# Design and Fabrication of Concentrated Solar Thermal Power Plant by using Molten Salt

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*Abstract:* **After photovoltaic's (PV), concentrating solar power (CSP) is at present the major technology for producing solar electricity. Solar power-tower systems (also known as central receiver systems) can efficiently achieve high temperatures because of the high concentration ratios they can achieve using different configurations of the collector field and receiver. The combination of solar power towers with high-temperature cycles permits to increase the global efficiency in the conversion of solar radiation to electricity with respect to today's CSP plants based on the sub-critical Rankine cycle and could result in LCOE reduction, as far as the increase in efficiency outweighs the increased costs associated to the use of more expensive equipment and materials. A distinct advantage of CST technology, in comparison to other intermittent forms of renewable energy such as wind or photovoltaic's, is the ability to integrate cost-effective thermal energy storage (TES) for increased dispatchability and load shifting. Furthermore, the addition of TES to a CST power plant has been shown to reduce its levelized cost of electricity (LCOE) because of the increase in capacity factor as it allows electricity to be generated even when solar radiation is not available. Hence, CST-based power plants integrated with TES can be a key component of the renewable energy portfolio that can function as a peaking or a load-following plant. I have studied CSP technologies and grid parity is analyzed and expected to be reached soon for locations with strong solar direct irradiation. Finally, in relation to CSP, it is important to emphasize how thermal storage as well as natural gas hybridization can be easily added, thus practically eliminating the power intermittencies of other important renewable technologies.**

*Keywords:* **Concentrated solar power, thermal energy storage, and heat transfer fluid.**

**NOMENCLATURE:**

| | |
|---|---|
| CSP | Concentrating solar power |
| CST | Concentrating solar thermal |
| PV | Photovoltaic |
| ST | Solar tower |
| CRS | Central receiver system |
| DNI | Direct normal irradiance |
| HTF | Heat transfer fluid |
| LCOE | Levelized cost of electricity |
| PCM | Phase change material |
| TPCM | Tank phase change material |
| EPCM | Encapsulated phase change material |
| TES | Thermal energy storage |
| STES | Sensible heat thermal energy storage |
| LTES | Latent heat thermal energy storage |
| UV | Ultraviolet |
| HX | Heat exchanger |
| PCS | Power Conversion System |
| STE | Solar Thermal Energy |
| EHT | Electrical heat tracing |
| HP | Heat pipe |

## I. INTRODUCTION

Concentrating solar thermal (CST) technologies collect and concentrate radiation from the sun to transform it into high-temperature thermal energy. This thermal energy can later be used for a plethora of high-temperature thermal applications, such as heating and cooling, process heat, material processing, electricity production, or chemical processes.

Typically, the receiver of a CST system consists of an absorber material, or absorber coated material, upon which the concentrated solar radiation impinges and is transformed in thermal energy. A large fraction of this thermal energy is transformed into useful energy, for example, in the form of the increase in enthalpy of a working fluid. The rest is used to heat up the absorber material to its operating temperature and after that dissipated as thermal losses.

The thermal losses are proportional to the receiver area and temperature difference between the receiver area and the ambient. Conductive and convective losses are linearly proportional to this temperature difference, while radiative losses are proportional the difference of the fourth power of these temperatures. Because of this, as the operating temperature increases, radiative losses become more and more dominant.

This is the reason why, for low- to mid-temperature CST systems, the system designers make a significant effort to keep convection and conduction losses at bay, using for instant vacuum technologies to reduce these losses to a minimum, while for very high-temperature CST systems where the dominant losses are radiative these techniques are seldom used, since they are ineffective in reducing radiative losses.

Thus, in order to increase the thermal efficiency, that is, the ratio of the useful energy delivered by the receiver to the concentrated solar radiation impinging upon it, the system designer can:

- increase the concentration, that is, the ratio between the total area of the solar collecting surfaces and the total area of the surface of the receiver;
- decrease the operating temperature of the receiver, thereby, reducing the temperature difference with the ambient;
- Use specially engineered materials and techniques to increase the absorption of the solar radiation in the receiver and to minimize its thermal losses, such as spectrally selective absorber coatings, evacuated tubes, and materials and meta-materials with the appropriate thermal properties.

