storage volume. Factors may be varied according to required application. Sensible thermal energy storage system is selected because of more factors support.

1.5.1 Selection of Materials

The TES material is chosen based on the application. The primary criterion for first material selection is the melting temperature. Various features of the material, such as thermo-physical and chemical qualities, are vital to consider while selecting materials. These attributes are important as inherent material features, but there are also some external factors that influence material selection, such as cost, commercial availability, product safety, flexibility, and reliability after repeated temperature cycles. Concrete has numerous benefits as a prospective solid TES material, including low cost, consistent mechanical and chemical performance, large volumetric heat capacity, and a wide working temperature range. Laing et al. [11] has put in a lot of time and effort into developing high-temperature concrete. At high temperatures, they investigated the thermal performance of concrete and the mechanical compatibility of concrete and metal tubes. Solar trough plants, industrial waste heat, and combined heat and power systems can all benefit from the technique. Concrete storage is expandable from kW h to GW h due to its modular construction. Thermal storage in concrete has only been tested and proved in temperatures up to 400°C so far. Currently, progress is being made reaching a temperature of 500°C. After consideration of various factors concrete material is selected for TES tank. Thermal energy storage is recognized as a promising thermal energy storage technology because of its low heat loss absorption and high thermal storage density [12]. While sensible energy is kept in liquids, today's energy storage technology is at an advanced state [13]. Comparison of three different sensible thermal energy storage systems conclude that lower thermal mass storage system charged quickly [14]. Improved concrete thermal conductivity helps to produce a more uniform temperature distribution in concrete, resulting in higher energy efficiency [15]. The behavior of a concrete thermal storage module may be predicted using a simple lumped capacitance model, which has been validated, developed, and suggested [16]. Slag is used as a waste material in the thermal energy storage tank. Slag is stable up to 1000 degrees Celsius. The heat capacity is large, and as the temperature rises, so does the specific heat capacity. It also has a high wear resistance, indicating that slag is useful for thermal energy storage systems [17].

1.6 Problem statement

Excessive amount of energy is wasted during various processes. Basically, there is a need to store the excess thermal energy in thermal processes, as we stated for medium to high temperature applications. A lot of thermal energy is wasted in industrial processes and in this research, thermal energy storage tank configuration is given in which can store that waste energy and used later when needed.

1.7 Objectives

The literature review indicates that studies have been conducted for sensible thermal energy storage system but there is a gap to investigate the thermal performance of new introduced storage materials. The objectives of current research work are

1. To propose a sensible heat TES system using naturally occurring and cost-effective sensible heat storage filler
2. To investigate thermal performance of the proposed TES configuration during charging and discharging cycles through numerical simulations.
3. To compare thermal performance of TES system filled with concrete storage material, and waste material slag.

1.8 Scope of Study

The use and recovery of renewable and waste energy through thermal energy storage devices is a problem addressed in this thesis. A TES tank has been designed to effectively overcome this problem. This tank can be used in conjunction with industrial waste heat or renewable energy sources to store excess energy for future use. Energy scarcity is a serious concern these days, and TES system technology should be integrated to address it.

1.9 Organization of the thesis

The following is a synopsis of the thesis proceedings.

- **Chapter 2**

The literature relevant to TES systems will be discussed in this chapter. Different materials and systems will be discussed from the literature. The material characteristics of Concrete and Slag will be explored in detail. The system's formulation and modelling will be examined, and the research gap will be identified based on the available literature.

- **Chapter 3**

This chapter will describe the modelling of TES system discussed in the thesis. 2D cad model is presented with its dimensions. Governing equations are described along with mesh details and boundary conditions of 2 cases (Charging cycle and discharging cycle).

- **Chapter 4**

Simulations results on Software are presented through various figures and graphs. In this chapter comparison of 2 different cases will be discussed. Temperature profiles of storage materials and HTF at various time intervals will be discussed.

- **Chapter 5**

Conclusion and future work recommendations.

Summary

In this chapter problem statement is discussed. In the beginning different storage systems are discussed and then the suitable and cost-effective method to utilize the abundant energy or waste heat during processes through efficient storage materials are discussed. From various storage materials cheaper materials are selected to examine their performance for thermal energy storage systems. Different thermal energy storage systems basics are discussed and classified. After that storage materials are discussed and at the end of chapter problem statement was described for better understanding.

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CHAPTER 2

Literature Review

Due to the daily scarcity of nonrenewable energy reserves, renewable energy options must be investigated for energy needs. They are also pricey owing to limited supply due to higher cost, environmental pollution, and health issues. Renewable energy-based smart energy systems are gaining popularity. The temporal mismatch between energy supply and demand is also a difficult issue to deal with which can be bridged by designing a thermal energy storage system for adding or removing heat from a storage medium at different time intervals [1].

TES devices may store heat or cold for later use, depending on a number of criteria such as temperature, location, and power. Sensible heat, latent heat, sorption, and chemical energy storage (sometimes known as thermochemical) are the three categories of TES systems that all rely on heat [2]. The increasing usage of renewable energy sources has enhanced the importance of research and development in the field of energy storage during the last two decades. Infrequent sources of energy like as wind, sun, and tides provide energy, but they may not always provide it at the same pace as that which is required in urban areas to meet demand. Mismatches between power supply and demand arise as a result of the transition from old fossil-fuel-based energy systems to new energy systems that include a significant proportion of renewable energy [3].

According to the International Energy Agency, global energy consumption is expected to grow at an exponential rate. In most nations, natural gas and coal resources account for a significant portion of overall energy output. It's crucial to remember that they're very rare, and their numbers are dwindling as a consequence of misuse. If their prices continue to climb in the near future [4] they may become more expensive in the near future. Thermal Energy Storage (TES) devices, in the form of thermal energy storage devices, may be considered a solution for energy conservation in the industrial and construction sectors (TES) [5]. The TES is well-equipped to cope with the issue of energy supply and demand being out of sync. Because they may be utilized in both active and passive systems, they improve waste energy efficiency. The effective use of thermal energy and the application of peak load shifting technologies [6] are two more key benefits. They are more cost-effective in general, requiring less investment and maintenance, emitting less CO2, and so contributing to pollution reduction [7].

2.1 Types of Thermal Energy Storage (TES) Systems

The following are the three types of sensible heat storage:

1. Sensible heat storage
2. Latent heat storage
3. Thermo-Chemical Storage (TCS)

Thermochemical energy storage and latent heat energy storage are two separate methods of energy storage.

Thermal energy may be stored via the sensible heat storage method, which involves heating or cooling a solid or liquid heat storage medium. As a result of the supply or removal of heat, temperature changes may occur. Sand, dissolved salt, pebbles, water, and a variety of other materials are among the materials that may be employed. Water is the most cost-effective solution for a practical heat storage system owing to its high heat capacity and cheap cost of manufacturing. Several different materials are used to transmit latent heat from one phase to another (PCMs). The quantity of energy taken or released is the major focus of attention with each phase transition. When designing a latent heat storage system, temperature variations are ignored. A phase shift is the transition from a solid to a liquid state that happens as a consequence of a chemical reaction. TCS is a chemical-based technique for storing and releasing thermal energy [7], [8]. Thermodynamic storage and release (TCS) is a method for storing and releasing thermal energy. The many diverse kinds of heat storage materials that are presently accessible are shown in Figure B1. Sensible heat storage is often favored over PCM and TCS systems because it is more cost-effective. This kind of storage may be used for a variety of reasons, both home and commercial, with solar energy for district heating being one of the most often requested solar energy applications. In comparison to PCM systems, which have about three times the energy density of TCS systems and nearly five times the energy density of TCS systems, sensible heat storage systems have a comparatively low energy density. As a consequence, these systems need a significant quantity of material. They should also be built in such a manner that thermal energy may be released at a consistent temperature.

Thermal energy storage is an essential and dynamic subject in applied energy since it includes energy efficiency and conservation mechanism [9]. It can meet the energy demands of peak-load hours by storing energy during off-peak hours. Solar energy, for example, conserves energy during sunny days and utilizes the same stored energy for space heating and cooling and energy demands at night. It also reduces renewable resources' erratic behavior [10]. The fundamental goal of using thermal energy storage (TES) systems is to overcome the gap between energy use and generation [11]. Thermal energy storage systems can be divided into (1) physical storage, which involves no chemical changes in substances, and (2) chemical/thermochemical storage, which includes chemical changes in substances during each cycle. The sensible (no change during the heat cycle) and latent (no change during the thermal cycle) types of physical storage systems are further separated (phase change occurs due to thermal cycle) [12].

2.1.1 Sensible heat storage

One of the main goals of a Sensible Heat Storage (SHS) system that stores thermal energy released by raising the temperature of a substance in either the solid or liquid phase is to increase the quantity of thermal energy stored. A system like this uses the heat capacity and temperature change that occurs in the material during charging and discharging activities, both of which are crucial, to achieve these tasks. As the temperature, specific heat of a medium, and amount of storage material present all change, the amount of heat that can be stored increases. When it comes to constructing a productive company, selecting the most appropriate materials for the task is crucial. In a nutshell, the following are the essential characteristics for a storage media, in no particular order:

- It also has to have a lengthy service life and a large heat storage capacity.
- It should be able to resist several charging and discharging cycles without deteriorating structurally, in terms of storage capacity, or in terms of performance.

- They are less expensive since they are simple to get, handle, and store in basic containers.

2.1.2 Latent heat storage

Phase Change Materials (PCM) play a crucial role in the efficacy of latent heat storage systems. The chemical bonds that keep the PCMs together weaken as the temperature of the source rises, causing the material to go through a phase transition and solidify. This transition happens from solid to liquid in PCMs that have both solid and liquid phases. This phase shift is an endothermic reaction, meaning it requires heat to complete its transformation cycle. As a consequence of this technique, the PCM absorbs heat. The heat that has been held in the storage medium during the transition causes the material to melt once it reaches the phase transition temperature. The temperature remains constant during the melting process until the whole treatment is done. For the sake of this discussion, latent heat is defined as heat stored during a phase transition process, which in this case is the melting process. The following are some of the advantages of latent heat storage (LHS):

- It has a high storage density, which is helpful; moreover, since changing phase at a steady temperature takes time, temperature differences may be smoothed out.
- it has a long lifespan.

When latent heat storage systems are compared to sensible heat storage systems, it is discovered that LHS systems may reach storage densities five to ten times higher than sense heat storage systems (SHS). The volume of PCM storage is about two times that of water storage. In terms of temperature range, there are no limitations on how these LHS systems may be used. It is generally known that at any requisite heat of fusion temperature, a significant portion of PCMs melt. However, the reason behind this is unknown. Most crucially, a PCM system used in the design of a thermal storage system must meet a number of thermophysical, kinetic, and chemical requirements, all of which are detailed below [13], [14].

2.1.3 Thermo-Chemical Storage (TCS)

A phase transition material must have the following thermophysical properties, which may be expressed in the following ways:

- It has a high latent heat of fusion per unit volume, allowing it to retain a given amount of energy with a smaller volume of container than would otherwise be necessary, and it has a high specific heat capacity, allowing it to store more sensible heat, in order to ensure that the melting temperature is within the predicted range of the operational temperature range.
- High thermal conductivity in both the solid and liquid phases of energy storage devices aids in the charging and discharging of energy stored in them.
- Low vapor pressure at working temperatures and minimum volume changes during phase transition should be employed to make containment easier.
- It must be continually melted throughout each freezing/melting cycle in order to maintain a consistent storage capacity across all of the cycles.

Associated with chemical reaction processes, thermo-chemical heat storage methods operate at temperatures ranging from 40 degrees Celsius to more than 400 degrees Celsius and include sensible heat, latent heat, and thermo-chemical heat storage [15].

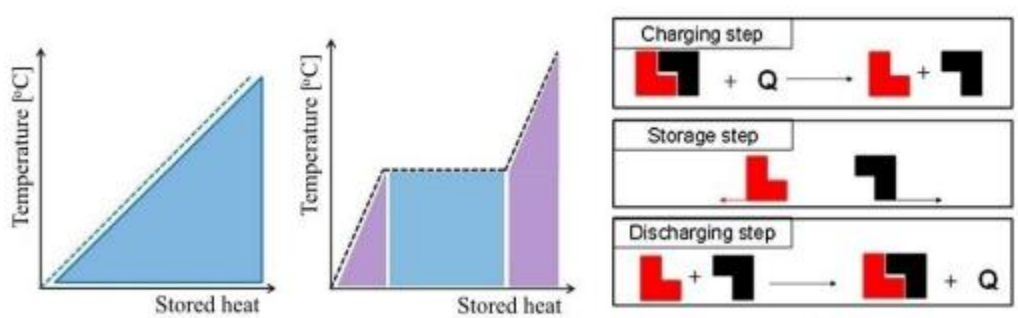

Figure 2-1 Methods of thermal energy storage: (a) sensible heat; (b) latent heat; (c) thermo-chemical [15]

2.2 Practical Implications of TES Systems

Building heating, ventilation, industrial drying, and temperature maintenance activities involve phase change materials. They store energy to be utilized for heating purposes later as needed, allowing the primary energy load to be lowered by using PCMs to provide a part of the energy demand. Al-Abidi et al. [16] examined the use of PCMs in air distribution networks, microencapsulated slurries, chiller water heaters, heat rejection, and thermal power in absorption air conditioning systems. It has been determined that integrating thermal energy storage devices into air conditioning systems can decrease system size while increasing efficiency. Liu et al. [17] looked at high-temperature thermal energy storage solutions for concentrated solar power plants, including all areas such as receivers, thermal storage, power blocks, and heat transfer fluids, as well as material degradation and system economics. It is determined that the creation of novel molten salts with low freezing temperatures and high decomposition temperatures, as well as the use of Nano fluids technology, are necessary for sensible thermal energy storage systems. Gulfam et al. [18]looked at sophisticated thermal systems powered by paraffin waxes and divided them into four categories: thermo-management, thermo-responsive, thermo-mechanical, and thermo-chemical. Thermo-management systems are optimal for duplex thermal composites with high thermal conductivity and substantial virgin latent heat of fusion. Microporous thermal reinforcement is preferred over nonporous thermal support. According to the researchers, paraffin phase transition materials should also be created with regulated responses for use in thermo-responsive, thermo-mechanical, and thermo-chemical systems.

2.3 Sensible Thermal Energy Storage (STES) System

Since the early 1970s, thermal energy storage has been the subject of research. Materials for sensible and latent storage were explored 30 years ago, and their performance for many applications is continually improving. Thousands of studies have been undertaken over the years to identify the most excellent feasible energy storage material.

Pilar et al. [19] published a study on Magnesium Chloride Hexahydrate as a heat storage material for TES, finding that the heat capacity is between 289K-400K. Thermal chilling tests up to 50 cycles and super-cooling up to 37 K were conducted, and it was determined that nucleating agents constitute a viable choice for thermal energy storage. Safari et al. [20] reviewed the use of super-cooling materials for PCM in thermal energy storage, focusing on the super-cooling region's operational capabilities for specific applications. It is concluded that super-cooled liquids and super-cooling measures influence the degree of super-cooling. Milián et al. [21] reviewed the use of super-cooling materials for PCM in thermal energy storage, focusing on the super-cooling region's operational capabilities for specific applications. Findings show that super-cooled liquids and super-cooling measures influence the degree of super-cooling. Lin et al. [22] reviewed thermal performance and applications of TES with inorganic PCMs by analyzing their integration with heat exchangers. They concluded that they have a wide range of temperatures, and their integration with heat exchangers can improve energy efficiency. It is also mentioned that hydrated salts are suitable but have problems with supercooling/subcooling and phase segregation.

Kuravi et al. [23] used air as a heat transfer fluid (HTF) to study a high temperature sensible heat thermal energy storage system for a central receiver CSP plant. The air intake temperature has been changed between 300°C and 600°C, and the flow rate has been altered between 50 and 90 cubic feet per minute (CFM). The charging time reduces as the mass flow increases. The findings are then evaluated using a 1D energy conservation equation model for convection and conduction heat transfer for charging and discharging cycles. Lugolole et al. [24] evaluated and compared three sensible heat storage systems during the charging cycle at flow rates of 4 ml/s, 8 ml/s, and 12 ml/s using sunflower oil as HTF with diameters of 10.5 mm and 31.9 mm with oil only storage tank Small pebbles in the oil storage charge it up quicker, allowing it to attain thermal equilibrium faster and oil-only systems have higher charging energy and exergy. Because of its lower thermal mass, the TES system for oil displays a rapid increase and fall in stratification numbers. Even though the system with big stones is preferred due to stratification, it is recommended that small pebbles be used. Yang & Cai [25] investigated the outlet temperature profile, temperature differential, total energy storage, and charging time of a thermocline storage system using suitable heat material and PCM. The most significant temperature difference occurs in the center of the thermocline, and it decreases as charging time increases. Alptekin & Ezan [26] used a sensible heat TES tank with a flat plate solar collector to analyze spatial and temporal temperature differences over a day under various climatic circumstances. The TES tank's stratification number, exergy, energy, efficiency, diameter, and height have been quantitatively examined under different working settings. According to the findings, the temperature of the storage medium ranges between 40 and 60 degrees Celsius. It is suggested that stored thermal energy be employed in buildings for a variety of applications, including hot water delivery, indirect heating using a heat pump system, and underfloor space heating. Li [27] reviewed the available technologies for sensible heat storage under various conditions and storage tank geometry on the basis of water stratification, influencing factors for energy and exergy performance, heat storage transfer mode from storage tank geometrical structure, fluid inlet temperature, fluid mass flow rate, and fluid properties. The findings indicate that the study will assist researchers and engineers in developing more efficient and optimum sensible storage systems.

