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Optimization of Phase Change Materials (PCMS) for Thermal Energy Storage

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Abstract- **Concentrated solar power (CSP) uses solar insolation to increase the temperature of heat transfer fluid (HTF), which can be used in a power block to produce power either by using a steam turbine or gas turbine. In CSP, the levelized cost of electricity is higher than conventional sources due to the intermittent nature of solar energy. The levelized Cost of electricity can be reduced by integrating CSP with thermal energy storage (TES) system. This paper provides a comprehensive review of sensible TES technologies for CSP applications. It includes a brief discussion of various sensible heat TES systems, i.e., molten salt TES system, single media TES system, and DMT (Dual-Media Tank) TES systems.**

This research work consists of systematic analysis of a dual-media thermal energy storage system consisting of ceramic pebbles as a storage material and high-temperature heat transfer fluid (HTF) for 1 MW National Solar Thermal Power Plant. A numerical model has been formulated to study the thermocline behavior of tanks at different operating conditions. Based on the numerical model, a lab-scale test facility is developed to validate the numerical model. The main objective of this study is to analyze the formation of the thermocline thickness for various operating parameters such as mass flow rate, void fraction, pebbles diameter, and thermal diffusivity of HTF and storage materials, along with a parametric optimization. The numerical result shows that, as the mass flow rate increases, the discharge time can cause the varying temperature at the outlet that is unenviable.

Keywords- Thermal Energy Storage (TES), Concentrated Solar Power (CSP), Thermocline, Shell and tube heat exchanger, Segmental baffles, Process optimization.

I. INTRODUCTION

Energy since ages has been mankind's necessity. Humans have always relied upon various sources of energy in order to fulfill their day-to-day needs. Biofuels were the earliest sources of energy. But due to its inefficiency, several other sources of energy saw significant growth. After several years fossil fuels became the primary source of energy. Exploration of fossil fuels led to a remarkable turnaround in the energy sector. It changed the scenario worldwide. Energy now plays an indispensable role in a nation's growth. Growth in economies also leads to an increase in energy demand; hence energy plays a vital role in nation-building.

Various other technologies such as solar air heating, solar photovoltaic plus thermal technology, solar water heating technology under SHC systems are being used for multiple domestic and industrial purposes [1]. The third major technology to harness solar energy is CSP. In CSP solar energy is converted into high-temperature heat with the help of mirrors that concentrate the sun's light onto a receiver. This thermal power can be utilized to convert water to steam which is further used for producing electricity by running a turbine with the help of power cycles like Rankine, Brayton, etc. [2]. The concentrated solar power consists of three building blocks: Solar field, TES and power system.

Figure 1 shows the share of electricity generation in India. Similarly, solar heating and cooling (SHC) has proved to be a viable alternative. SHC systems are used for space heating, producing hot water for domestic purposes, or used in absorption.

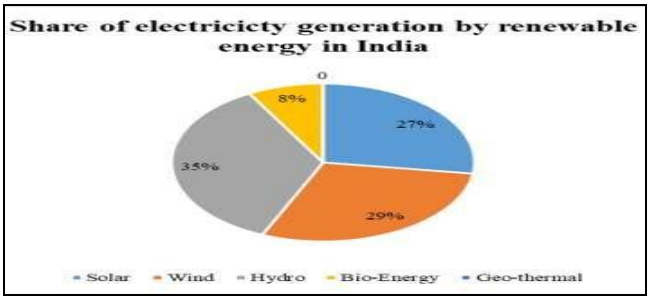

Figure 1: Share of electricity generation by renewable energy in India

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CSP operates on four other technologies, namely solar tower, dish stirling, PTC, and LFR. The solar tower operates at the highest temperature and has the highest concentration ratio. It is followed by dish stirling, which operates in the range of 300℃-1500℃. Both of these technologies have high thermodynamic efficiency. Aforesaid are recent developments in the field of CSP, while PTC and LFR are mature technologies, but they have relatively low thermodynamic efficiency and operate at lower temperatures [3]. To make sure that the use of costly and toxic HTF in CSPs are minimized, a new technology named Direct Steam Generation (DSG) was developed. It has been forecasted that CSP based on DSG technology would work on higher temperatures in the coming years. Presently inorganic salts are used as HTF in high-temperature CSPs based on the central receiver. According to the REN21 global status report 2018, saw a considerable increase in the CSP technology. Cumulative capacity grew by 11% and approximately, 550MW of concentrated solar thermal power was added.

The author has used a truncated conical shape tank immersed in the ground for studying thermocline behavior of tank. [4] analyzed the technical and economic modeling of the thermocline TES system for CSP application. In addition to the techno-economic model, the author also performed the parametric optimization by implementing genetic algorithms (GA) of the MATLAB optimization toolbox.