To achieve high thermal efficiencies while operating at high temperature almost inevitably requires achieving high concentration ratios.

The second law of thermodynamics also limits the conversion of thermal energy into work. The maximum efficiency at which heat taken from a heat reservoir at temperature $T_{hot}$ can be transformed into work by a heat engine in contact also with a cold reservoir at temperature $T_{cold}$ is given by Carnot's law:

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

According to this law, the efficiency of the conversion of thermal energy into work increases with the temperature at which the thermal energy is delivered to the heat engine.

In a CST system designed to produce work, the overall light-to-work efficiency is the product of two efficiencies:

- the thermal efficiency with which the direct solar radiation from the sun is transformed into useful thermal energy;
- The efficiency with which the useful thermal energy is subsequently transformed into work by a heat engine.

While the efficiency at which the direct solar radiation is transformed into useful thermal energy decreases with the operating temperature, the efficiency at which the useful thermal energy is transformed into work increases with it.

The overall light-to-work efficiency is, therefore, the product of two functions with opposite tendencies with regard to the variation of the operating temperature of the receiver and as such it must have an optimum; that is, a value of the operating temperature of the receiver for which the light-to-work efficiency is a maximum

**Radiation data in India**

The efficiency of a solar collector field is defined as the quotient of usable thermal energy versus received solar energy. The power generation subsystem efficiency is the ratio of net power out to the heat input. The total specific radiant power per unit area, or radiant flux, which reaches a receiver surface, is called irradiance and it is measured in $W/m^2$. When integrating the irradiance over a certain time period, it becomes solar irradiation and is measured in $Wh/m^2$. When this irradiation is considered over the course of a given day, it is referred to as solar insolation, which has units of $kWh/m^2/day$ (=3.6 $MJ/m^2/day$). CSP technologies require sufficiently large (>5.2 $kWh/m^2/day$) direct normal irradiance (DNI), as opposed to PV technologies that can use diffuse, or scattered, irradiance as well.