Kibria et al. used computational and experimental methods to examine the thermal unit of PCM under different flow parameters and system dimensions. Shell and tube are employed in the TES, while paraffin wax is used as the PCM. The computational findings confirm the experimental data, and it is determined that paraffin wax is an excellent PCM because of its thermal properties [28]. Wang et al. [29] investigated the transient heat transfer performance and operational characteristics of latent and sensible thermal energy storage systems enclosed in vertical annuli, concluding that latent TES systems can perform at a much higher density than sensible TES systems and provide a more satisfactory charging/discharging rate.

For stabilizing the discharging outflow air temperature, a thermal energy storage tank containing sensible and latent thermal energy is designed, tested, and simulated at 575°C and above [30]. The use of solid bricks as a storage material in a thermal energy storage system (TES) is intended to improve the performance of sensible storage systems and the results indicated that the ability to store data is excellent under this system [23]. During the charging cycle, heated heat Transfer Fluid is transported to a thermal energy storage system through solar fields. Cold fluid absorbs heat from the thermal energy storage system to complete the discharging cycle. Because of its low cost, stability, and other thermal characteristics, concrete is employed as a storage medium [31]. The impact of different concrete structures on the performance of thermal energy storage devices is investigated. Through the thinnest thermocline region of a concrete thermal energy storage tank, rod bundle construction has the greatest discharge efficiency and the longest discharge duration [32].

Industrial efficiency can be improved by utilizing maximum amount of energy from industrial waste heat recovery operations to offset variations Thermal energy storage devices must be developed to get the full potential solar thermal energy [33]. Furthermore, in order to satisfy the demands of nature, it is necessary to create more affordable storage solutions. Because solar thermal energy is not available at any time at specific locations.

Summary

In this chapter detailed literature review is discussed. Literature review was listed in such a way so that the development in the area should be highlighted. The aim of this chapter to elaborate the function and development of Thermal energy storage systems in various applications and then specifically in thermal energy storage. Two major types of TESS that are sensible and latent are discussed. Different storage materials are discussed to understand their thermal performance during charging and discharging cycles which is the main topic of research.

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Chapter 03

Methodology

For the implementation of conceptual design, the physical geometry with proper dimensions is necessary for required operation. The materials used for proposed design will be discussed in the following chapter. The 2-D model of proposed solar tower receiver is discussed in detail with respective geometry and detail diagram. A TES system comprising of a 5m diameter was simulated having 46 channels. TES system is simulated with high computational power through ANSYS Fluent software. Multiple CFD steps of preprocessing and post processing are involved throughout simulations. Materials selection is defined for the system components. The nature of physical system can be easily pre-judge by utilizing or solving different set of governing equations and boundary conditions. The numerical analyses give details of thermal profile of system under pre-determine working conditions. The TES system was modelled in ANSYS Design modeler and meshed in ANSYS Mesh. Two cases were studied one having slag circular particles and other having concrete circular particles. The details are as follows.

3.1 Thermal Energy Storage Tank Design

A 2-D CAD model comprising of surface bodies was created in ANSYS Design modeler. The CAD Figure is shown in Figure 3-1. The model is axis symmetric. The HTF passage and circular particles are visible in Figure 3-2. The length of tank is 7.5 m with 2.5 m radius having porosity of 0.3 as shown in Table 3-1.

Table 3-1 Parameters of TES tank

Tank Radius (m)	2.5
Tank length (m)	7.5
Porosity (ε)	0.3

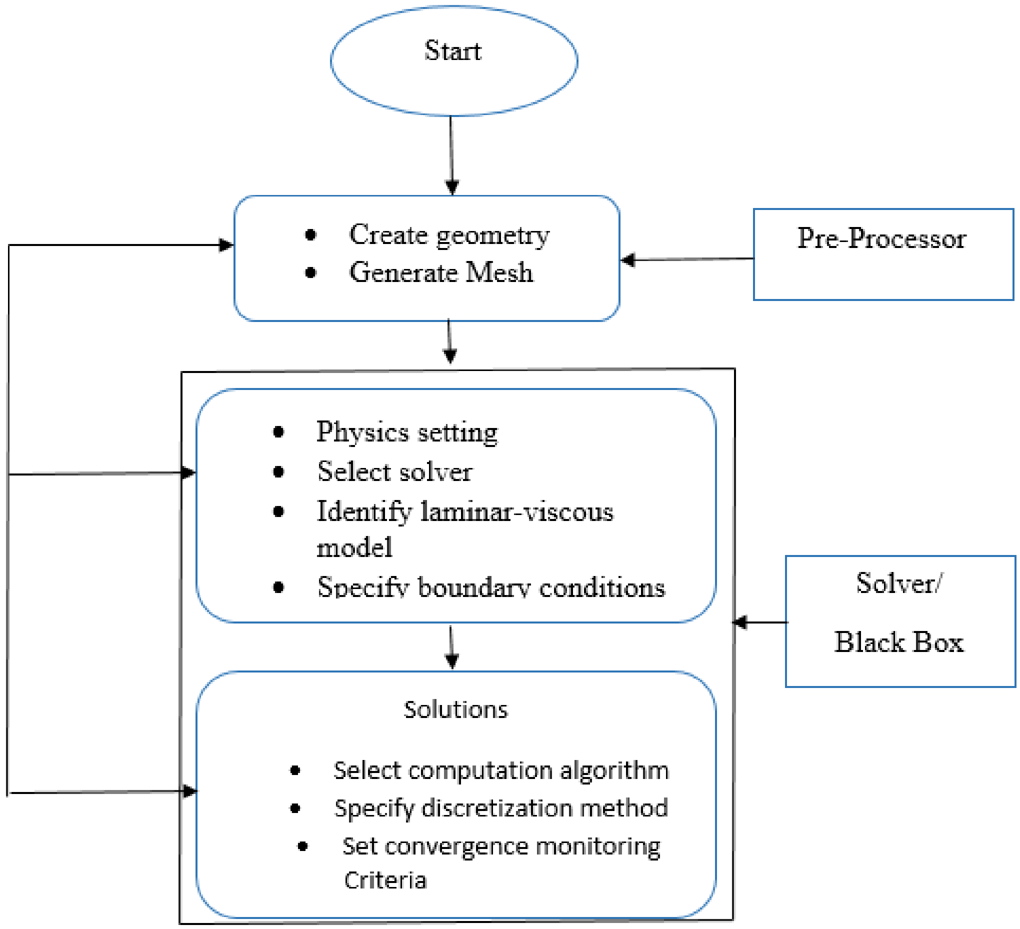


Figure 3-1 Methodology flowchart

3.2 Materials for Proposed TES Tank

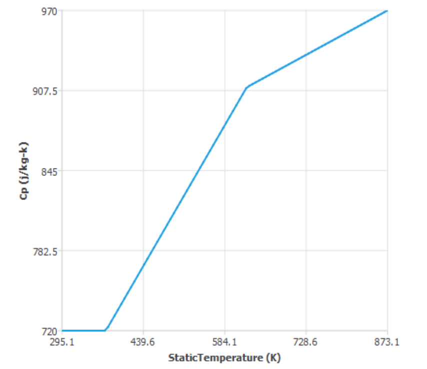
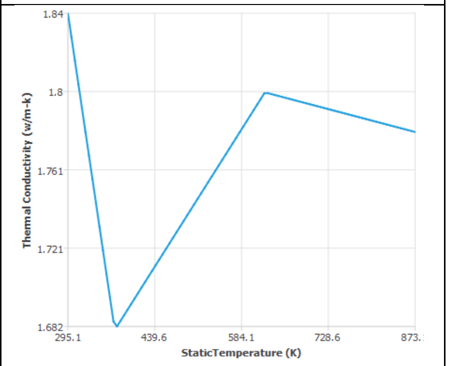
Different storage materials and a HTF is used in this proposed tank design to check the thermal performance during charging and discharging cycles. A specific temperature range is selected to examine the performance. In first scenario, concrete and slag are used for heat storage materials. Concrete is placed outside the HTF channel while circular slag particles are placed in front of fluid flow. There are total number of 46 channels as well as one channel contains 250 slag particles. HTF used is Therminol VP-1. Thermophysical properties of HTF are listed in below table. Concrete and Therminol VP-1 properties are constant, but the properties of storage material slag are changed due to change in temperature. Specific heat capacity value is increased by increasing the temperature as well as thermal conductivity value is also vary.

Table 3-2 Material description of simulated cases

Case #	Materials involved	Description
1	HTF, Concrete, Slag	HTF as working fluid Concrete as walls Slag as circular particles
2	HTF, Concrete	HTF as working fluid Concrete as walls Concrete as circular particles

Table 3-3 Physical properties of used materials [1]–[3]

Sr.#	Material name	Property	Value
1	HTF Therminol VP-1	Density	773 kg/m^3
		Specific Heat (Cp)	2425 j/kgk
		Thermal Conductivity (k)	0.089 w/mk
		Viscosity	0.0001866 kg/ms
2	Concrete	Density	2750 kg/m^3
		Specific Heat (Cp)	916 j/kgk
		Thermal Conductivity (k)	5 w/mk
3	Slag	Density	3610 kg/m^3

		Specific Heat (Cp)	
		Thermal Conductivity (k)	

3.3 Tank Heat Transfer Mechanism and HTF Flow

Thermal energy storage tank is charged by receiving thermal energy from heat transfer fluid. Abundant thermal energy is stored for later usage. For sensible thermal energy storage different storage materials are introduced at specific temperature range to check their performance in both cycles. Heat transfer fluid flow in x-axis during charging of tank and reverse for discharging of tank. At outside the fluid flow concrete material is placed but in front of the flow slag/concrete circular particles are placed. Due to the circular particle's fluid transfers heat due to surface area increased. In charging cycle fluid transfers heat to storage materials and in discharging cycle receives heat from storage materials.

Figure 3-2 process flow of fluid through the thermal energy storage tank channels

3.4 Numerical Analysis

The objectives of proposed design, either it satisfied or not are done using numerical analysis. The system can be easily pre-judge by utilizing or solving different set of governing equations and boundary conditions, which although required high computation power. High computation power is required even after the analysis is done by taking the model axis symmetric. The numerical analysis gives details of thermal conditions under pre-determine working conditions, which are essential to designed process. Charging and discharging initial conditions are set according to desired temperature range. Through literature appropriate velocity is set for better heat transfer. The properties of heat transfer fluid and storage materials are isotropic in y-axis. Velocity is also same in vertical direction. Also, at symmetric axis velocity and HTF has no change in y-axis direction. For each temperature range, the thermal characteristics of heat transfer fluids are assumed to be constant.

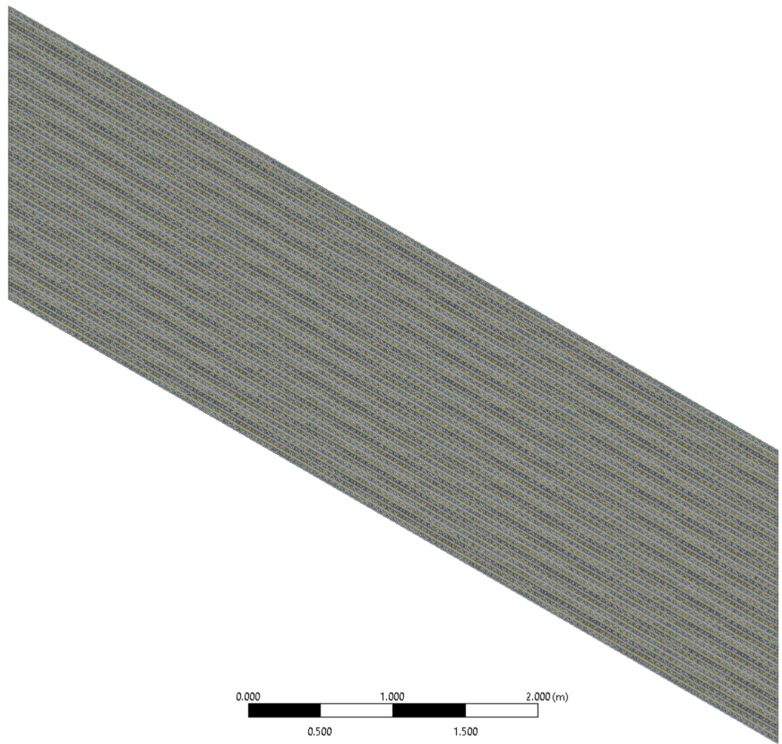


Figure 3-3 Isometric View of thermal energy storage tank

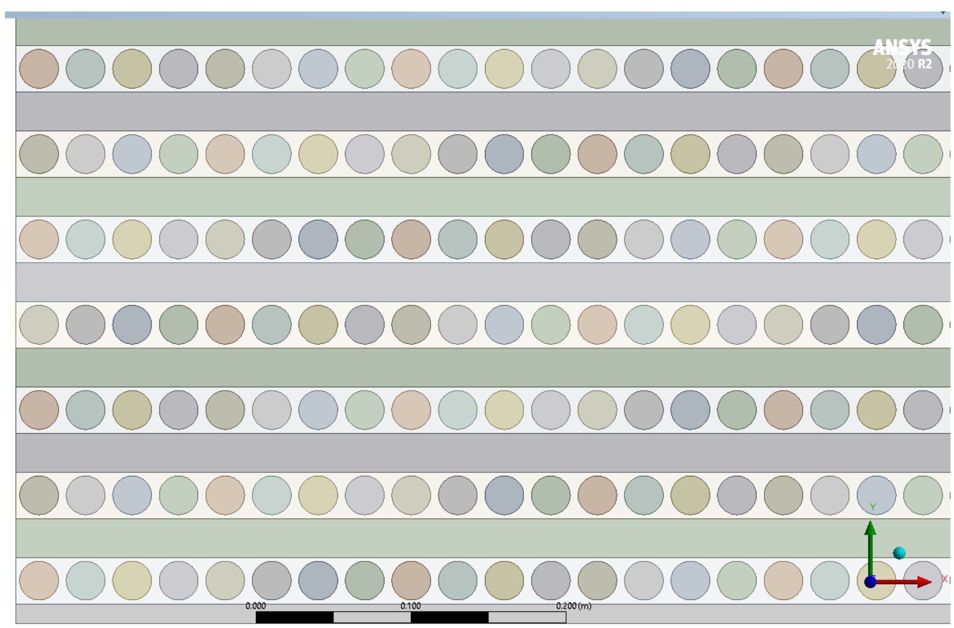


Figure 3-4 Enlarged front view of CAD model for thermal energy storage channel

3.5 Governing Equations

Energy, momentum, and continuity equations are utilized for governing the heat transfer and flow parameters in thin channels of different storage systems [4].

Continuity equation for cylindrical coordinates of TESS.

$$\frac{\partial V_r}{\partial r} + \frac{V_r}{r} + \frac{\partial V_\theta}{\partial \theta} + \frac{\partial V_\theta}{\partial z} = 0 \qquad (1)$$

Momentum equations for (r, θ, z) coordinates

$$\rho\left(\frac{\partial V_r}{\partial t} + V_r\frac{\partial V_r}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_r}{\partial \theta} - \frac{V_\theta^2}{r} + V_z\frac{\partial V_r}{\partial z}\right) = -\frac{\partial p}{\partial r} + \mu\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2} + \frac{1}{r^2}\frac{\partial^2 V_r}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial V_\theta}{\partial \theta} + \frac{\partial^2 V_r}{\partial z^2}\right) + \rho g_r \qquad (2)$$

$$\rho\left(\frac{\partial V_\theta}{\partial t} + V_r\frac{\partial V_\theta}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_\theta}{\partial \theta} + \frac{V_r V_\theta}{r} + V_z\frac{\partial V_\theta}{\partial z}\right) = -\frac{1\partial p}{r\partial \theta} + \mu\left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial V_\theta}{\partial r} - \frac{V_\theta}{r^2} + \frac{1}{r^2}\frac{\partial^2 V_\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial V_r}{\partial \theta} + \frac{\partial^2 V_\theta}{\partial z^2}\right) + \rho g_\theta \qquad (3)$$

$$\rho\left(\frac{\partial V_z}{\partial t} + V_r\frac{\partial V_z}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_z}{\partial \theta} + V_z\frac{\partial V_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 V_z}{\partial r^2} + \frac{1}{r}\frac{\partial V_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 V_z}{\partial \theta^2} + \frac{\partial^2 V_z}{\partial z^2}\right) + \rho g_z \qquad (4)$$

Energy Equation for cylindrical coordinates.

$$\rho c_p\frac{\partial T}{\partial t} + \rho c_p\left(V_r\frac{\partial T}{\partial t} + \frac{V_\theta}{r}\frac{\partial T}{\partial \theta} + V_z\frac{\partial T}{\partial z}\right) = k\left[\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] + \mu\varphi \qquad (5)$$

In above mentioned equations dynamic viscosity and density are presented by μ and ρ respectively. In energy equation $\mu\varphi$ is viscous dissipation. V_r and V_θ are radial and angular components while V_z is linear velocity of HTF flow.

3.6 Grid Independence Test

Mesh of the TES tank is shown in Figure 3-3. It can be seen from figure that a Hybrid mesh comprising of triangle and rectangles was created using hybrid meshing scheme. The HTF part was also mesh with surface inflation algorithm. 5 layers of surface inflation were created.