Most of the above studies focused on the thermocline behavior of DMTES systems under various operating variables such as mass flow rate, pebbles diameter, void fraction, and thermos physical properties of the storage material. However, none of the authors has studied the effect of operating variables on thermocline thickness. This study examines the influence of variables such as void fraction, pebbles diameter, and mass flow rate to close these gaps with thermodynamic modelling and parametric optimization. In addition, an empirical correlation is also developed to evaluate the thermocline thickness under various operating conditions.

II. PROBLEM STATEMENT

The intermittency of solar energy is a major factor for high levelized cost of electricity based on solar power plant. However, this limitation can be overcome by integrating CSP with TES. The TES system are based on sensible heat are commercially available but still economically not so viable due to high cost. Of all sensible based TES system, dual media tank energy storage system is economically more viable due to its lower cost but still this system is not on commercialized state. However, the commercialization is possible by integrating the DMT TES system with CSP plant based on micro grid. The smallest commercial CSP plant, which was operational in 2019, was of a 9 MW capacity with a 36 MWh energy storage system. Therefore, research needs to be done to integrate micro solar power plants with the TES.

III. OBJECTIVE

The primary objective of this work is characteristic analysis of solar-based packed bed TES system using synthetic oil as a HTF for CSP:

- Parametric optimization of TES system using Design of Experiments (DOE).
- Experimental setup: Design and fabrications.

IV. LITERATURE REVIEW

CSP TECHNOLOGY

Unlike PV, Concentrated Solar Power (CSP) does not convert sunlight directly to electricity; instead works as an interstage step. It consists of a reflector and absorber. The reflector focuses the sunlight on the absorber. Sunlight is converted into heat and absorbed in the absorber. This heat can be utilized to generate steam. It consists of four parts, namely solar field, power block, and Thermal Energy Storage (TES) system [5]. When TES is combined with CSP, it increases operating capacity, improves the power dispatch of the plant, reduces peak demand and ultimately increases the value of the power produced. The system is most efficient when the energy- carrying material is removed from the system at a temperature, which correspond to its initial value [6]. CSP technology can be classified into two components i.e. point focus concentrator and line focus concentrator. Point focus concentrators achieve high temperatures at the receiver, in the range of 700℃ -1000℃. They produce high temperatures due to the high concentration ratio. Line focus based technologies, on the other hand, attain lower temperatures [7]. Electricity generation from CSP grew at a rate of 25 % between 2011and 2017, in which the total capacity increased to three times. Its demand increases at a rate of 17% in the year 2018. It is forecasted to grow by 3.4 GW from 2019 to 2024 [8].

GLOBAL STATUS OF CONCENTRATED SOLAR POWER

CSP global capacity till 2018was 5610 GW. The percentage growth of CSP in 2019 was 11.9%, however it is 24% below than the average annual increase from the past decade (Members,2020).

Five countries come up with the implementation of first commercial CSP plant.The solar field of the majority of the CSP system consists of a parabolic trough collector. Majority of CSP plants are integrated with TES system. China continued with 200 MW capacity in integration with molten salt TES system. The smallest commercial CSP plant of nine MW capacity with 36 MWh energy storage system, it is operational since 2019.

Figure-CSP Global capacity and addition in 2019 (Members, 2020) The journey of CSP in India was began in 2010 under Jawaharlal Nehru Solar Mission (JNNSM) with seven projects. Currently, five CSP are operational, and six are under construction. In India, the lack of DNI data is the main reason forthe delay in the growing CSP market [8]. The CSP under constructionor operational needs to be integrated with the TES system. The CSP in integration with the TES system reduces the per unit of electricity cost by increasing the operational time. Figure 2-2 shows the status of CSP integration with the TES system. In India, only three CSP is integrated with the TES system. In CSP, solar radiation is concentrated on the receiver through several technologies, i.e., PTC, LFR, Solar Tower, and solar dish. However, the solartower is the most favorable concentrator for CSP applications due to its high concentration and maximum temperature.

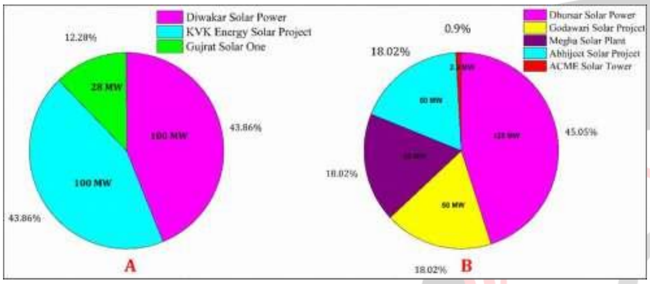

Figure 2 - National status: (A) CSP in integration with TES (B) CSP withoutTES.