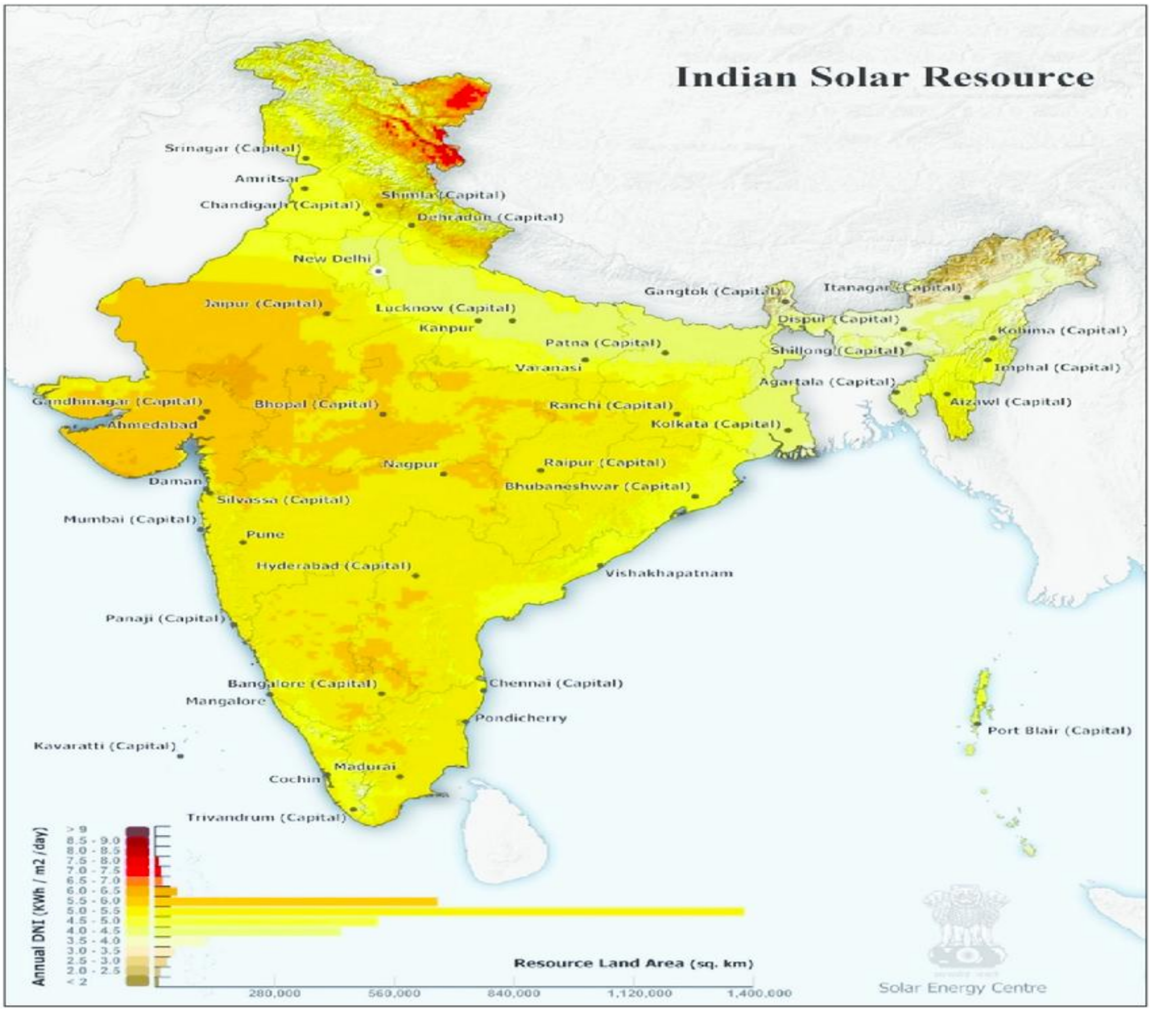



**Fig 1: Solar radiation data in India**

Solar radiation ows continuously through the earth's atmosphere onto its surface. Each square metre of surface area at the atmospheric boundary intercepts a normal (i.e. perpendicular) radiation, when facing the sun, of almost constant value. Universally Solar radiation rate can be expressed as "Solar Constant" which has a present value of 1377 $W/m^2$. If the earth is assumed to be perfectly spherical it has a diametric plane $\pi r^2$, where r is the mean earth radius. The solar radiation intercepted is therefore at a rate $1377\pi r^2$ watts, if radius r is in metres. For the mean earth radius is 6.324 million metres, resulting in

$$\text{Earth Radiation rate} = 1377*\pi*\left(6.324*10^6\right)^2$$
$$= 1.73*10^{17}\ \text{W}$$
$$= 1.73*10^{17}\ \text{J/s}$$

In a year of 365.25 days the total input radiation energy is therefore

$$W_{annual} = 365.25*24*3600*1.73*10^{17}$$
$$= 5.46*10^{24}\ \text{J}$$

Calculation of solar radiation received by the India

$$\text{Intensity of solar radiation}\left(I\right) = 200\ \text{MW/m}^2$$

$$\text{Geographical Area}\left(A\right) = 3.287*10^6\ \text{m}^2$$

$$\text{Earth Radiation rate in india} = 200*3.287*10^6$$
$$= 657.4*10^6\ \text{MW}$$

India is endowed with rich solar energy resource. The average intensity of solar radiation received on India is 200 MW/km square (megawatt per kilometre square). With a geographical area of 3.287 million km square, this amounts to 657.4 million MW. However, 87.5% of the land is used for agriculture, forests, fallow lands, etc., 6.7% for housing, industry, etc., and 5.8% is either barren, snow bound, or generally inhabitable. Thus, only 12.5% of the land area amounting to 0.413 million km square can, in theory, be used for solar energy installations. Even if 10% of this area can be used, the available solar energy would be 8 million MW, which is equivalent to 5 909 mtoe (million tons of oil equivalent) per year.