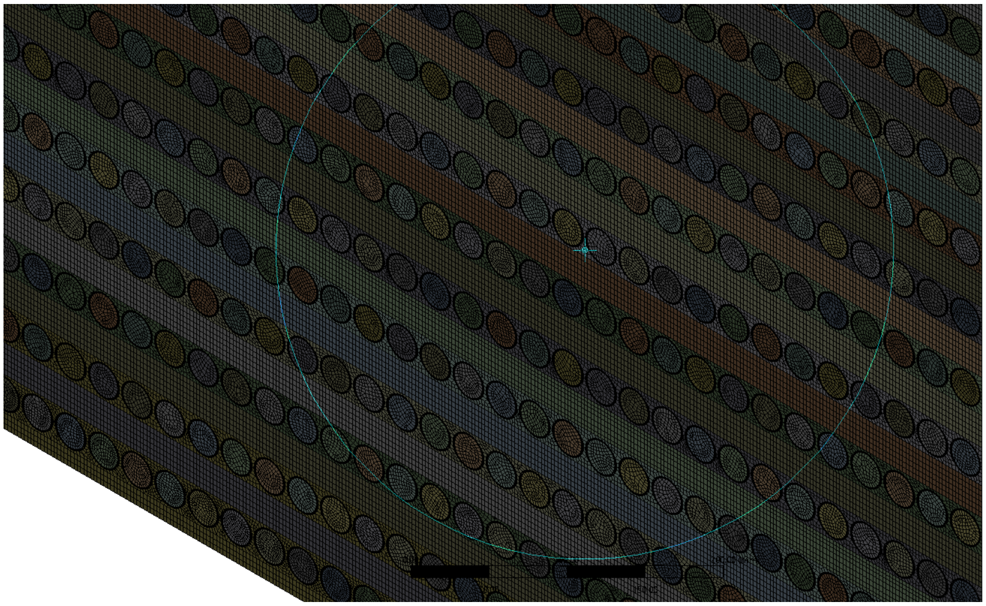


Figure 3-5 Meshing of Thermal Energy Storage tank

Mesh independent study was performed to ensure accuracy of results. Various meshes comprising of hybrid meshes were created. Details are shown in Table 3-2.

Table 3- 4 Details of applied meshes on Thermal Energy Storage tank

Sr.#	Mesh	Elements	Pressure Drop [Pa]
1	M01	2.7 million	52.01
2	M02	3 million	51.3
3	M03	3.5 million	49.35
4	M04	4.1 million	49.36
5	M05	4.3 million	49.34

It can be seen from table that mesh independency is obtained in results at M03 and M04. M03 was thus opted as mesh independent solution. The M03 mesh comprises of 3.5 million elements.

3.7 Boundary Conditions

Applied boundary conditions are shown in Figure 3-4. It can be seen from the figure that the simulation is axis symmetric. Inlet boundary condition was taken as velocity inlet while outlet boundary condition was chosen as pressure outlet with back flow condition.

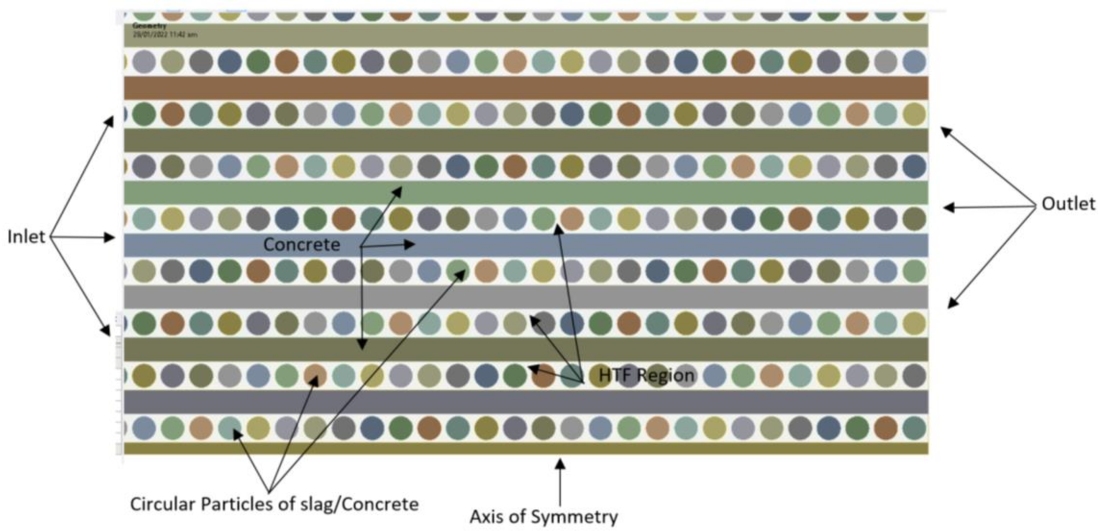


Figure 3-6 Applied boundary conditions on the proposed thermal energy storage tank

The simulation was divided into two main parts, Case-I and Case-II. Brief description of materials involved in both cases is described in Table 3-3. Both cases were studied for charging and discharging characteristics. Physical properties are listed in Table 3-4.

At t = 0:

$T_i = T_{htf} = 585.15$K (For discharging)

$T_i = T_{htf} = 885.15$K (For Charging)

At inlet section for t > 0

$T_{htf} = 858.15$K

$v = 0.005\, m/s$

At symmetry axis:

$$\frac{dT_{htf}}{dy} = 0\,,\quad \frac{dv}{dy} = 0$$

At outer wall:

$$\frac{dT_{htf}}{dy} = 0\,,\quad v = 0$$

At outlet of storage tank:

$$\frac{dT_{htf}}{dy} = 0$$

3.8 Initial Conditions of Charging and Discharging Cycles

Thermal energy storage tank is operated at specific conditions according to desired temperature range. Charging starts at 585.15k while discharging starts at 858.15k. Below shows the initial conditions of TES tank.

Table 3-5 Initial conditions of charging and discharging

Sr. #	Property	Initial state of TES	Inlet
1	Charging	585.15 K	858.15 K
2	Discharging	858.15 K	585.15

3.9 Charging of Thermal Energy Storage system

In charging of TES system, HTF enters at higher temperature of 858.15 K. Initially all system is at 585.15 K temperature. The HTF then passes over the circular particles of slag in Case-I and circular particles of concrete in Case-II. The HTF loses its heat to concrete walls and circular particles. At fully charged stage the temperature of entire system becomes 858.15 k.

3.10 Discharging

In discharging system, HTF enters at a temperature of 585.15 K. For discharging system entire TES system is assumed to be at 858.15 K. The HTF gains heat as it flows over circular particles and walls in both cases.

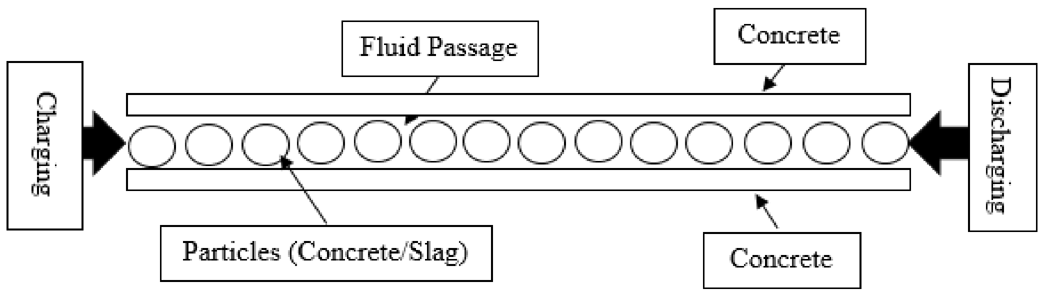


Figure 3-7 Flow diagram of heat transfer fluid

Summary

In this chapter 2D cad drawing is presented and the detailed dimensions, governing equations and mesh quality was discussed. After that the storage system boundary conditions were discussed. The storage materials are defined and thermophysical properties were described. The simulations were divided into two different cases for charging and discharging cycles.

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CHAPTER 04

Results and Discussion

Simulation was performed to characterize the thermal hydraulic behavior of Thermal Energy Storage System (TESS). TES system as stated earlier is used to store energy and later that energy can be extracted as a sensible heat for various applications. Simulations of charging and discharging cycles for two cases were performed. Results and discussion of both cases with charging and discharging cycles is as follows,

4.1 Thermal Performance analysis of TESS Case-I

As stated earlier, the Case-I is the TES system where circular slag particles were used to absorb or dissipate energy along with concrete from HTF. The charging and discharging behavior of TES system with circular slag particles is discussed under.

4.1.1 Charging of TES system for Case-I

Figure 4-1 to Figure 4-8 shows the charging behavior of TES system. Table 4-1 shows the average rise in temperatures of HTF, concrete and slag particles. It can be seen from contours and graphs plot that the entire system is at 285 °C. Figure 4-1 and Figure 4-2 shows the behavior of system at T=30 mins. HTF entered the system at 585.15 °C. It raised the temperature of concrete walls and slag. Average rise in temperature of HTF, concrete and slag after 30 mins is 443.9, 411.8 and 434.09 °C respectively. Temperature contours and graphs after 60 mins are shown in Figure 4-3 and Figure 4-4. It can be seen from figures that more of TES system has acquired a steady temperature of 585.15 °C. Outlet temperature of slag, concrete and HTF are 538.27, 524.9 and 543.3 °C. Thermal picture of system after 90 mins is shown in Figure 4-5 and Figure 4-6. Outlet temperature of slag is 530 °C. Outlet temperature of concrete and HTF has also risen to 520 °C and 540 °C respectively. Finally, at 120 mins entire TES system is at inlet HTF temperature, 585 °C as seen from Figure 4-7 and Figure 4-8. After this time no rise in system energy will take place.

Table 4-1 Average temperatures of TES system for Case-I, Charging

	Case-I, Charging		
Time (min)	HTF (°C)	Concrete (°C)	Slag (°C)
0	312	312	312
30	443.902	411.845	434.099
60	543.36	524.943	538.276
90	577.058	572.143	575.641
120	583.48	582.96	583.067

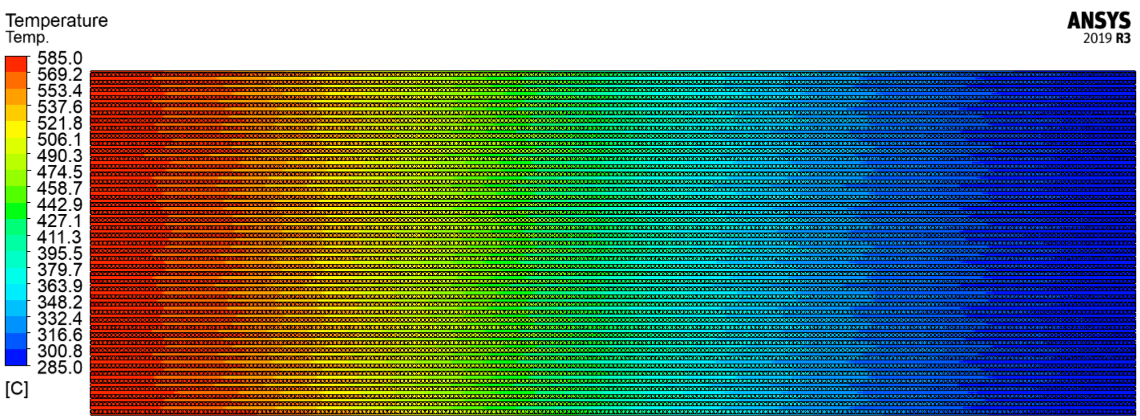

Figure 4- 1 Temperature contours of TESS at t=30 min, Case-I, Charging

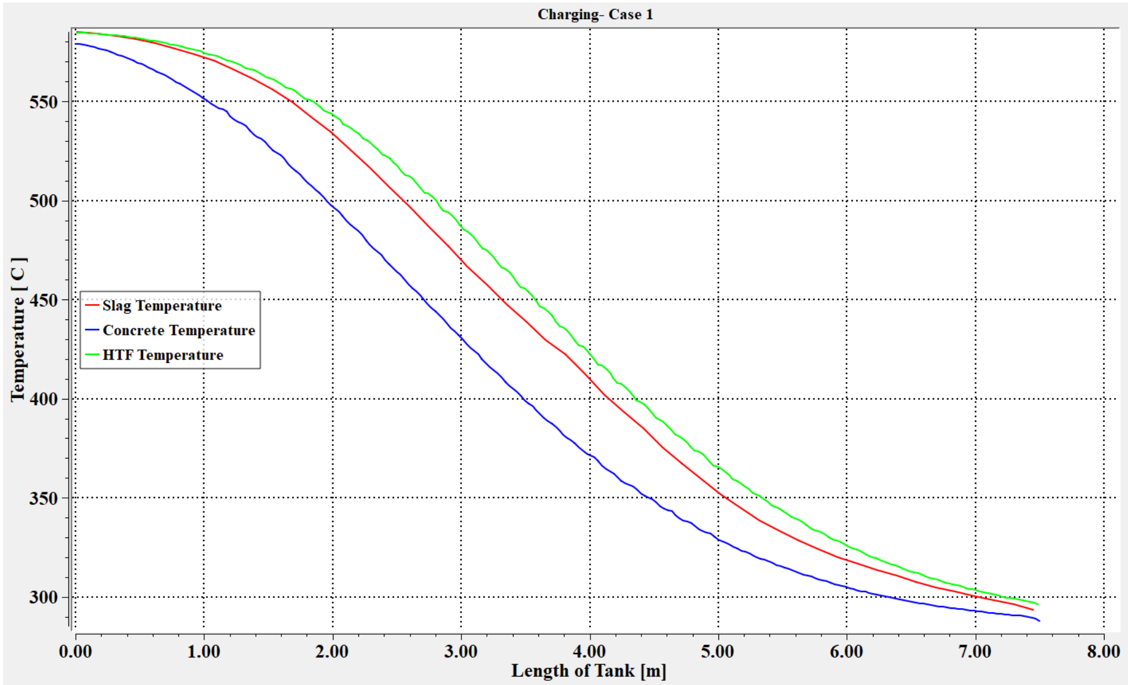

Figure 4-2 Temperature profiles of TESS at t=30 min, Case-I, Charging

As the HTF passes through the tank channels, it delivers its thermal energy to the storage materials. Which are placed in the flow of fluid. Figure 4-1 and figure 4-2 shows that thermal energy is transferred from one material to other materials and average temperature rise occurs of overall storage tank. Both materials show good behavior in obtaining the heat. But due to the placement of slag particles in front of fluid flow, surface area in contact increased and as a result, slag line is closed with the HTF line in figure 4-2.

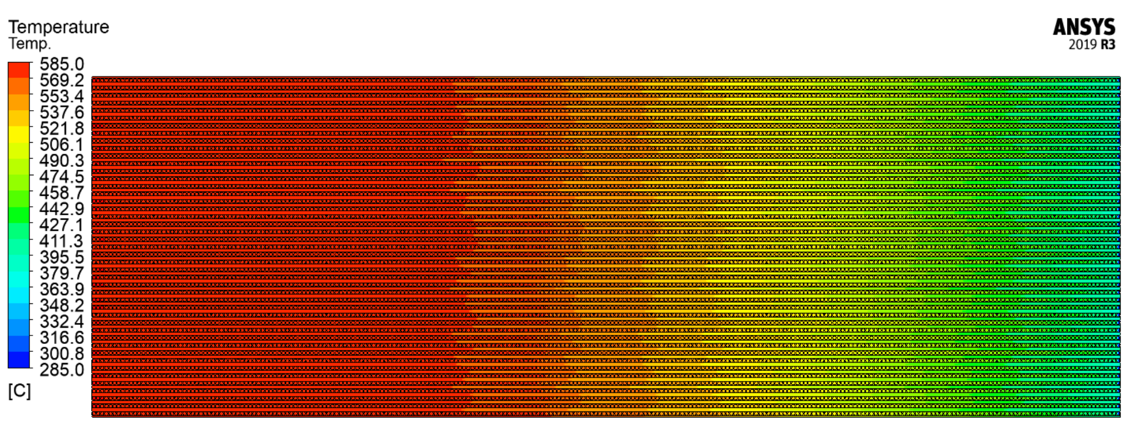

Figure 4-3Temperature contours of TESS at t=60 min, Case-I, Charging

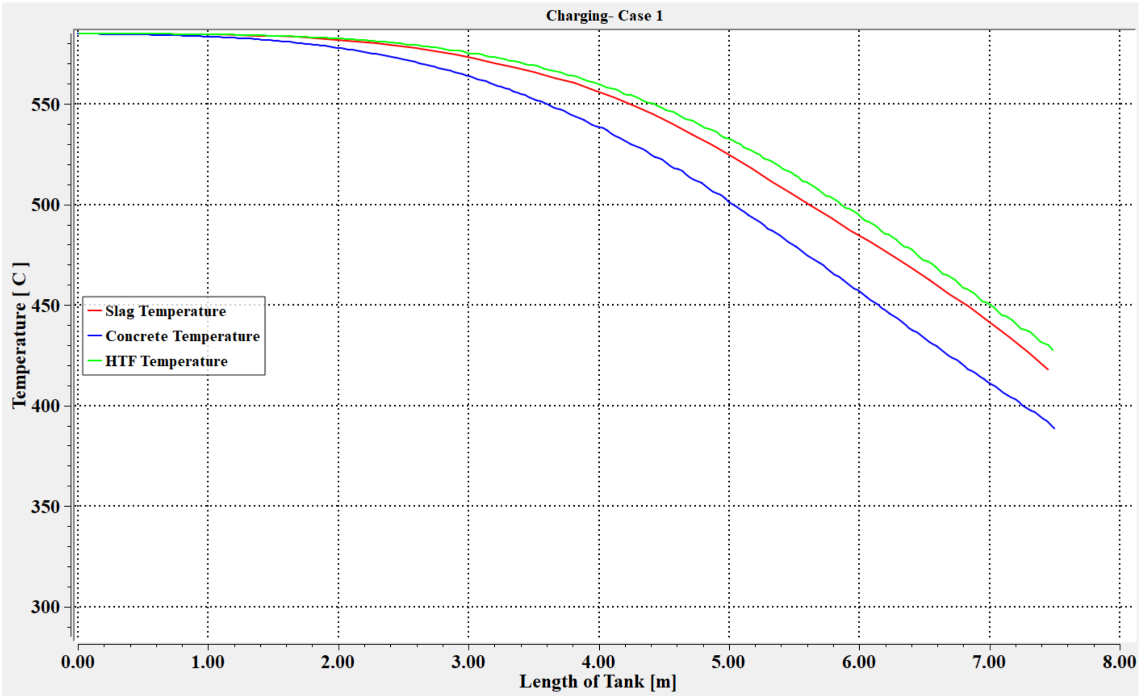

Figure 4-4 Temperature profiles of TESS at t=60 min, Case-I, Charging

Figure 4-3 and Figure 4-4 shows the average rise in temperature of slag, concrete and HTF are 538.27, 524.9 and 543.3 °C. After 60 min duration HTF passes thermal energy to storage materials as shown through contours of figure 4-3. Due to increase in thermal conductivity and specific heat capacity slag temperature gets more closer to the HTF temperature as shown in Figure 4-4. It can be seen from figures that more of TES system has acquired a steady temperature of 585.15 °C.