Figure 2 compares the maximum concentration ratio and the maximum temperature of the different concentrators. CSP operates on four other technologies, namely solar tower, dish Stirling, PTC (Parabolic Trough Collector), and LFR (Linear Fresnel Reflector). Solar tower operates at the highest temperature and has the highest maximum concentration ratio. It is followed by Dish Stirling, which operates in the range of 300°C-1500°C. Both of these technologies have high thermodynamic efficiency. They are recent developments in the field of CSP technologies [9]

Figure 3 - Operating temperature and concentration ratio of solar reflector (Barlev et al., 2011)

According to REN21 global status report, 2018 saw a considerable increase in the CSP technology. The cumulative capacity increased by 11% and approximately, 550MW of concentrated solar thermal power was added. Figure 1-4 shows the capacity and expansion in each year from 2008 to 2018. Between 2016-18 the capital cost of CSP also fell sharply.

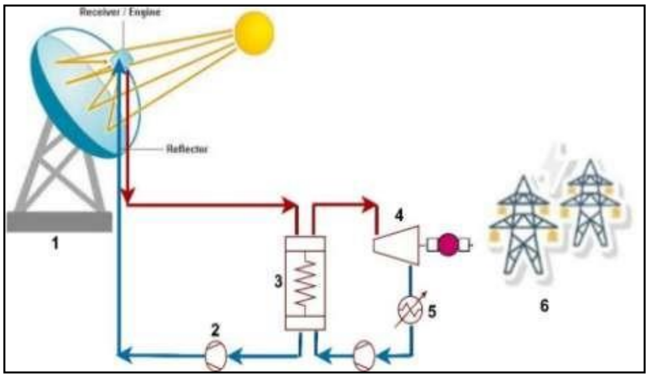

Figure 4 - Concentrated Solar Power (CSP) Technology

Figure 4 shows the CSP technology to produce power employing a solar field and power block

THERMAL ENERGY STORAGE SYSTEM (TES)

Figure 5 represents the schematic classification of TES systems. TES systems are classified into active and passive modes. Active TES can be further classified in two systems: Direct and Indirect. The active TES system conventionally uses liquid. This fluid helps in heat transfer through forced convection and heat exchange operation in steam generators. The passive type of TES system is a dual media system.

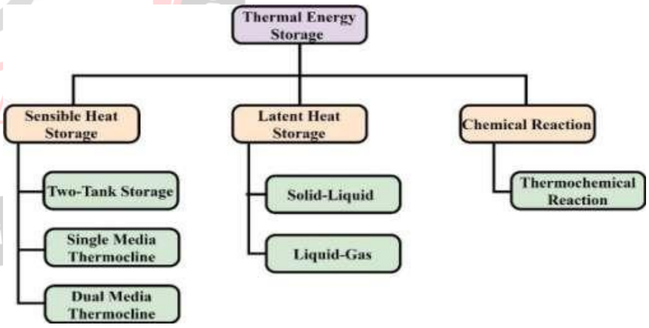

Figure 5 - Classification of TES System

Thermal storage media itself does not participate in the heat exchange process; instead, charging and discharging takes place through the circulation of heat transfer fluid [10]. Figure-shows the functional characteristics of the TES system. TES has many advantages over mechanical or chemical storage. The main reasons are the lower capital costs and higher operational efficiency than mechanical or chemical storage systems. A TES system stores the thermal energy in three forms: SH, LHV, and reversible chemical reactions [11].

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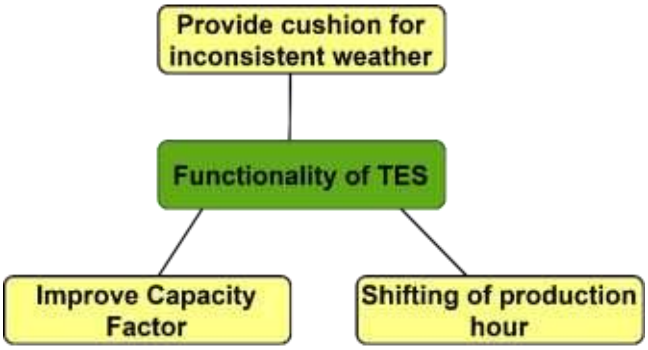

Figure 6 -Functionality of TES systems

Figure 6 shows the functional characteristics of the TES system. It has illustrated the share of different TES technologies regarding the quantity of energy stored. Molten saltsare widely used in CSPs, and account for almost 77% of stored thermal energy.Ithas reviewed TES systems based on the absorption cycle. With the absorption cycle based TES, both hot and cold storages are possible. This type of storage system has a high storage density, so the system is usually compact. It is broadly categorized into two types, namely single-stage absorption and double stage absorption TES.

TWO-TANK THERMAL ENERGY STORAGE SYSTEM

In the two-tank molten salt TES system, solar energy can be stored in the hot and cold reservoirs using molten salt. The MSTES system offers high temperatures when used as receiver fluid instead of thermal oil. High- temperature molten salt provides high-temperature steam and better efficiency. The block diagram of molten salt. *TES* system is shown in Figure.