## II. REVIEW OF LITERATURE:

### Solar flat plate mirror

Heliostats are mirrors that track the sun and reflect the sunlight onto a central receiving point. Most heliostat solar power systems consist of arrays of heliostats.

If the mirrors are inexpensive enough then they can collect solar power at a cost that is less expensive and with higher efficiency than flat plate collectors. The arrays of heliostats concentrate the power on a relatively small collection point that, though more expensive per ft2 than flat plate collectors, are smaller and thus the total cost is lower.

Anti-soiling coatings are currently receiving major attention by reflector manufacturers, researchers, and plant developers because of their potential to achieve a significant reduction of the soiling accumulation on the reflector surfaces and, consequently, on the cleaning activities and water consumption of CST plants. At the same time that these coatings accomplish their main goal, that is, preventing the dust particles from settling or sticking on the mirror surface, they should not have a detrimental effect on the optical properties of the reflector. Additionally, the coating and reflector combination must be durable and reliable while experiencing high temperatures, sandstorms, and higher than normal exposure to both ultraviolet (UV), visible, and infrared radiation, and must prove their ability to withstand any cleaning procedures. Raising the reflectance of the solar mirror permits a reduction in the solar field size, while maintaining the electricity output and the investment cost for collectors or heliostats.

Even small improvements of 0.5 ppt in reflectance will have a high impact on the annual revenues of the power plant. High reflectance can be achieved with silver as the reflecting surface and thin transparent front coats. Silvered-polymer films achieve solar-weighted hemispherical reflectance values around 94%, which is still below the state-of-the-art 4 mm silvered-glass mirror reflectance (they achieve around 94.7%). The trend is therefore going toward thin silvered-glass mirrors. The reduction of the glass thickness from 4 mm to 1 mm boosts the reflectance around 1 ppt. Commercially available thin-glass mirrors (around 1 mm glass thickness) achieve around 95.7% solar-weighted hemispherical reflectance. Thin-glass mirrors need to be supported by a backing structure to provide stiffness against wind loads. Several substrate materials are being investigated for this purpose (concrete, composite materials, aluminium, steel, and glass).

CSP and heliostats theoretically offer much higher solar-thermal efficiency because they use the energy of many suns on a smaller surface area. Heat loss from any surface is linearly proportional to its surface area. If surface area is halved, then heat loss is halved. Heat loss is also proportional to the temperature difference between a hot surface and a cold environment (although not in a strictly linear way, heat losses increase to the 4th power at very high temperatures). These two straightforward principles place strong constraints on passive solar energy systems when higher temperatures are desired.

$$\text{Heat loss}\left(Q_{loss}\right) = C * A * T^4$$

Where,

A is the surface area in $m^2$

T is the surface temperature in Kelvin

C is Boltzman constant

$$C = 5.67*10^{-8}\ \frac{W}{m^2K^4}$$

Properties of Solar flat Plate mirror are given below

- High optical performance: - reflectance/transmittance, - specularity, - geometrical configuration,
- Low maintenance (dust free),
- Low initial cost and Long life.

### Heat transfer fluid (HTF)

Molten salts have several benefits. The first one is the possibility to work at higher temperature in the solar field (550 to 560 ºC) thus overcoming the thermal limit imposed by current Heat transfer fluids. This higher temperature at the solar field not only increases the efficiency of the PCS thermodynamic cycle, but it also enhances the integration of the TES into the plant because the heat exchangers (HXs) acting as interface between the TES and the solar field are no longer needed. Additionally, the investment cost of the TES is significantly cut down because the inventory of storage media is reduced by 64% due to the higher temperature difference between the cold and hot tanks (from 290 ºC to 550 ºC)

Molten salts have high density, high heat capacity, high thermal stability, and very low vapour pressure even at elevated temperatures, what are important features for a heat transfer fluid. However, working temperatures higher than 400 ºC with current molten salts require the use of stainless steel in piping, vessels, and elements, because of corrosion issues when carbon steel is used for sodium and potassium nitrates at this temperature,

Another benefit of molten salts is the avoidance of the fire and contamination hazards due to leaks in piping and vessels, because molten salts currently used (binary mixture of potassium nitrate and sodium nitrate) have been traditionally used by farmers as fertilizer. Furthermore, when molten salt is poured onto the ground it freezes immediately and remains as a thick solid film that can be easily recovered and reused, thus avoiding the high decontamination costs associated with leakages on ground.