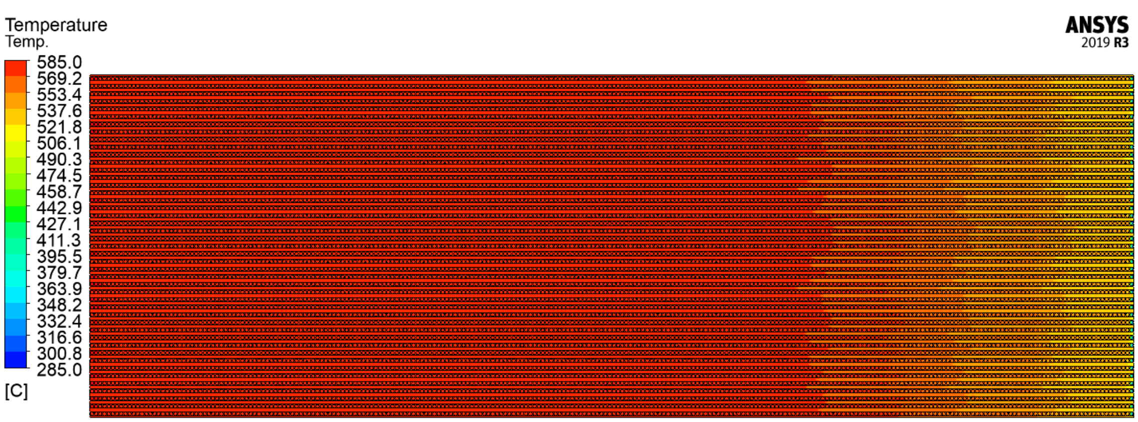

Figure 4-5 Temperature contours of TESS at t=90 min, Case-I, Charging

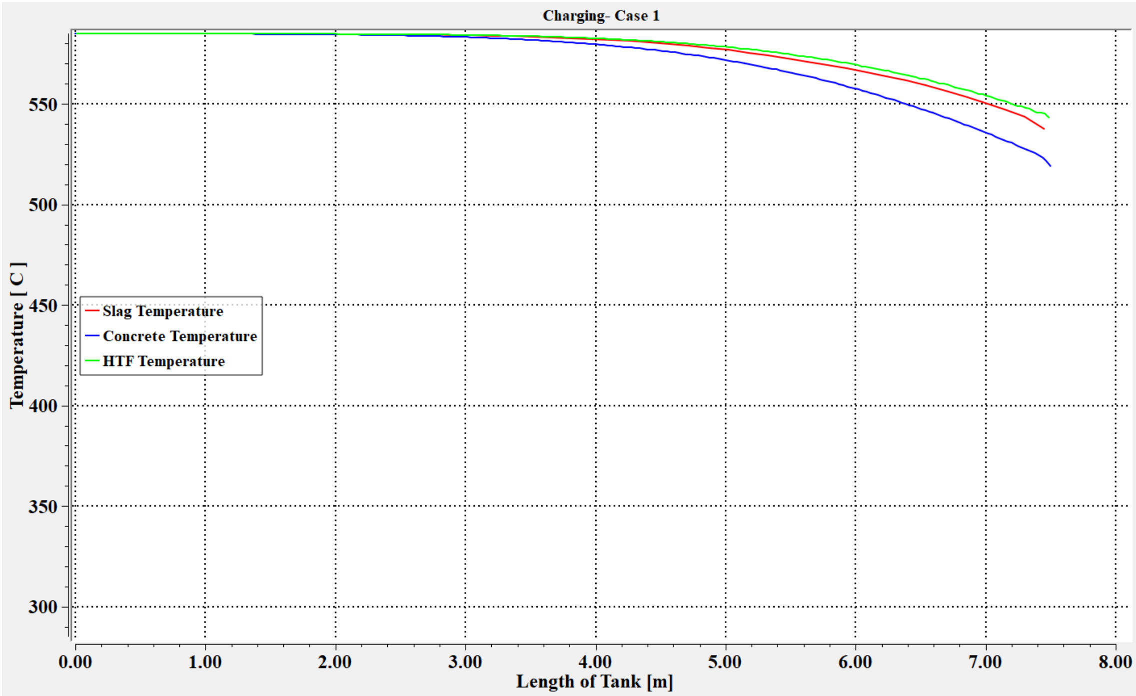

Figure 4-6 Temperature profiles of TESS at t=90 min, Case-I, Charging

After the time interval of 90 min the outlet temperature of slag, concrete and HTF increases to 530,520 and 540°C as shown in figure 4-6. The curves of storage materials are getting closer to the HTF curve. Efficiently heat transfer occurs between HTF and heat storage materials.

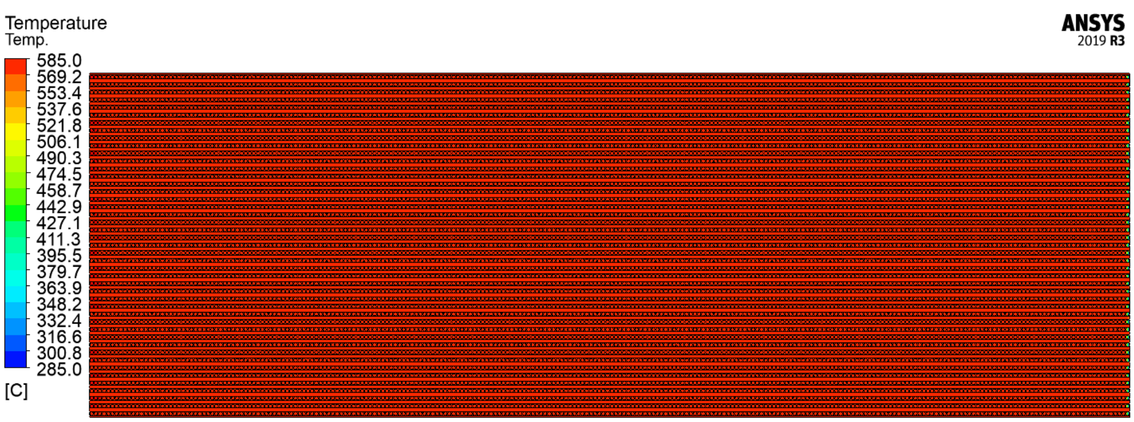

Figure 4-7 Temperature contours of TESS at t=120 min, Case-I, Charging

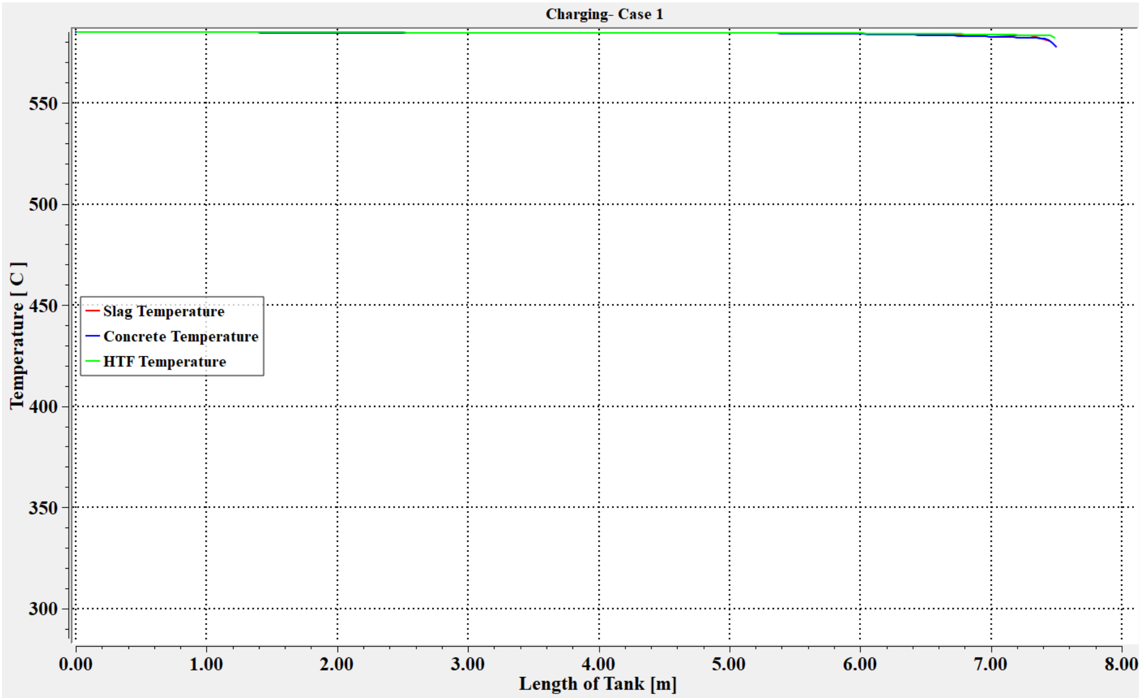

Figure 4-8 Temperature profiles of TESS at t=120 min, Case-I, Charging

Figure 4-7 and figure 4-8 shows that thermal energy storage tank is fully charged, and Storage materials gained maximum amount of thermal energy from the heat transfer fluid. After 120 min duration almost temperature curves are same as shown in figure 4-8. After this no energy is transfers.

4.1.2 Discharging for Case-I

Case-I, TES system discharging is shown from Figure 4-9 to Figure 4-16. Table 4-2 represents the average values of slag, concrete and HTF during discharging. The initial temperature of entire TES system is 585 °C. As the HTF enters the TEE at 285 °C, it starts to gain heat from concrete walls and slag particles. After 30 mins the thermal picture of TES is shown in Figure 4-9 and Figure 4-10. The outlet temperature of entire TES system is close to 585 °C, but TES system close to inlet has lost energy. The temperatures are close to inlet HTF temperature of 285 °C. 60 mins picture is shown in Figure 4-11 and Figure 4-12. Outlet temperature of slag, concrete and HTF has come down to 450, 480 and 440 °C respectively. Downward trend of loss in temperature can be seen in Figure 4-13 to Figure 4-16. Figure 4-13 and Figure 4-14 shows thermal picture at 90 and Figure 4-

15 and Figure 4-16 shows thermal picture at 120 mins. After 120 mins entire TES system has been discharged to 285 °C.

Table 4-2 Average temperatures of TES system for Case-I, discharging

	Case-I, Discharging		
Time (min)	HTF (°C)	Concrete (°C)	Slag (°C)
0	585	585	585
30	426.698	459.336	436.337
60	325.272	344.773	329.951
90	291.631	297.1	292.555
120	285.685	286.753	285.721

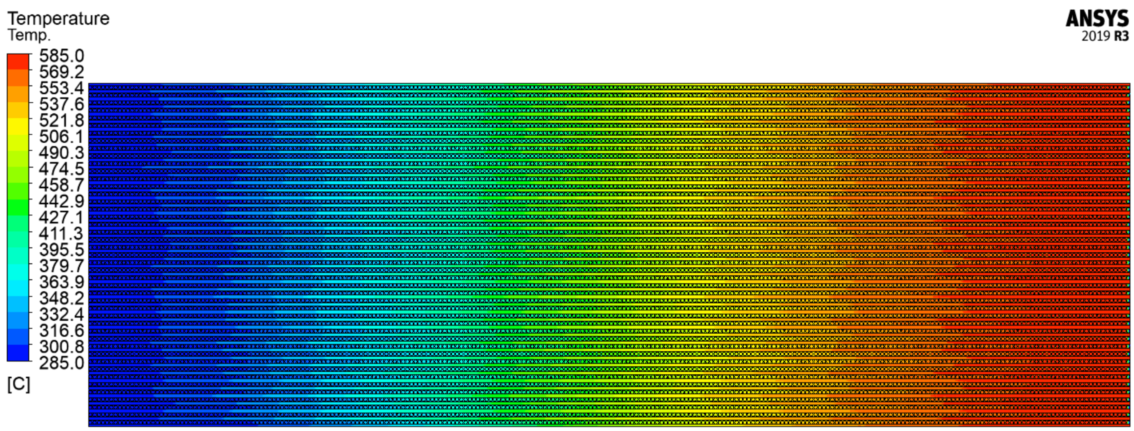

Figure 4-9 Temperature contours of TESS at t=30 min, Case-I, Discharging

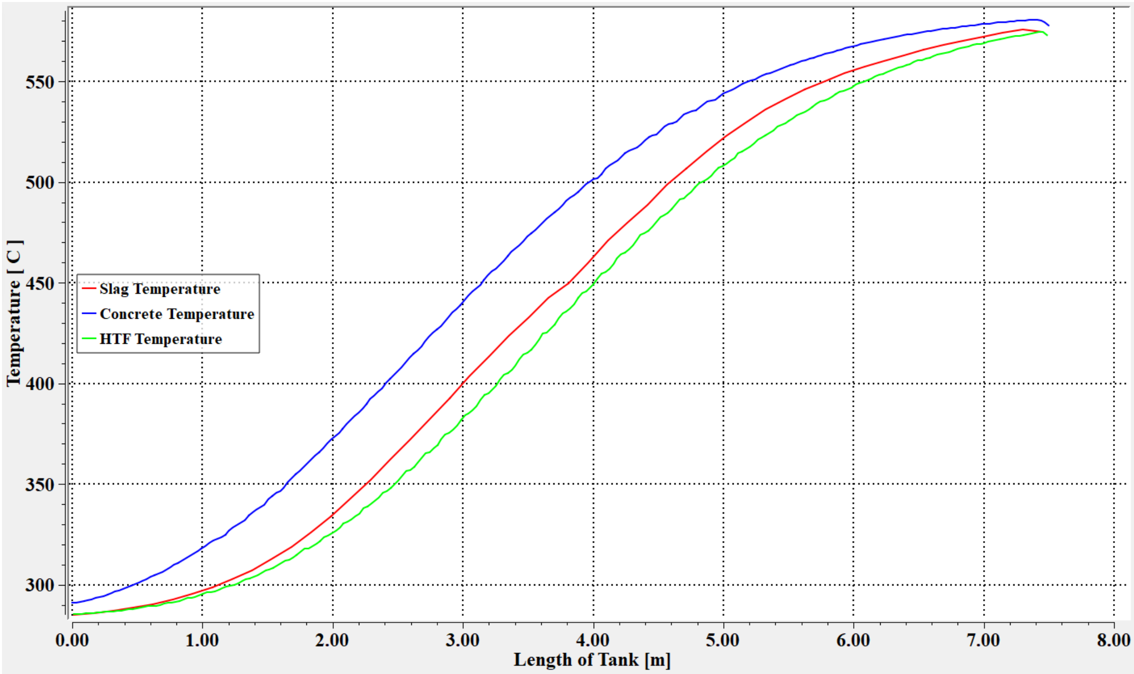

Figure 4-10 Temperature profiles of TESS at t=30 min, Case-I, Discharging

As the heat transfer fluid enters the tank starts losing its thermal energy to the HTF. Heat transfer fluid gains thermal energy to attain the higher temperature of the tank. Figure 4-9 and 4-10 shows the discharging of tank. Concrete losing its thermal energy slowly as compared to the slag. Slag quickly gaining the thermal energy and discharge in shorter time due to its thermophysical properties as shown in figure 4-10.