Two tank systems consist of two tanks, namely a hot tank and a cold tank. Hot tank to store the material at a higher temperature and cold tank to store the material at a lower temperature. Most TES systems with two tanks use nitrate salts as a storage material. This type of technology is widely used in parabolic trough collectors and central tower-based solar power plants. All CSP plant operational from year 2014 to 2018 was based on TES, and nearly 17 GWh of the available TES was entirely based on two tanks of molten salt. The TES enables CSP as a dispatchable source of power by providing grid flexibility. Solar salt (NaNO3-KNO3: 60-40%) and HITEC (NaNO3-KNO3-NaNO2: 7-53-40 wt%) are the most common molten salt used in CSP plant. Additionally, Li et al. (X. Li, Wu, Wang, & Xie, 2018) suggested a eutectic ternary mixture of NaCl- NaF-Na2CO3 based on the thermodynamic and experimental approach. The eutectic point of ternary mixture consists of XNaF = 21.66 mol %, XNaCl = 41.87 mol% and XNa2CO3 = 36.47 mol % at temperature of 849 K. Furthermore, results were verified experimentally using DSC method. The thermophysical properties of molten salt can be determined specifically using the thermal analysis method. The molten salt with two tanks has a higher melting point and required additional heating to prevent clogging of the flow tubes. Hoffmann et al. developed a low temperature and inexpensive molten salt and reduced the cost of auxiliary heater used to maintain the temperature above the melting point. Peiro et al. (Peiró et al., 2018) conducted an empirical pilot-scale review of the TES system to test the viability of storage material, HTF, and CSP components on the integration of TES with CSP facility. The author recommended uniform heating to avoid any kind of vapor or air along with the thermal stress. Zhu et al. (Zhu, Yuan, Zhang, Xie, & Tan, 2019) carried out numerical investigation to identify the effect on thermocline behavior considering radiative losses. In the high-temperature molten salt TES system, however, the radiative heat transfer increases with an increasing temperature. In the high-temperature TES system, radiative heat transfer cannot be neglected due to its high proportion of total heat transfer. Theradiation model used by the author to investigate thermal performance was a discrete coordinate method. Numerical simulation [12] based on a modular- object-oriented methodology was carried out to examine critical parameters for the TES system. The parameter investigated are metrological data, insulation thickness, and foundation of the TES system. The thickness of insulation is the important parameter for the design of the tank. However, the foundation of the tank has not a great impact on the TES system. Cocco et al. (Cocco & Serra, 2015) did a numerical investigation to compare the two-tank TES system and thermocline tank for ORC. The result shows that the molten salt *TES* system has high-energy conversion efficiency as compared to the thermocline tank. However, the thermocline tank is economically more viable as compared to the two tank TES systems.

THERMOCLINE TANK SYSTEM

Two-tank molten salt TES systems are not economically so viable due to their initial cost. To overcome the limitations of TES system uses molten salt, a singletank TES system came into existence. The single media thermocline system consists of high-temperature HTF, which increases its temperature and energy content of working fluid in solar field and power block respectively. The power block generally consists of a vapor power cycle or gas power cycle; the selection is based on requirement and space. In a thermocline tank, hot and cold fluid are stored in the same tank, and hot fluid is always lies above the cold fluid due to the difference in density. The performance of the Thermocline container depends on the thermal stratification of the Thermocline container. However, the thermocline thickness also plays a major role in thermal performance tank. Figure-shows the single medium thermocline tank for CSP application. Water-based thermocline tanks operate at lower temperature differences as compared to molten salt-based thermocline tanks.