Parasitic pumping losses are lower with molten salt because the volumetric flow and the pressure drop are lower than with thermal oil. This is another benefit of using molten salts in the solar field.

Nevertheless, the use of molten salts in STE plants also has some problems. The most outstanding problem is the significant freezing hazard due to the high melting point of the current salts. The salt used in commercial STE plants is not a eutectic mixture of potassium and sodium nitrate, and therefore the freezing and melting processes take place in the temperature range from 220 ºC (melting) to 240 ºC (freezing). This high freezing temperature introduces a significant hazard of salt plug formation in the pipes when the plant is not operating and the ambient temperature is low. Once a salt plug is formed, the first problem is the difficulty to find its location. This search for the location of the plug can take a lot of time, and it could even be an impossible task when the circuit layout is very complex (e.g., a high number of valves, pipe fittings, and accessories). If the search is successful, the second problem to face is the melting of the salt plug without damaging the element at that place. Salt-specific volume increases by 4 to 6% during the melting process, and this volume increase will produce an extremely high overpressure if melting does not start at either of the ends of the plug. If melting starts inside the salt plug, the overpressure caused by the volume increase is likely to burst the pipe or valve casing. The design and implementation of an efficient heating system is the only way to prevent salt from freezing and to avoid these problems.

Two different electricity-based concepts are used in solar plants for heating pipelines and components in salts systems: impedance heating and mineral insulated heat tracing.

Impedance heating directly heats the pipeline by flowing electrical current through the pipeline wall (Joule effect) by direct connection to a low voltage, high current source from a dual-winding power transformer. Mineral-insulated electrical heat tracing (EHT) is nowadays the most common option in molten salt applications to maintain the temperature of pipelines (not the receiver tubes) and components above the salt freezing point, typically at 290 ºC.

Table 1 Main salts currently available for STE plants

| Salt | Components | Melting point (ºC) | Maximum working Temperature (ºC) |
|---|---|---|---|
| Hitec XL | Sodium nitrate<br>Potassium nitrate<br>Calcium nitrate | 140 | 500 |
| Hitec | Sodium nitrate<br>Potassium nitrate<br>Calcium nitrate | 142 | 538 |
| Solar salt | Sodium nitrate<br>Potassium nitrate | 240 | 593 |

Table 2: Heat transfer fluid and filler material data with storage model assumptions

| Heat transfer fluid | Solar Salt ($NaNO_3/KNO_3$) |
|---|---|
| Upper temperature [°C] | 565 ºC |
| Lower temperature [°C] | 250 ºC |
| Density [kg/m$^3$] | 1831 kg/m$^3$ |
| Heat capacity [kJ/kg/K] | 1.51 kJ/kgK |

**Thermal Storage System:**

**Sensible Thermal Energy Storage (STES)**

When heat is transferred at constant pressure to/from a pure substance, either the temperature of the substance changes with phase remaining the same or its phase changes while temperature remains constant. In the former case, when the heat transferred causes change in temperature, it is referred to as sensible heat. In the latter case, when the heat transferred causes change in phase, it is referred to as latent heat. Sensible heat transfer is apparent as it is noticed in the form of a change in temperature, whereas latent heat transfer remains latent and is noticed only by a change of phase of the substance.

The specific heat or heat capacity of the substance is the amount of heat required to change the temperature of a unit mass of the substance by one degree. And the sensible heat, Q, gained or lost by the substance in changing temperature from $T_a$ to $T_b$ is therefore

$$Q = m\int_{T_a}^{T_b} c_p.dT = V.\int_{T_a}^{T_b} \rho.c_p.dT \qquad 12.1$$

Where m is the mass, $c_p$ is its specific heat, V is the volume of substance, and ρ is its density. From Eq. (12.1) it is seen that higher the $c_p$ and ρ of the material, more energy would be stored in a certain volume of material.