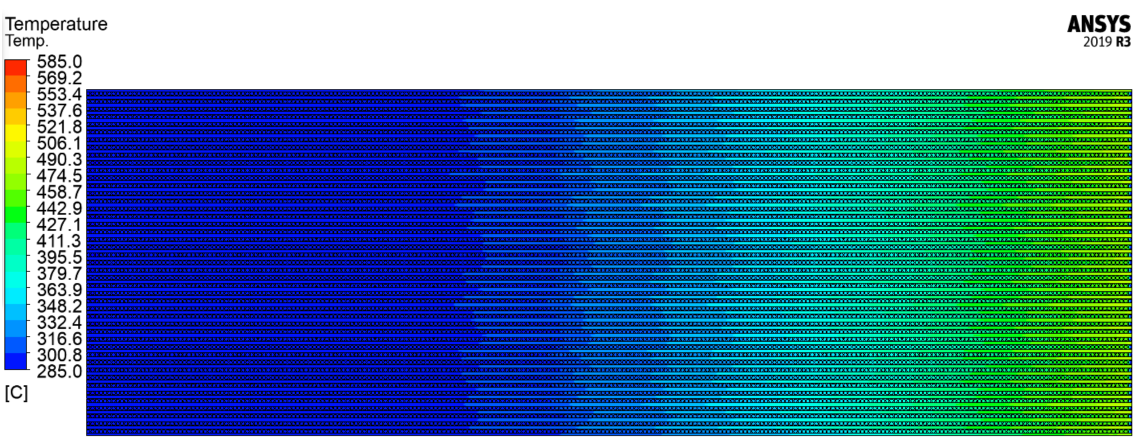

Figure 4-11 Temperature contours of TESS at t=60 min, Case-I, Discharging

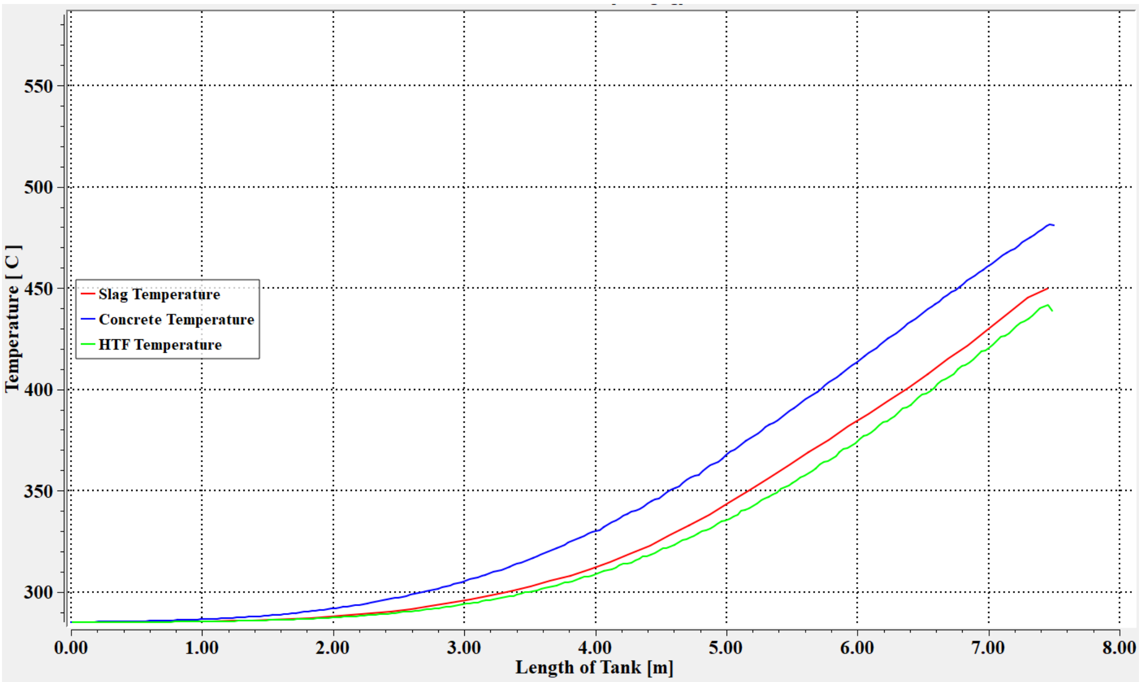

Figure 4-12 Temperature profiles of TESS at t=60 min, Case-I, Discharging

After the 60 min time interval heat is dissipated from tank to the HTF. Both materials are showing discharging, but slag is dissipating heat quickly. Average decrease in temperatures occurs in discharging cycle. Outlet temperature of slag, concrete and HTF has come down to 450, 480 and 440 °C respectively. Thermal picture in Figure 4-11 shows the discharging of TES tank.

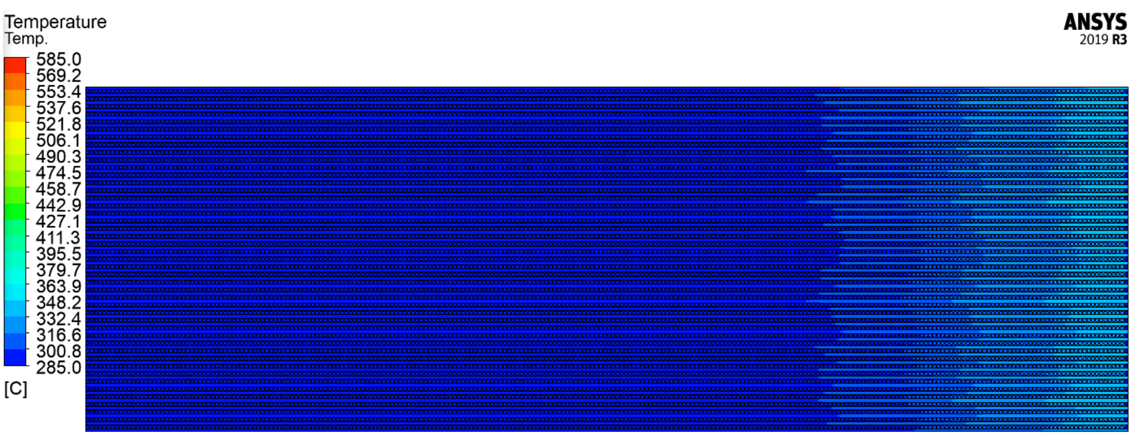

Figure 4-13 Temperature contours of TESS at t=90 min, Case-I, Discharging

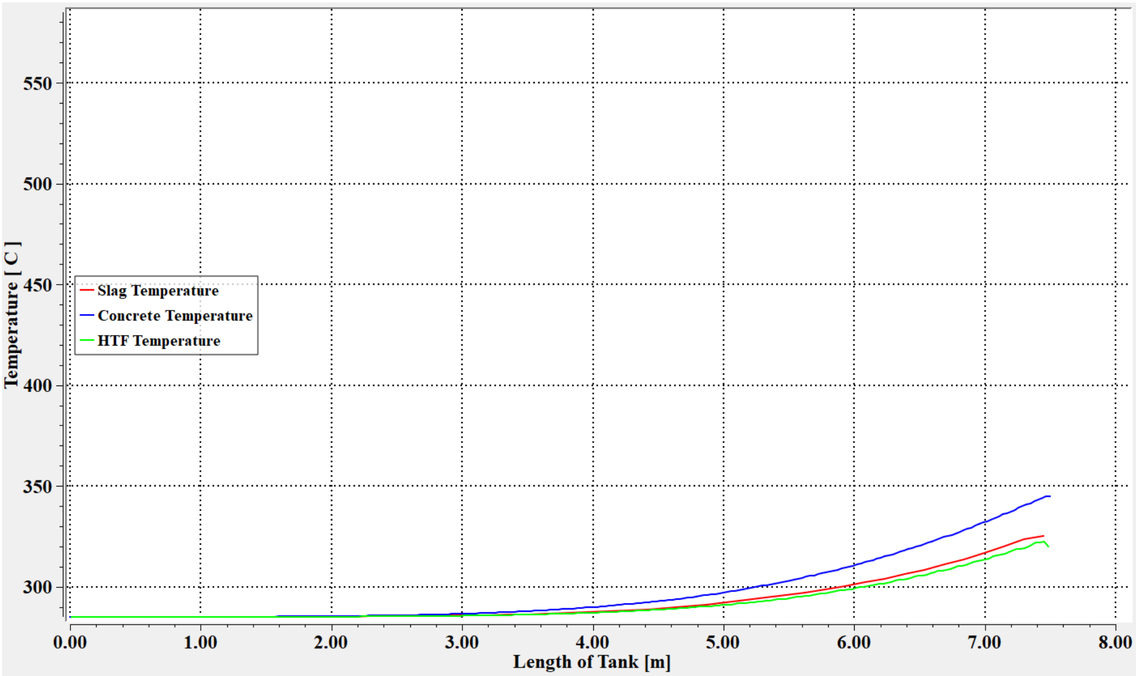

Figure 4-14 Temperature profiles of TESS at t=90 min, Case-I, Discharging

After the time interval of 90 min, thermal profiles show discharging of TES tank almost 85 percent as shown in figure 4-14. Storage materials temperature curves are approaching the HTF curve. Slag material is dissipating thermal energy in shorter time as compared to concrete. Temperature contours show that the tank discharging occurs as shown in figure 4-13.

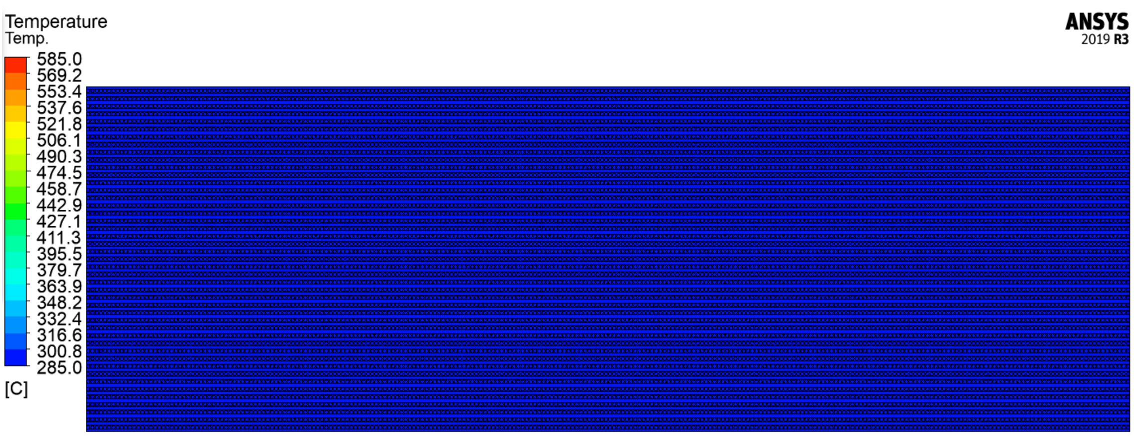

Figure 4-15 Temperature contours of TESS at t=120 min, Case-I, Discharging

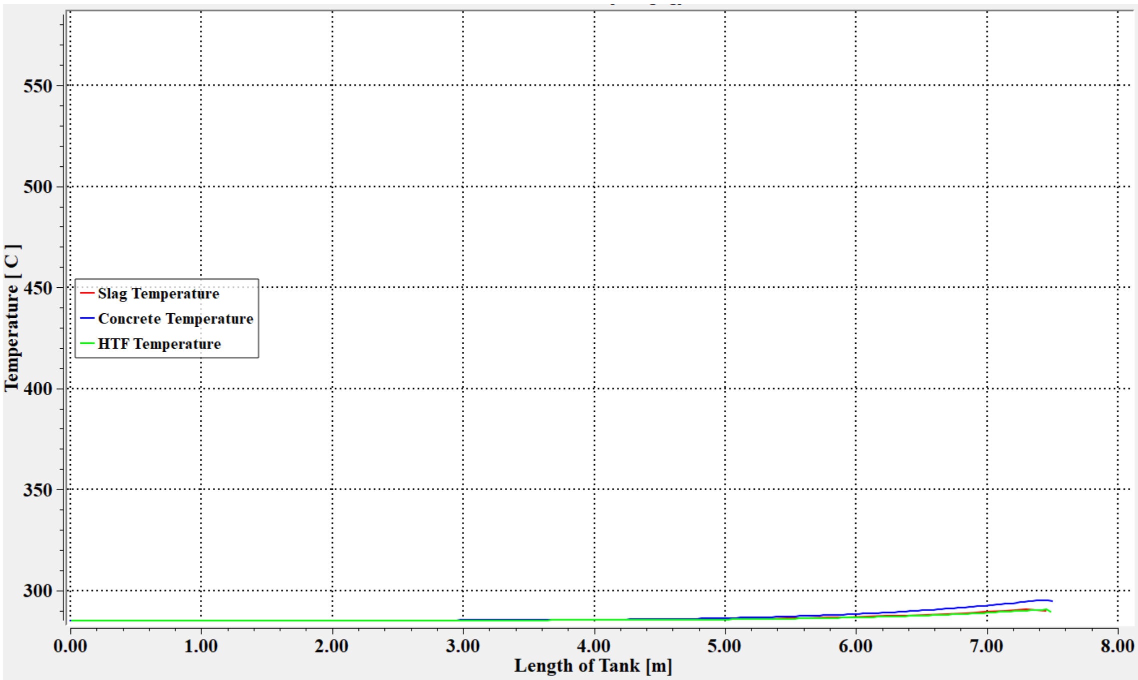

Figure 4-16 Temperature profiles of TESS at t=120 min, Case-I, Discharging

4.2 Thermal Performance analysis of TES Tank Case-II

In studies of case II the circular slag particles were replaced with circular concrete particles. Same cycles of charging and discharging were applied, and temperature profiles observed.

4.2.1 Charging for Case-II

Average rise in temperature of Case II, TES is shown in Table 4-3. Charging of Case II, TES system is shown from Figure 4-17 to Figure 4-26.Entire system is at 285 °C. As the HTF at 585 °C enters the system, its temperature falls. While that of constituent elements rises. The thermal picture of 30, 60 and 90 min is given from Figures 4-17 to Figure 4-23. During this time the average temperature of HTF, concrete and slag has reached 580.2, 576.78 and 579.4 °C respectively. The same trend continues till 140 mins where entire system becomes charged at 585 °C. The time variation of temperature and their respective profiles is shown in Figure 4-24 to Figure 4-26.

Table 4-3 Average temperatures of TES system for Case-II, Charging

	Case-II, Charging		
Time (min)	HTF (°C)	Concrete (°C)	Circular Shaped Concrete (°C)
0	312	312	312
30	458.557	423.391	452.228
60	554.473	537.801	551.984
90	580.02	576.568	579.413
120	583.457	582.758	583.167
140	584.401	584.68	584.21

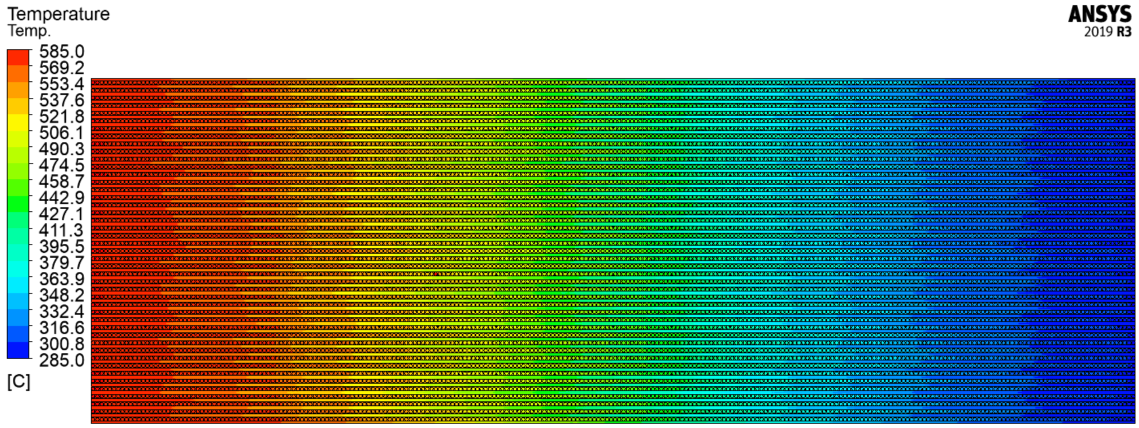

Figure 4-17 Temperature contours of TESS at t=30 min, Case-II, Charging

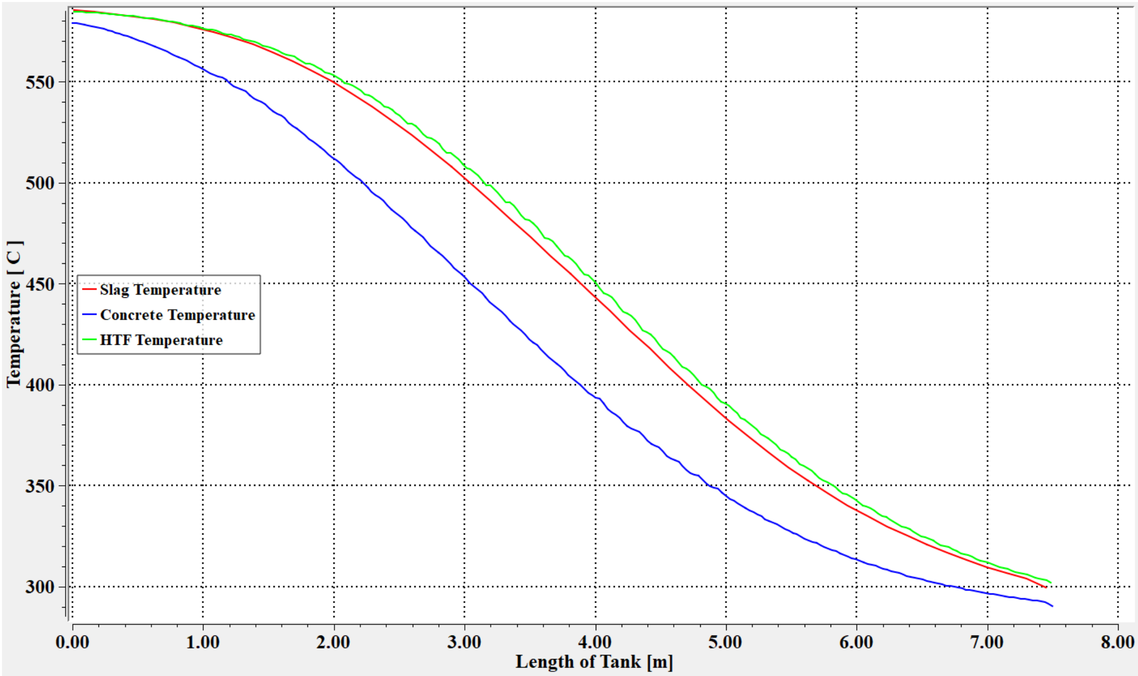

Figure 4-18 Temperature profiles of TESS at t=30 min, Case-II, Charging

In this thermal performance analysis HTF enters in the TES system to transfer thermal energy to same storage material but placed at two different locations. At outside fluid flow and in front of the fluid flow. Circular shaped concrete particles are introduced in the place of slag particles to examine the thermal performance of both materials. HTF enters at 585 °C and entire tank is at 285 °C. In charging phase after the 30 min time interval the average rise in temperature occurs as shown in fig 4-17.