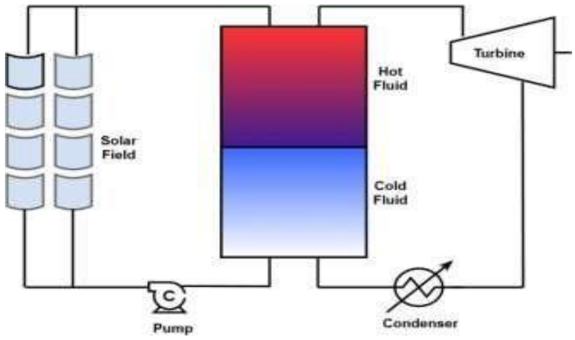

Figure 7 - Single Media TES system for CSP application

Figure 7 shows a Single Media TES system for CSP application Thermocline tanks for molten salt have higher thermal stratification forces. In order to ensure a higher degree of thermal stratification in the thermocline system; the distributor is fitted at the top so that the flow is uniform and no mixing of hot and cold fluid can takes place. Thermal stratification can be improved by using perforated inlet and a slotted inlet. For the flow rate is 5 L/min, the discharge efficiency is 21% higher than that of the direct inlet, and when the flow rate is increased to 15 L/min, the discharge efficiency is 40% higher than that of the direct inlet According to the study carried out by Reddy et al. the movement of thermocline thickness is rapid in solar salt as compared to that of HITEC. The author has also studied the effect of porosity on charging and discharging effectiveness. The result shows that discharge effectiveness drops with an increase in voids for all kind of HTFs. As values of porosity increases from 0.1 to 0.7, the discharge effectiveness falls continuously. The most suited HTF for thermocline tanks is therminol if it is not being subjected to high pressure. Baba et al. (Filali Baba et al., 2020) has estimated the thermal performance of a thermocline TES system using a dimensional model based on the dual-phase approach. Three critical variables were examined namely: thermocline zone thickness, dimensionless discharge time, and discharge efficiency. Gajbhiye et al. (Gajbhiye, Salunkhe, Kedare, & Bose, 2018) used eccentrically mounted vertical porous flow distributor to maintain the tank's thermal stratification. The author has also investigated the effect of Peclet.

The major advantage of packed bed storage system (PBSS) is to reduce storage costs. It can be operated at wide temperature ranges, and it is simple and efficient. PBSS with improved thermal stratification increases the collector efficiency. Unlike other TES systems, PBSS has high chemical stability, high safety and negligible corrosion issues. PBSS consists of a storage medium, and energy exchange system. Storage system stores thermal energy in the form of SH, LH, or in the thermo-chemical form (Erregueragui, Boutammachte, & Bouatem, 2016). The energy transfer mechanism takes the help of HTF, which supplies or extracts energy. PBSS contains packing elements in the form of particles that act as a heat storage medium. There are voids in the bed, HTF occupies these voids, and it exchange heat with the storage material [14]. Charging and discharging are done by shifting thermocline by circulating HTF through the packed bed. The HTF fluid is heated through solar radiation and then supplied to storage material, which then takes up the heat. On the other hand, during the discharging operation to extract the stored energy, the flow direction is reversed, low-temperature fluid is passed through the heated bed. Low-temperature fluid gains heat and leaving at a higher temperature, which can be utilized in the power cycle. Charging is done from the top to exploit the buoyancy effect to maintain thermal stratification where the hot HTF is at the top and cold HTF at the bottom. A higher degree of thermal stratification in a packed bed provides higher efficiency, as higher exergy can be recovered when the mixing of hot and cold zones is minimal (Gautam & Saini, 2020; Haller et al., 2009; Laing & Zunft, 2015; Zanganeh et al., 2012). The particle size in packed bed TES system ranges from few mm to several cm; it is one of the main characteristics of the packed bed. A packed bed with a minimum thermocline thickness contains a high exergy than a well-mixed bed, which has a lower temperature variation in the thermocline region. The dimensioning of the storage tank in PBSS depends on the required load, and is proportional to the collector area. A packed bed has inlet and outlet at top and lower part of the tank to foster thermal stratification [13]. Air-based solar systems are best suited to packed bed storage system.

The size of storage system depends on variables such as storage temperature, material, losses, etc. Packed beds are compact, simple, and economical. Steel gives the best results as a storage material in packed bed because it has a higherstorage rate and higher storage capacity than rock and aluminium (Singh, Saini, & Saini, 2010; L. Wang, Yang, & Duan, 2015). Bruch et al. (Bruch, Fourmigue, Couturier, & Molina, 2014) Illustrated by testing that mass flow rate, temperature difference, and partial load affects axial temperature profile. It is also an indication of the fact that dual-media thermocline tanks are robust and controllable and therefore well suited for CSP. Nandi et al. (Nandi, Bandyopadhyay, & Banerjee, 2018) has studied the thermocline system and developed a computational model of the same. It was concluded that aspect ratio and porosity play the most important roles in the design of the thermocline energy storage system. A transient 3D model is developed to predict the thermal behavior of packed bed. Wang et al.(L. Wang et al., 2015) has studied the influence of flow distribution in a dual-media thermocline system. It has been shown that if the flow distribution at the inlet is non-uniform, then the thickness of the thermocline decreases. So the flow distribution does not affect the performance of the tank much. In order to protect the tank from thermal ratcheting, which takes place due to constant thermal expansion and contraction, the tank is given a