For sensible heat storage, apart from specific heat capacity and density, there are other parameters that affect the performance of the TES systems such as thermal conductivity, thermal diffusivity, viscosity, and vapour pressure. The rate of heat penetration into any specific storage media (e.g., into concrete) is dependent on the thermal diffusivity. This is a combination of two factors, the thermal conductivity (how well heat is conducted through the substance) divided by the heat capacity (how much heat it takes to increase the temperature of the substance). For latent heat storage, the importance of most of these parameters is also noticeable.

The desired characteristics of any type of thermal storage systems can be summarized as follows

- Compact, large storage capacity per unit mass and volume
- High storage efficiency
- Heat storage media with suitable properties in the operating temperature range

- Uniform temperature
- Capability of charge and discharge with the largest heat input/output rates but without large temperature gradients
- Ability to undergo large number of charging/discharging cycles without loss in performance and storage capacity.
- Small self-discharging rate, i.e. negligible heat loss to the surroundings
- Long lifetime
- Low cost

Any TES should have at least the following three components: (1) a storage material in the desired operating temperature range; (2) a suitable container to store the heat; and (3) a suitable heat exchanger (HX) for an efficient heat transfer from the heat source to the storage material and from the storage material to the working fluid of the steam cycle.

The molten salt mixture considered is the standard solar salt (60% $NaNO3$ + 40% $KNO3$). For a two tank configuration, where the hot tank operates with an operating temperature of ~560 ºC and the cold tank with a temperature of ~290 ºC, with the improved method suggested, when charging the storage, the molten salts are heated only by desuperheating and partially condensing live steam, which means that only the sensible heat above the water-steam saturation temperature, along with a small fraction of latent heat of evaporation, would be transferred to the salts via the HX. In a typical 2-h storage system, the partially condensed steam leaving the HX during charging would contain 30% wetness. This wet steam is then further condensed and sub cooled by the boiler feedwater using a recovery HX. Considering the key system design parameters in the case study proposed by Koretz, the 2-h discharge capacity and the 8-h charging rate were selected to achieve the largest temperature difference possible while providing an economically viable storage solution.

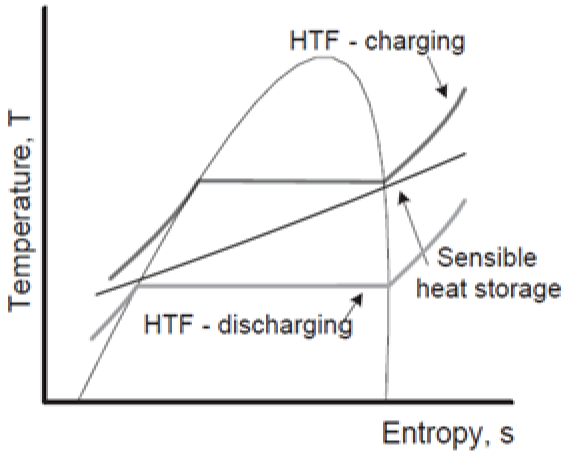



**Fig 2: T-s plot of STES**

### Latent Thermal Energy Storage (LTES)

Latent heat storage is accompanied by the storage of energy in a material via a phase transition from one state of matter to another. For CST applications, the phase transition most studied for LHS is between the solid and liquid states due to its low volumetric expansion compared to liquid-gas phase transition and high volumetric energy density compared to solid-solid phase transition. The material undergoing the phase change in an LHS system is commonly referred to PCM.

The energy (Q) stored in a PCM of mass m is given by

$$Q = m\left[c_{p,s}\left(T_m - T_s\right) + h_{sl} + c_{p,l}\left(T_l - T_m\right)\right]$$

Where

$c_{p,l}$ and $c_{p,s}$ are the average specific heats in the liquid and solid phases

$h_{sl}$ is latent heat of fusion or enthalpy of phase change due to sold-liquid transition

$T_m$ is the melting temperature of PCM

$T_s$ is the temperature of PCM in solid phase

$T_l$ is the temperature of PCM in liquid phase

The primary advantages of an LHS system are

**High volumetric energy density**: For a given temperature difference (DT); the heat stored in an LHS system is greater than that in an SHS system due to the inclusion of latent heat of fusion. LHS, by virtue of its higher energy density, requires a smaller volume of PCM to store energy and, in turn, offers compact energy storage, less construction material, and ultimately lower cost advantages over SHS counterpart.