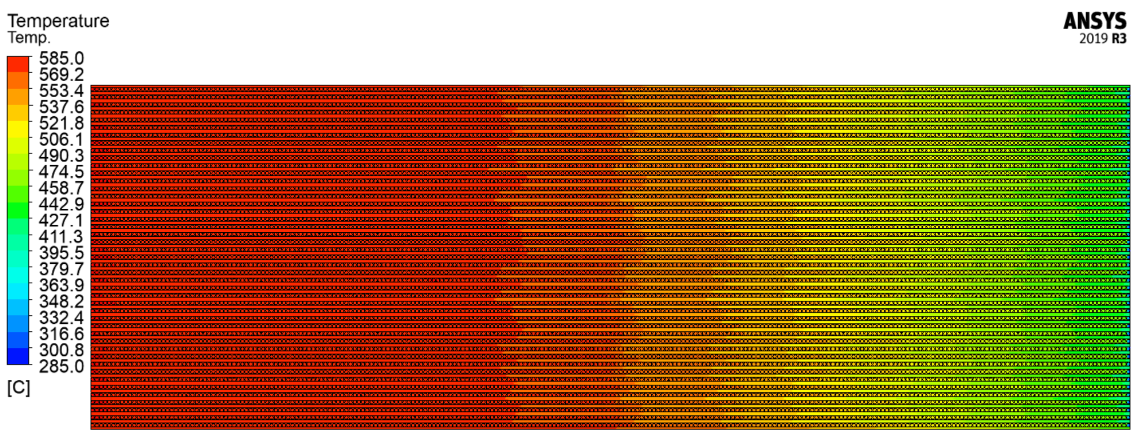

Figure 4-19 Temperature contours of TESS at t=60 min, Case-II, Charging

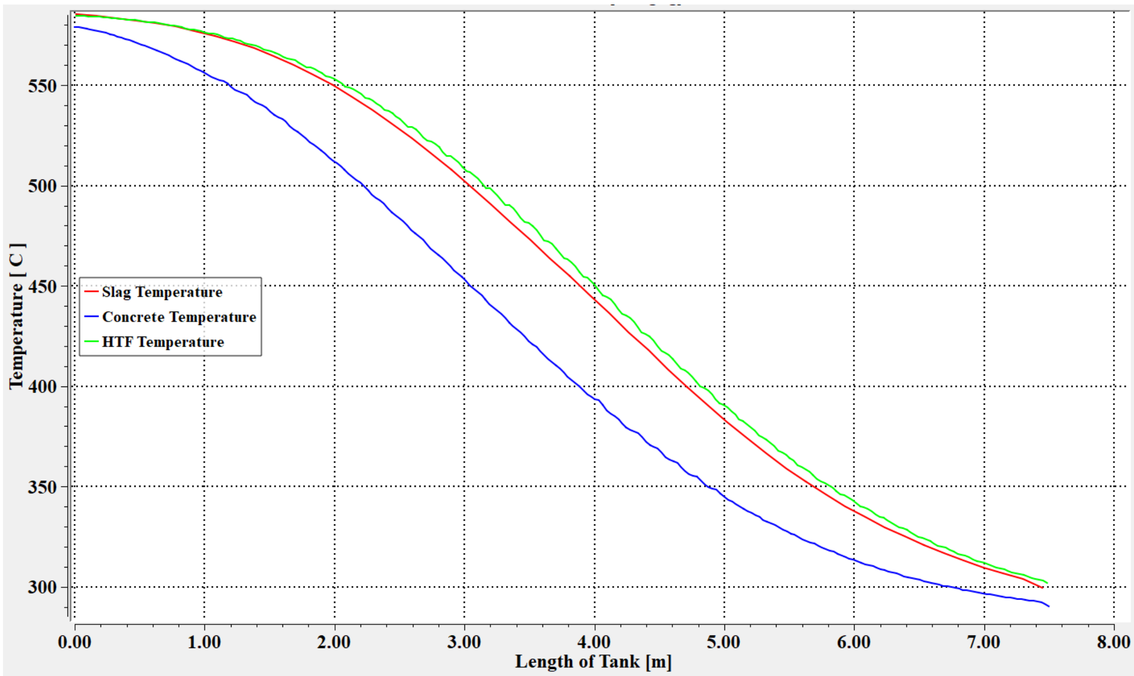

Figure 4-20 Temperature profiles of TESS at t=60 min, Case-II, Charging

Similarly, after the time interval of 60 min HTF is continuously charging the tank and it is observed that average rise in temperature of tank occurs. The thermal profile of tank shows the charging of system as shown in figure 4-19. In figure 4-20 graphical representation of temperature profiles is presented.

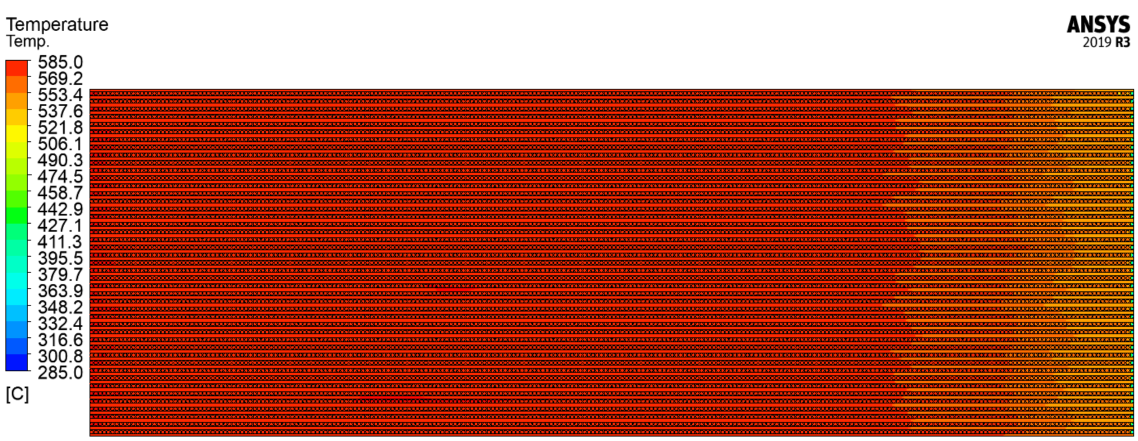

Figure 4-21 Temperature contours of TESS at t=90 min, Case-II, Charging

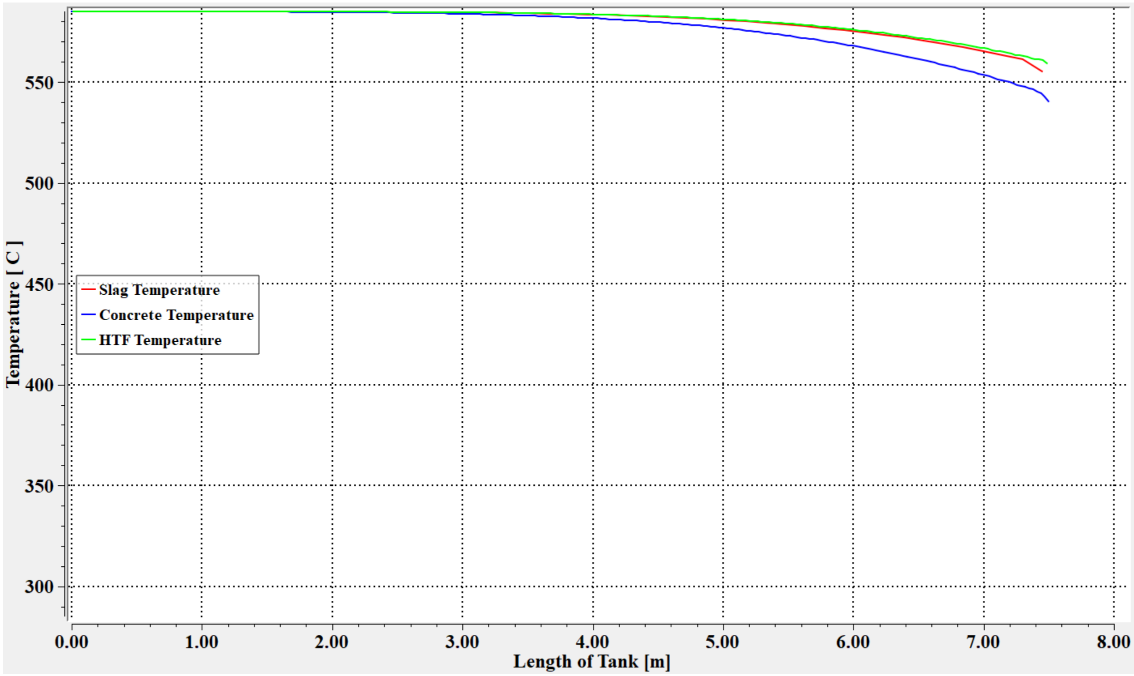

Figure 4-22 Temperature profiles of TESS at t=90 min, Case-II, Charging

As shown in figure 4-21 and 4-22 the tank is almost charged and the average rise in temperatures occurred in tank. During this time the average temperature of HTF, concrete and slag has reached 580.2, 576.78 and 579.4 °C respectively.

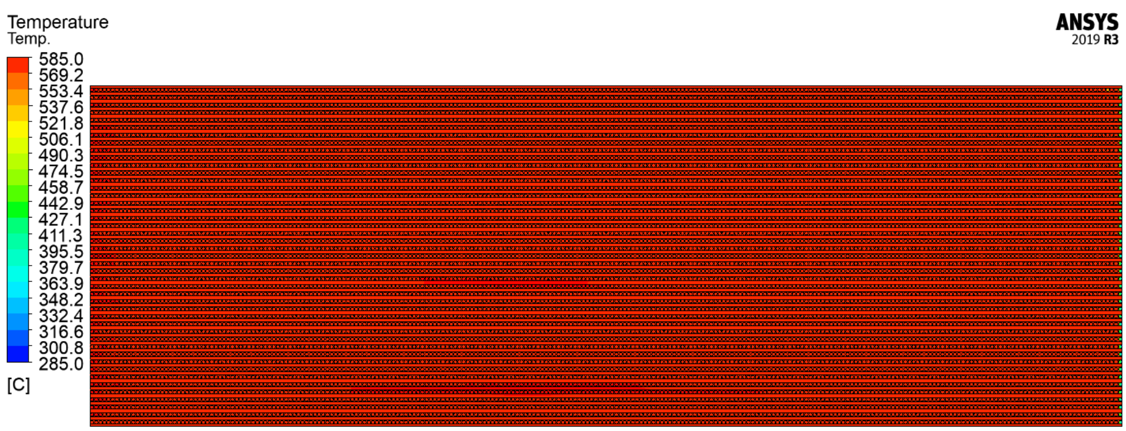

Figure 4-23 Temperature contours of TESS at t=120 min, Case-II, Charging

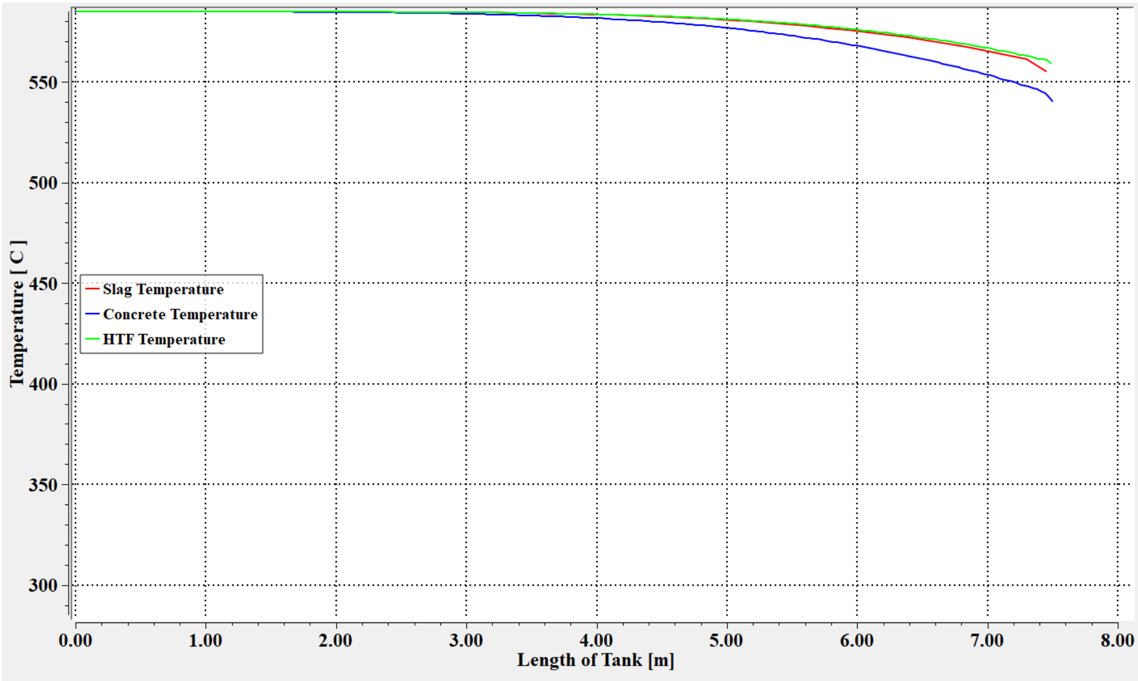

Figure 4-24 Temperature profiles of TESS at t=120 min, Case-II, Charging

In figure 4-23 and fig 4-24 shown that tank is still in charging phase. HTF is dissipating heat and storage material is absorbing heat. Temperature curves are showing heat gain continuously. Average rise in temperatures of thermal energy storage tank is occurred.

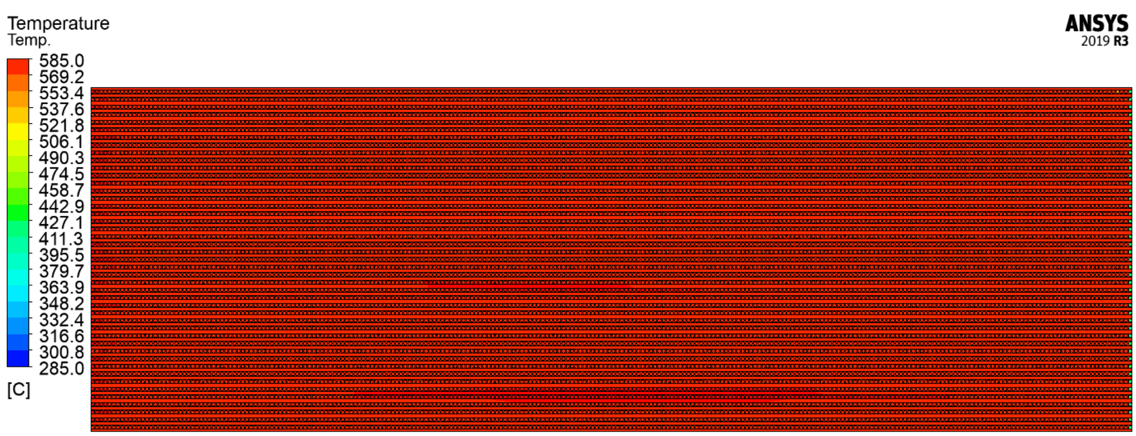

Figure 4-25 Temperature contours of TESS at t=140 min, Case-II, Charging

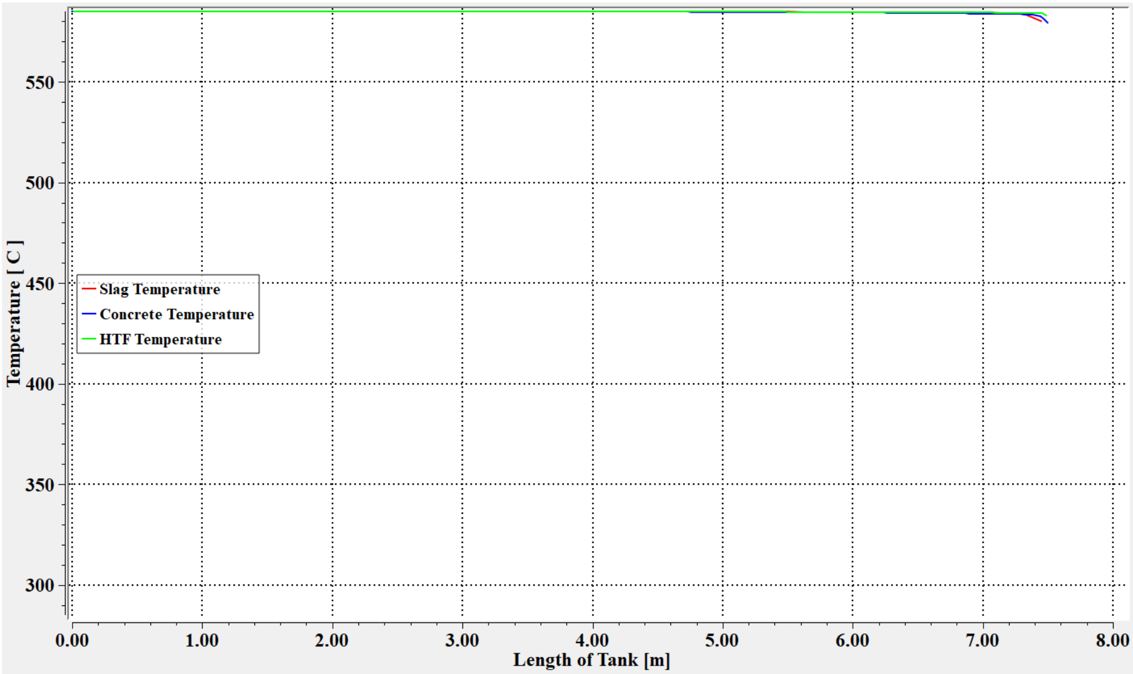

Figure 4-26 Temperature profiles of TESS at t=140 min, Case-II, Charging

After the time interval of 140 min tank is fully charged. HTF dissipate all its heat to the absorbing material. Tank temperature now approaches to 585 °C. As shown in fig 4-25 temperature contours showed the charged tank.