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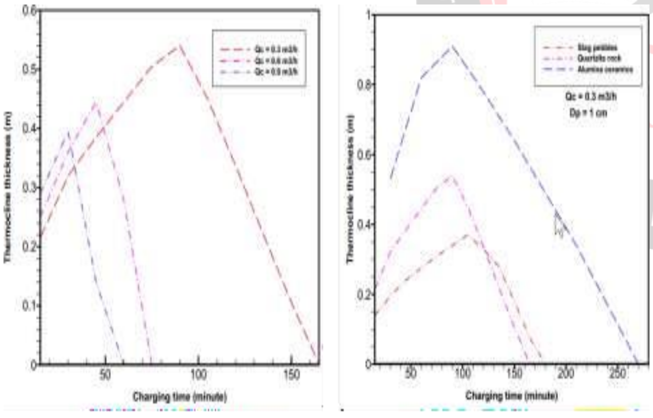
dodecagon cross-section, the diameter of which decreases from top to bottom. Also, the tank is imbued in the ground. All of these design factors help to utilize the lateral earth pressure with a higher load-bearing capacity and to reduce the normal force on the tank walls during thermal expansion. Another advantage of a conical-shaped tank over a cylindrical tank is the larger storage volume at the top of the tank where hot fluid rests, which is at a higher temperature. This leads to high V/A$_S$ (Volume-surface area) area ratio. On the other hand, the volume at the bottom is less where cold fluid rests and most of the energy is withdrawn, so that less storage material is required [15]. Liu et al. (Liu et al., 2016) investigated STHX with various TES media. Oro et al. (Oró, Castell, Chiu, Martin, & Cabeza, 2013) examined the stratification in a packed bed TES system. To study thermal stratification, two method were discussed, one based on density and other based on the temperature.

PARAMETER TO EVALUATE PERFORMANCE OF THE SYSTEM

Figure 8 shows gradual increase in thermocline thickness with increasing mass flow rate. The thermocline thickness for molten salt is not uniform in the radial direction due to the formation of velocity boundary layer near the wall (ELSihy, Liao, Xu, & Du, 2021). However, the thermocline thickness for packed bed TES system is uniform along the radial direction.

Figure 8 - Thermocline thickness of various storage material (ELSihy et al.,2021)



(c) Packed bed, Quartzite rock

(d) Packed bed of three various filler

HEAT-TRANSFER MODEL

The thermodynamic modeling of the thermal energy storage system can be subdivided into different groups [15]. The modeling of the two-tank TES system, the single media TES system and the dual media TES system can be carried out using a continuous solid phase model, Schumann model, Single-phase model and concentric dispersion model (Ismail & Jr, 1999). The basic heat transfer models used to formulate the thermal energy storage system's transient behavior are shown in Figure.

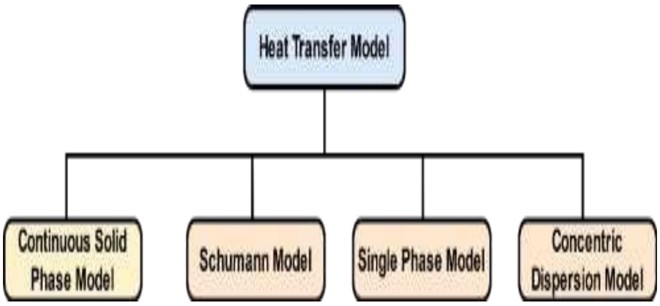


Figure 9 - Heat Transfer Model

The basic heat transfer models used to formulate the thermal energy storage system's transient behavior are shown in figure 9.

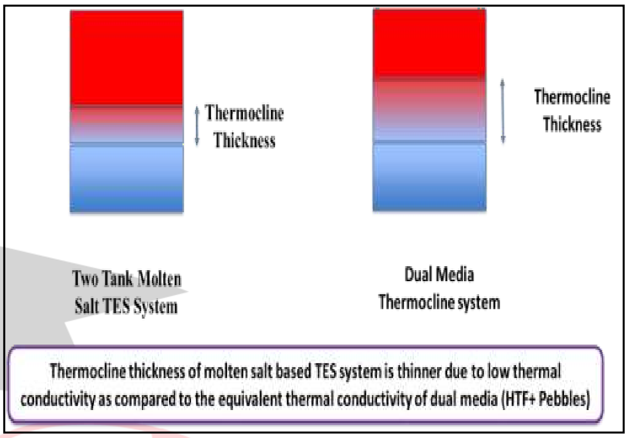


Figure 10 - Thermocline thickness comparison of two tank and dual media tank

Figure 10 shows the comparison of thermocline thickness of molten salt TES system and Dual Media TES system. MATLAB/Simulink environment to investigate the thermal performance of the regenerative horizontal flow storage tank. In addition, the author has also considered gaseous flow in a regularly shaped channel. The assumption used in this model was Plug flow, Ideal gas, Incompressible flow, No chemical reaction, and homogenous distribution of storage material. The research also shows that the deviation in temperature distribution without considering the correction factor is 10%. However, through the correction factor, the author wants to showthe effect of the plug flow assumption in temperature distribution. Zhao et al. (Zhao, Cheng, Liu, & Dai, 2017) used a dimensional enthalpy based C-D model to study the performance of TES for CSP application. However, the author presented the strategy to estimate the tank size to integrate TES with CSP technology. Niedermeier et al. (Niedermeier et al., 2018) studied the performance of the storage tank under two different heat transfer fluid, i.e., sodium and molten salt using a one-dimensional C-D model. The research shows that smaller size storage material gives better discharge efficiency for sodium. However, larger size storage material is suitable for molten salt. Galione et al. (Galione, Pérez-Segarra, Rodríguez, Torras, & Rigola, 2015) modeled a multi-layered-solid-PCM thermal energy storage system using a one- dimensional C-D model. The study shows that

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thermocline degradation can be prevented by using PCM as a dispersed storage material.