4.2.2 Discharging for Case-II

Figure 4-27 to Figure 4-36 shows the discharging behavior of Case II of TES system. Average temperature values are shown in Table 4-3. The table shows that at HTF temperature starts to drop from 585 °C to 285 °C in 140 mins. Similar trends of concrete and slag can be seen. Figure 4-33 and Figure 4-34 shows the initial picture of TES system. The time passes TES system starts to lose energy thus reduction in temperature of system can be seen from Figure 4-27 to Figure 4-36.

Table 4-4 Average temperatures of TES system for Case-II, Discharging

	Case-II, Charging		
Time (min)	HTF (°C)	Concrete (°C)	Circular Shaped Concrete (°C)
0	585	585	585

30	410.789	446.591	416.852
60	314.863	332.208	317.075
90	289.328	293.432	289.662
120	285.892	287.228	285.914
140	284.941	285.283	284.869

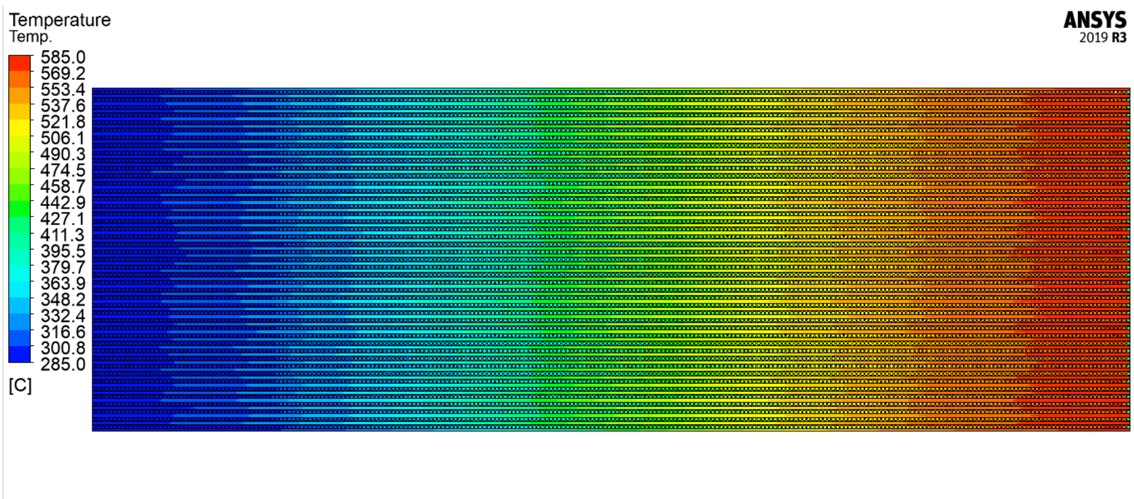

Figure 4-27Temperature contours of TESS at t=30 min, Case-II, Discharging

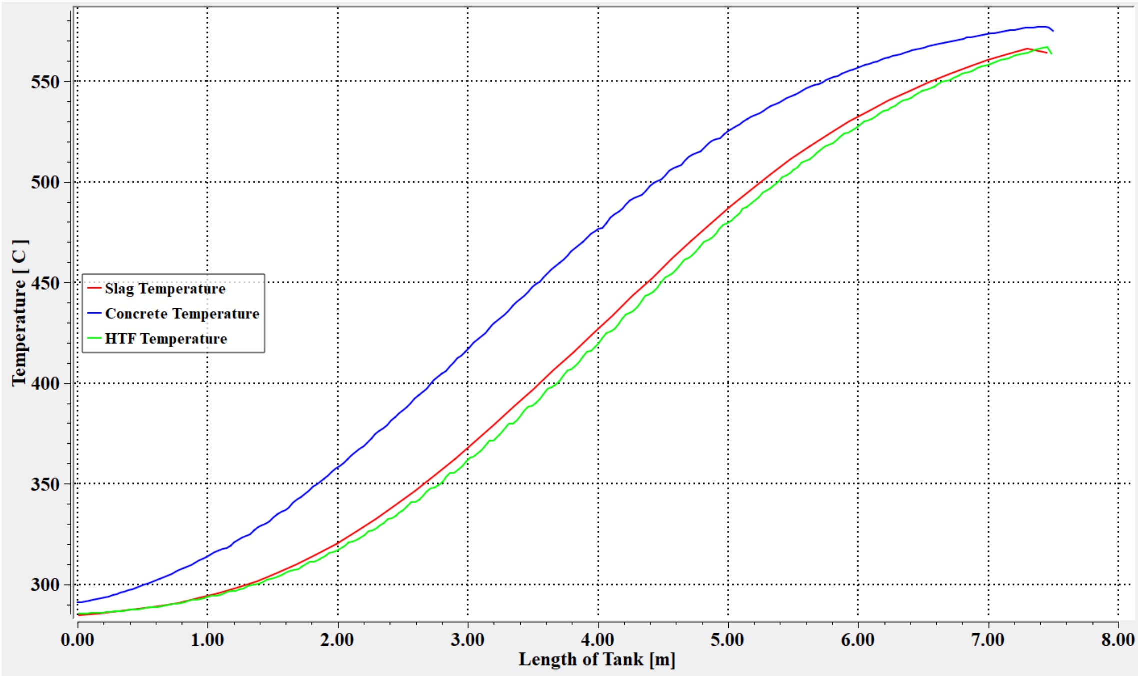

Figure 4-28 Temperature profiles of TESS at t=30 min, Case-II, Discharging

HTF enters at 285 °C in the TES tank. Tank is initially at 585 °C. Tank is dissipating thermal energy to HTF as shown in fig 4-28. Thermal profile shows the discharging of tank. Temperature contours show the significant change in decrease in average temperature of TES tank.

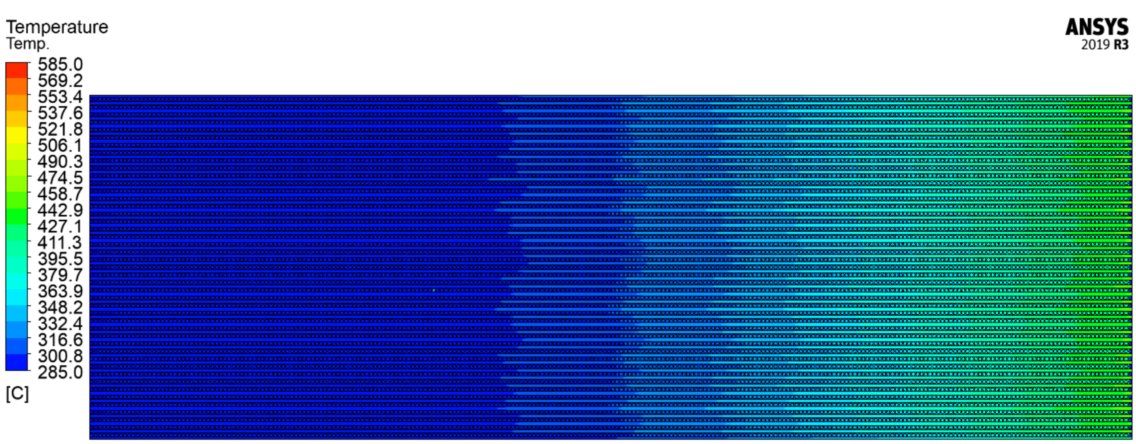

Figure 4-29 Temperature contours of TESS at t=60 min, Case-II, Discharging

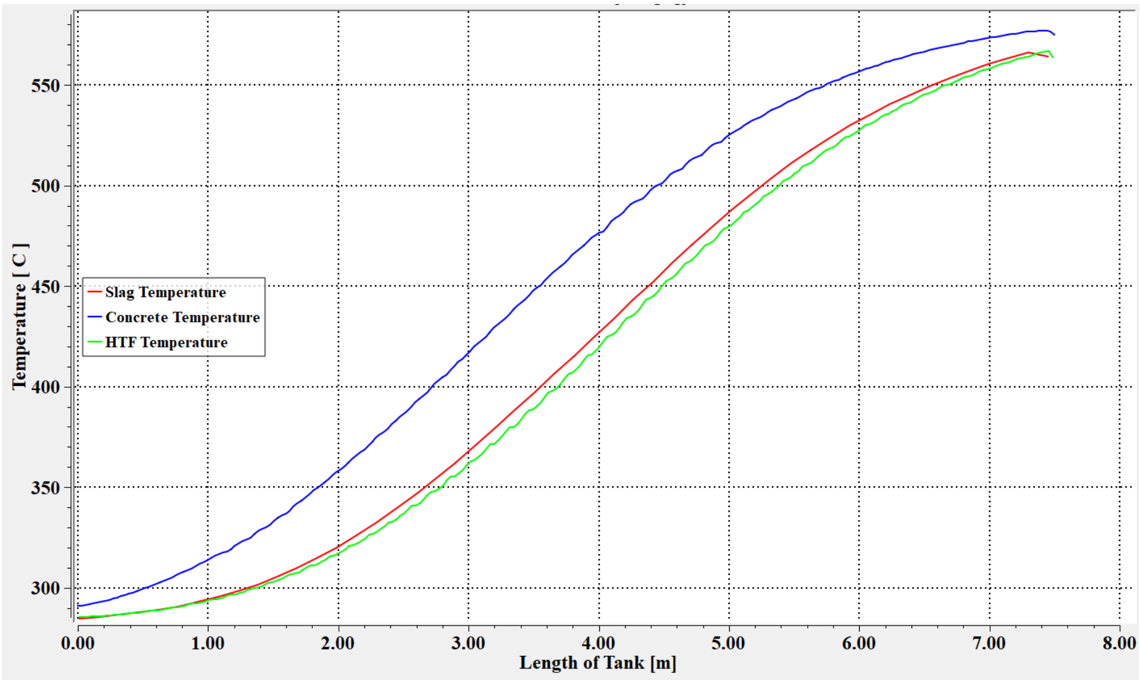

Figure 4-30 Temperature profiles of TESS at t=60 min, Case-II, Discharging

After the time interval of 60 min TES tank is discharging as shown in fig 4-30. Temperature contours show the discharging of tank. Concrete show stability in charging and discharging cycle. Average decrease in temperature of TES system occurs.

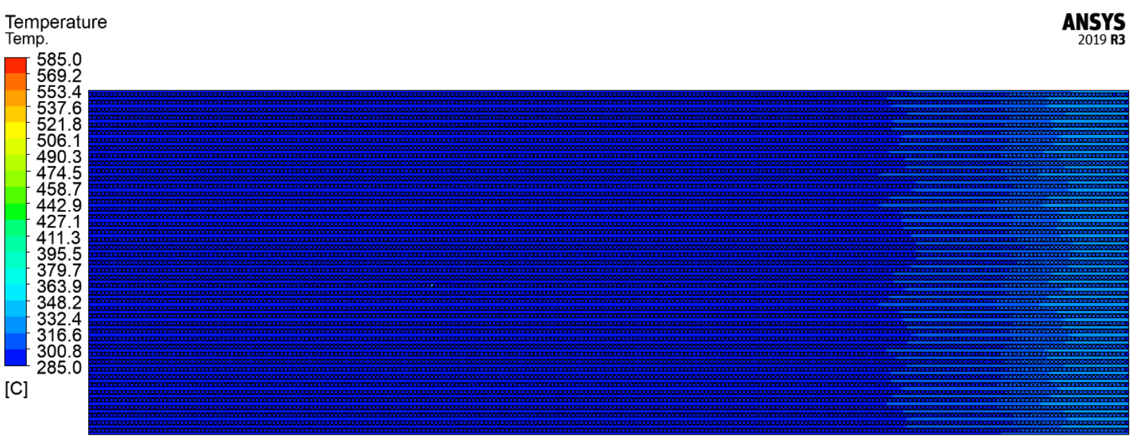

Figure 4- 31 Temperature contours of TESS at t=90 min, Case-II, Discharging

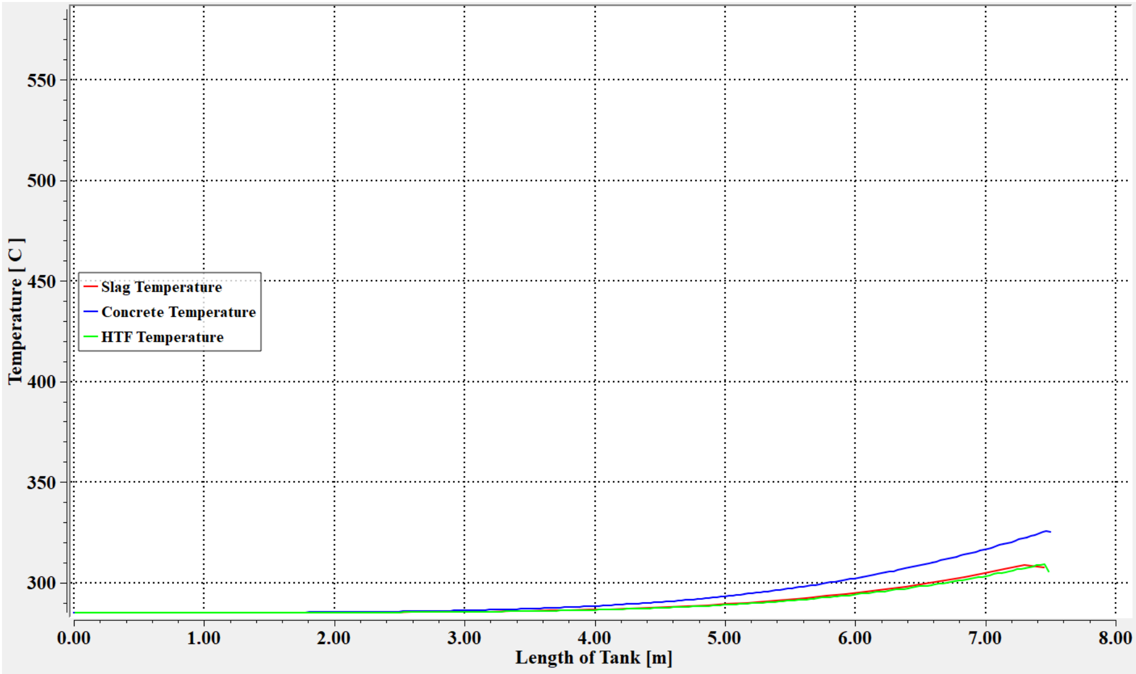

Figure 4-32 Temperature profiles of TESS at t=90 min, Case-II, Discharging

After the time interval of 90 min the TES system discharging is occurring as shown through the fig 4-32 and fig 4-31. Due to the thermophysical properties of storage material shows stability in charging as well as discharging. Temperature contours show that discharging is in progress not fully discharged as shown in fig 4-31.

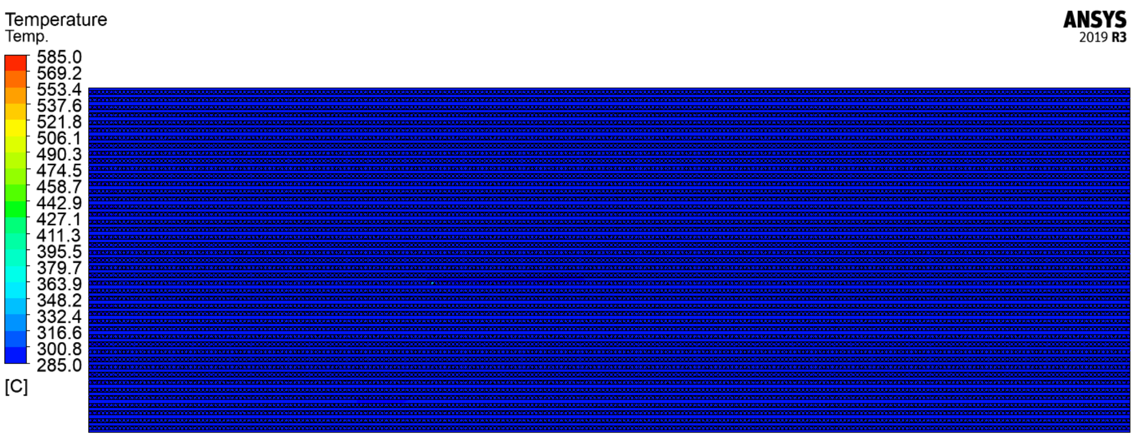

Figure 4-33 Temperature contours of TESS at t=120 min, Case-II, Discharging

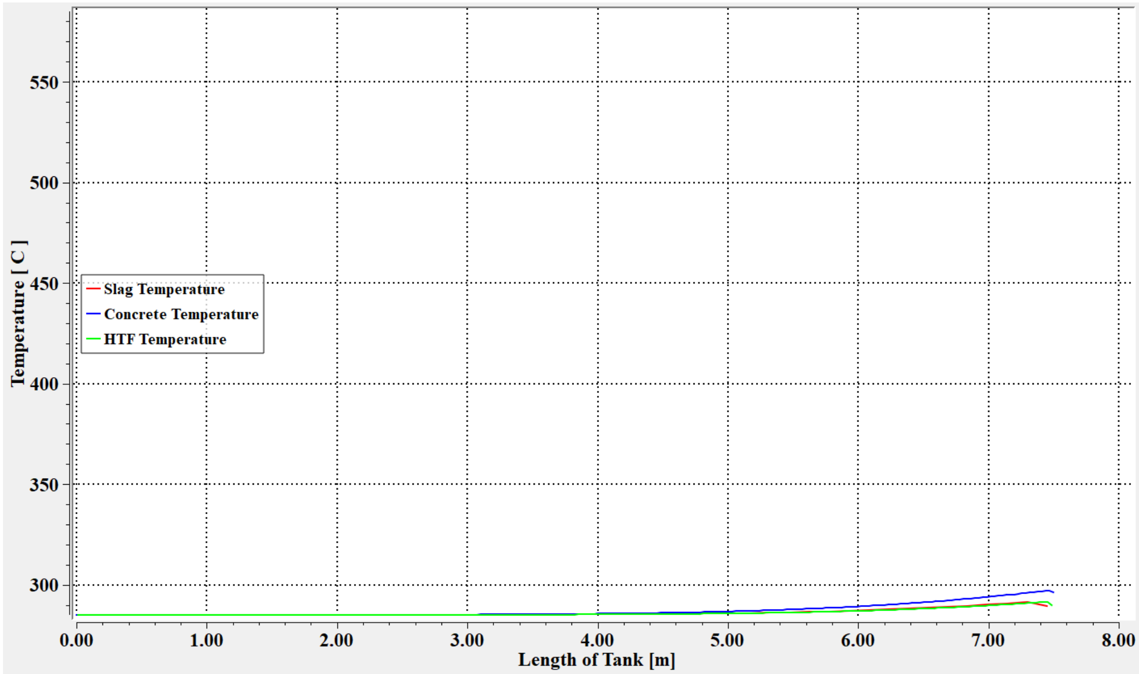

Figure 4-34 Temperature profiles of TESS at t=120 min, Case-II, Discharging

The TES tank is near to fully discharged, but still some thermal energy is remained in tank to transfer HTF as shown in fig 4-34. Graphical representation shows the remaining thermal energy. Tank is fully discharged when tank and HTF are at same temperatures. Due to the excellent specific heat capacity and thermal conductivity of storage material tank behaves stability in charging and discharging cycles.

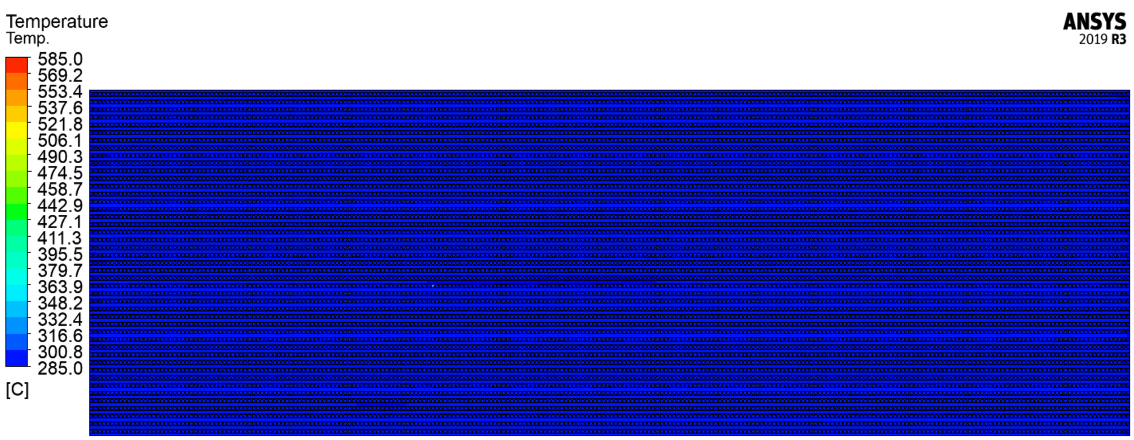

Figure 4-35 Temperature contours of TESS at t=140 min, Case-II, Discharging

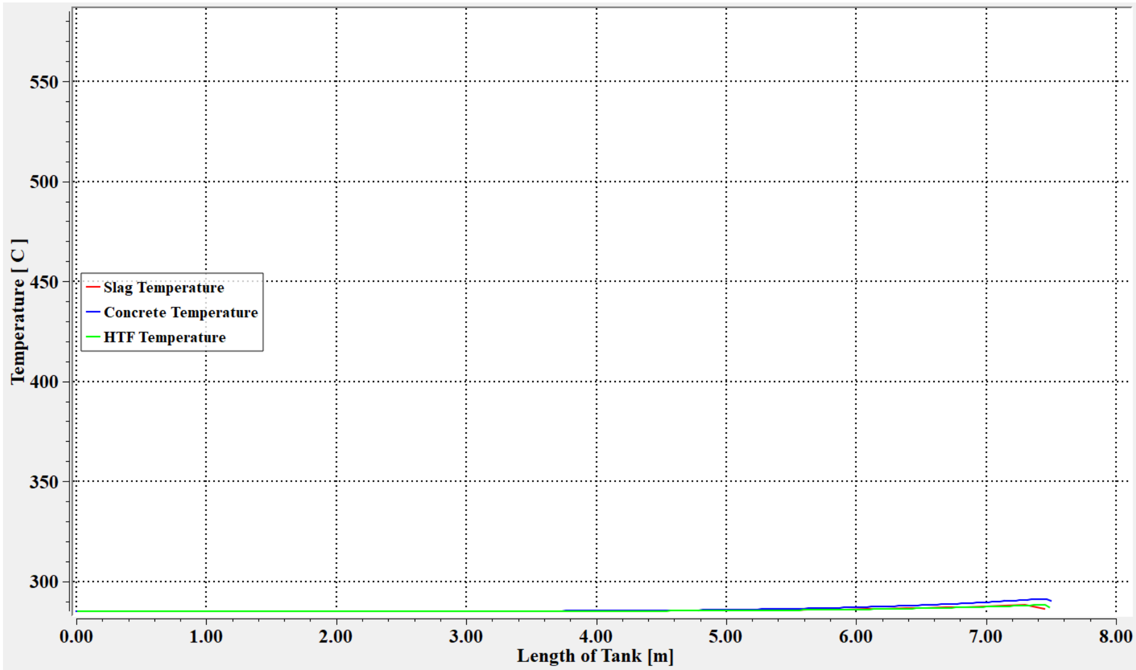

Figure 4-36 Temperature profiles of TESS at t=140 min, Case-II, Discharging

After the time interval of 140 min the tank is fully discharged. All the thermal energy present in the tank is dissipated to HTF. Temperature profile and contours show the discharged tank as shown in fig 4-35 and 4-36.

4.2.3 Capacity Utilization of TESS

Capacity Utilization Formula = $\frac{Actual\ Output}{Maximum\ possible\ output} \times 100$

All the thermal energy supplied to the tank is dissipated to the heat storage materials for fully charging and in discharging cycle heat is absorbed by HTF.

4.2.4 Charging period efficiency

$$\eta = \frac{Energy\ accumulation}{Energy\ Input}$$

Charging efficiency at t=60 min is calculated through the temperature values of thermal energy storage tank. At t=60 min, T(bottom)= 312 °C, T(top)= 585 °C.

$$T_{mean} = \frac{T_{top} + T_{bottom}}{2}$$

$$Q_{gain} = mcp(T_{mean} - T_{in})$$

$$m = \rho v$$

$$Q_{max} = mcp(T_{tank} - T_{in})$$

Density and specific heat capacity of concrete is taken from literature as mentioned above, while volume of concrete used in thermal energy storage tank is calculated. Similarly, density and specific heat capacity of slag is taken from literature, while volume of slag is calculated.

Efficiency of concrete at 60 min is 55.9 %.

Efficiency of slag at 60 min is 54 %.

4.2.5 Discharging period efficiency

$$\eta = \frac{Energy\ recovered}{\Delta E1 + \Delta E2}$$

During the process of discharging stability of heat dissipation is a problem. Discharging efficiency is less than the charging efficiency. The discharging efficiency of concrete and slag are 50 %and 49 %.

4.2.6 Velocity Contour

This contour shows the velocity variation of HTF in different sections of the passage. Velocity decreases between the circular bodies due to irregular flow of the fluid. However, the velocity of the fluid is maximum between the circular bodies and wall. Moreover, the velocity is also decreased near the walls. Velocity contour shows the variation of velocity between maximum and minimum level as shown in below figure.

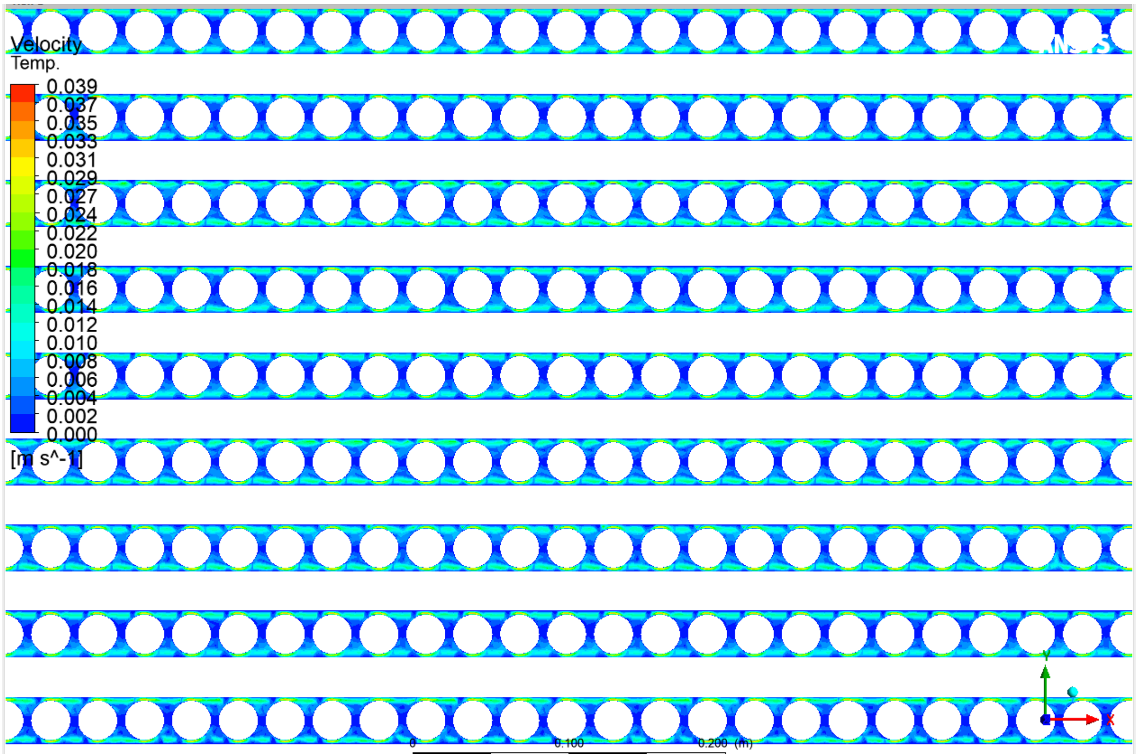

Figure 4-37 Velocity contours

4.3 Pressure Drop

The following contour shows the pressure drop of all configurations. Pressure values in x-axis due to flow pattern pressure variation occurs. Due to the curve edges pressure drop generates smaller in comparison to sharp ones. In this storage tank circular bodies are used to make curve edges for smaller pressure drop. Configuration is same for all scenarios, so pressure drop is same for all cases as shown below.

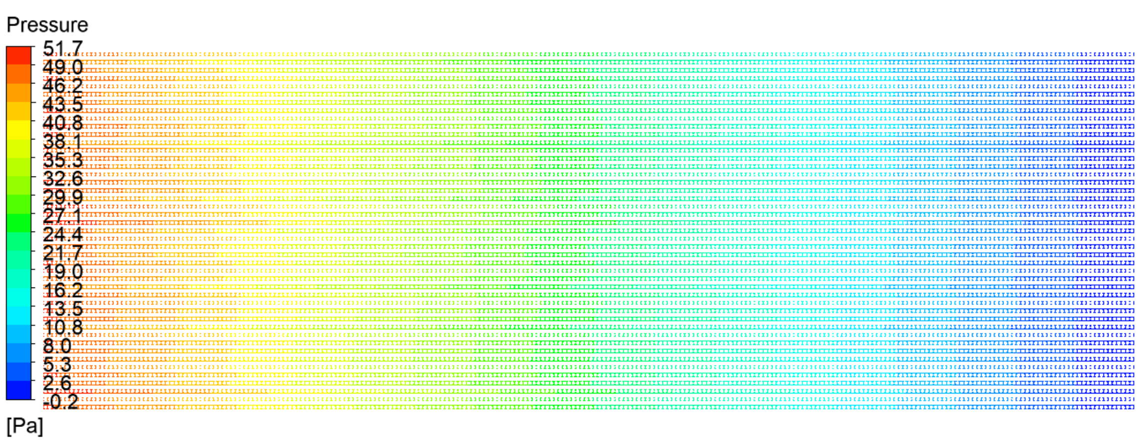

Figure 4-38 Pressure drop

Summary

The main objective of this chapter was the detailed discussions about the results. Two cases of charging and discharging were discussed and shown the variations in temperature, energy content storage and heat transfer rates were explained through graphs and average temperatures at different time intervals.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

Analysis of a TES system was performed for two cases. Case I had slag as circular particles while case two had concrete as circular particles. Following conclusions can be drawn from the simulations,

1. Both systems are efficient heat storage system thus can be used as TES systems. Temperature profiles of heat storage materials during both cycles shown their thermal performance according to their specific heat capacity and thermal conductivity values.
2. The charging and discharging time of slag system is 120 mins while that of concrete is 140 min. On basis of time, Case II seems more suitable if ample amount of high energy HTF is available. Slag material show the less stability during charging and discharging.
3. In short cycles Case I will perform better as it charges and discharges quickly. This system is more appropriate for saving waste heat or renewable anergy for shorter interval.
4. Velocity contours show that due to the circular pattern in front of flow velocity of HTF drops to very low level. This phenomenon alters the heat transfer rates due to velocity variation in the middle and walls. Velocity is minimum between the circular particles and maximum towards the wall. Therefore, slag particles are charged and discharged quickly due to the low velocity of HTF.
5. Pressure is dropped during the flow of HTF but due to the curve surfaces of bodies there is pressure drop is less in comparison to sharp edges. At the beginning of the flow pressure is higher and low at the end of flow. Excessive pressure drop has

disadvantage due to the requirement of more pumping power. Greater extent of turbulence is created due to the positive result of pressure drop. Turbulence is desirable in heat exchange because it enhances the heat transfer.

5.2 Future Recommendations

On the basis of simulations and analysis it is recommended that more simulation may be performed using validated numerical model. Moreover, the effects of shape of circular particles can also be studied. Financial analysis of manufacturing and application of TES system should also be studied for a comprehensive design solution to industry.

Appendix

The Thermal Analysis of a Sensible Heat Thermal Energy Storage System Using Circular-Shaped Slag and Concrete for Medium- to High-Temperature Applications

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Abstract:

Thermal energy storage (TES) system is a technique that stores thermal energy in a storage medium for later use to balance demand and supply in industrial operations. In this study, a sensible thermal energy storage tank composed of concrete block and heat transfer fluid (HTF) passages is proposed. Slag and concrete particles are introduced to analyze the performance of the TES system. A comprehensive numerical model is developed using an energy balance approach combined with an enthalpy-based methodology. The temperature distribution is presented at different time intervals during the charging and discharging cycle of TESS. In comparison with a slag-filled TES tank, the concrete-filled TES tank charged and discharged quickly. The findings reveal that a TES tank filled with concrete is more efficient than a TES tank filled with slag.

Keywords: **:** Thermal Energy Storage; Sensible Heat Storage; Temperature Distribution; Numerical Modeling; CFD

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