V. SUMMARY OF LITERATURE REVIEW

A systematic review of prospective observational studies showed that the integration of a solar TES system with CSP is an eminent method of power production using solar energy. The levelized cost of electricity using solar power is more as compared to the conventional power plant due to its intermittent nature. Hence, integration of thermal energy storage system with CSP is required to make the system economically more viable. Currently, molten Salt TES system is operational but economically not so viable due to its high initial cost. Further, various investigators studied the integration of other sensible based storage system with CSP and found dual media single tank (DMT) more economical and competitive as compared to other systems like single media tank and molten salt TES system. The authors throughout the world studied the performance of dual media tank under various operational conditions and found it more effective as compared to other systems. The authors has used the various parameter like thermocline thickness, stratification of tank, temperature variation along the tank, exegetic and energy efficiency during charging and discharging of tank at different input parameters like void fraction, mass flow rate, inlet temperature and D/L ratio of the tank. The study of thermocline thickness shows that two tank molten salt TES system has thinner thermocline thickness as compared to the dual media tank due to low thermal conductivity of molten salt as compared to the thermal conductivity of dual media (HTF and storage material). Figure, shows the comparison of thermocline thickness of molten salt TES system and Dual Media TES system. Figure shows Thermocline thickness comparison of two tank and dual mediatank

In dual media tank, the effectiveness of storage material has also been studied by the authors to investigate the thermal performance of TEs system. The thermocline thickness of storage system depends on the thermal diffusivity of

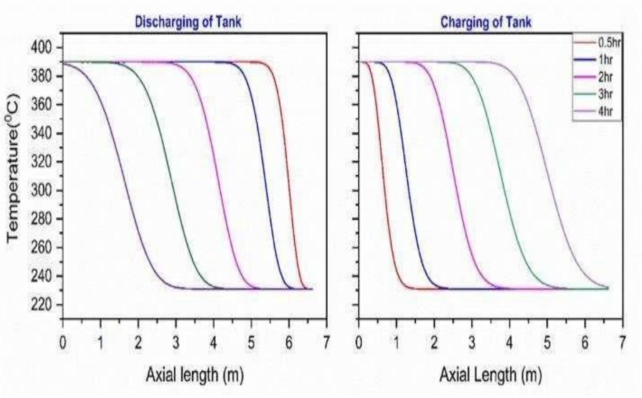

Figure 11 - Charging and discharging behavior of DMT

Figure 11 shows the thermocline behavior of DMT during the charging and discharging of the tank.

VI. CONCLUSION & FUTURE WORK

Aim of this research work was to investigate the characteristic behavior of DMT thermal energy storage system for CSP applications with focus on development of experimental test facility to integrate system with power cycle. The thermal energy storage system for concentrated solar power applications and described how the TES system integration with CSP could be used to overcome the intermittent nature of solar energy and high levelized cost of electricity. This research work is set out to investigate the effectof operating variables on thermal performance of TES system. The primary objective of this research work was to investigate the thermo-economic model of solar thermal energy storage system for CSP application and to use the optimization technique to identify the optimum variables for maximum charging and discharging efficiency of TES system. This research work is also focusses on the parametric optimization for minimum thermocline thickness under wide range of operating variables.

This paper comprises of a detailed study of Dual Media Tank along with its technical barrier and their solution in integration of TES system with CSP application. DMT is compared with other storage technology in terms of commercialization and technology advancement and DMT is found more economical as compared to other technologies. In spite of economical, this technology is still not commercially available. Additionally, comparative study of thermocline thickness for DMT and molten salt tank is studied and it was found that Two-Tank molten slat TES system has minimum thermocline thickness as compared to Dual media tank. DMT uses storage material (rock pebbles etc.) and HTF in a single tank and hot and cold fluid are thermally stratified within the tank. The selection of storage material and HTF is also discussed and it was found that higher thermal diffusive material.

Beside this, heat transfer model for TES systems is also studied and it was found that Schumann model is simplest energy model and requires less computational time as compared to other models. However, Single phase model is effective forTES system with high thermal conductivity and high heat capacity storage material. Contrary to this, concentric Dispersion model is most realistic model and requires more computational time as compared to other models. Further a detailed methodology is discussed to study the thermocline behaviour of tank under various operating conditions.

The DMT TES system is modelled using Schumann Energy model. Additionally, an empirical correlation was developed and validated with numerical and experiment results were found to be in reasonable agreement for a D/L ratio greater than 1. Based on the numerical results the following conclusion is summarized.

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The high thermal conductivity of HTF will cause disturbance in thermoclinethickness and reduce the discharging time

No significant change has been found in the thermocline thickness of DMT with an increase in the mass flow rate. The percentage movement of the thermocline layer was observed to be 70.37% with an increase of 18.75% in the mass flow rate. This shows that the mass flow rate has a greater influence on the discharge time. The percentage increase in volumetric heat transfer coefficient was found to be 9.56% with an increase of 18.75% in the mass flow rate. This shows that an increase in mass flow rate improves the volumetric heat transfer coefficient between pebbles and HTF. A decrease in pebbles diameter increases the void fraction resulting in a greater pressure drop. However, improvement in thermal exchange has been found with the decrease in pebble's diameter. The percentage improvement in volumetric heat transfer coefficient was found to be 80% with a 33.33% decrease in pebble diameter.

An experimental setup is developed to study the characteristic behavior of DMT for CSP applications. The experimental setup is designed for 1.2 kWe solar thermal power plant with 20% thermal efficiency. The system designed can give 17.3 kWhTh thermal power for 2h charging and discharging. A ceramic pebble is used as a storage material due to its higher heat and wear resistance. The HTF used was Syntherm due to its lower thermal conductivity and wide operating range. Further, the design of heat exchanger has also been done to integrate the system with CSP and to study the discharging behavior of tank. In this the effectiveness of shell and tube heat exchanger without baffle (WB), with segmented baffle with baffle cut of 30^0 and 50^0 (SB- 30 and SB-50) and align baffle with baffle cut of 30^0 and 50^0 are compared numerically.

A numerical result shows that effectiveness is nearly 22% higher than WB (Heat exchanger without baffle) and 2.5 % than align baffle with baffle cut of 50^0. The effectiveness decreased with an increase in baffle cut for both segmental and aligned baffle. The numerical result of AB-30 is validated with experimental setup consist of the same baffle design for different inlet temperatures in the range of 333K to 363 K. The deviation of 10.1% was observed in the numerical and experimental models. Pressure drop and Nusselt number are compared numerically using empirical correlation for helical baffle with a helix angle of 25^0 and segmental baffle at Reynold‟s number varied between 5000~2100 in the turbulent zone. The result shows that for helical baffle (25^0 helix angles).

The pressure drop is nearly 89 % lower than the segmental baffle at Reynoldnumber of 5790.38.

For maximum heat recovery rate and the low-cost segmental baffle is the most preferred configuration

The Colburn factor for segmental baffle is higher as compared to helical baffle. However, the pumping power of helical baffle is less as compared to segmental baffle. It is observed that align baffle with baffle cut of 30^0 is more effective as compared to other configurations like align baffle of 50^0, Segmental baffle of 30^0 and 50^0 cut and can be recommended for industrial use. Other than baffle, cut, the segmental and helical baffle is also compared, and comparison shows that helical baffle is more effective and can be recommended for industrial use. In Chapter 6 an experimental analysis has been done to study the validate the numerical model and to study the thermal behavior of TES system for CSP applications. Based on the experimental analysis carried out following conclusions are summarized. Thermocline thickness is due to the axial conduction along the length of the tank. The percentage drop in outlet temperature was found 40% for a mass flow rate of 0.02 kg/s and 60% for a mass flow rate of 0.04 kg/s. However, the duration of discharging time for higher mass flow rate was found less.

An increasing trend of energy stored was observed during the initial hour and later on it is suppressed. However, the energy stored is maximum for higher mass flow rate. A nominal change in charging efficiency was observed for a mass flow rateof 0.01 kg/s. However, 40% drop in charging efficiency was observed for a mass flow rate of 0.04 kg/s The temperature change of the storage material shows a decrease in the load-bearing capacity of the storage material.

The maximum tolerable pressure of the storage material during the initial cycle was ~ 60 KN and after 8 cycles its compressive strength decreased by 50%. However, thermal cracks were slower.

The thermocline model presented in this work showed a good agreementbetween numerical and experimental results with suitable boundary conditions.However, the wall effect with variable void fraction during charging anddischarging of the tank is not considered in the numerical model, and that needs to be addressed in the future. Since the thermocline thickness is a broad parameter for studying the thermocline behavior of tanks. Therefore, the use of empirical correlation to determine the thermocline thickness is strongly recommended for the initial investigation of TES tank design. Future studies will involve thermodynamic modeling of TES tank by considering wall effects with variable pebbles diameter. However, to investigate the influence of variable temperature, a realistic approach will be used in the experimental setup by integrating the system with a solar receiver and a parabolic trough collector.

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