**Isothermal operation**: Owing to the constant temperature solid to liquid phase transition, high power cycle efficiency could be obtained if the selected PCM melts at a temperature close to the maximum operating temperature of the power block.

**Low system pressure**: As mentioned earlier, LHS depends on the absorption and release of heat during solid-liquid phase transformations. Unlike liquid-vapour phase transformation, solid-liquid phase change transformation is accompanied only with a moderate change in density, which does not lead to a large increase in the pressure inside the PCM storage vessel. A low system pressure does not require a thick-walled vessel, which leads to savings in construction material cost.

LHS systems can be broadly considered in two configurations: (1) tank phase change material latent heat storage (TPCM-LHS) and (2) encapsulated phase change material latent heat storage (EPCM-LHS).

## TANK PHASE CHANGE MATERIAL LATENT HEAT STORAGE

TPCM-LHS systems are simply large tanks filled with a PCM, with an HTF flowing around and exchanging energy with PCM. The most straightforward, market-ready design of TPCM-LHS is the shell and tube heat exchanger, in which two different configurations are possible: (1) HTF flowing in the tubes and PCM stored inside the shell around the HTF pipes (Module 1) or (2) HTF flowing in the shell and PCM stored inside the tubes (Module 2).

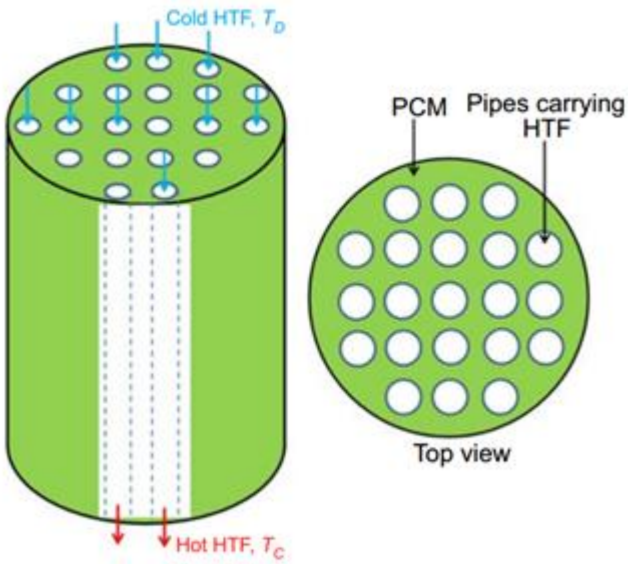



**Fig 3: Schematic of TPCM-TES**

Some of the prominent approaches for improving the heat transfer in a tank-based LHS configuration are discussed briefly here.

**Finned tubes**

The usage of fins has been shown to improve the melting and solidification rate of PCM. Velraj concluded that adding fins reduced the solidification time by a factor of $\frac{1}{N_{fins}}$

Where

$N_{fins}$ is the number of fins

**Heat pipe/thermosyphons**

The use of HPs, which can efficiently transfer heat along their length by means of evaporation and condensation of an internal working fluid between the HTF and the PCM, has been investigated as a means for increasing the heat transfer rate.

**Particles and metal structures**

Addition of high conductivity particles such as copper or aluminium is another means to enhance the thermal conductivity of inorganic salt PCMs

**Metal foams**

PCM stored within the framework of open-celled metal foam can substantially enhance the heat transfer rate. Metal foam is a porous lightweight structure with continuous metal matrices of high thermal conductivity and typically available in high porosities (>85%).

## ENCAPSULATED PHASE CHANGE MATERIAL LATENT HEAT STORAGE

EPCM-LHS represents a promising approach to increase the heat transfer area by incorporating the PCM mixture in small capsules using suitable shell materials. Encapsulating PCM material inside small capsules increases the specific surface area, and using HTF in direct contact with the capsules increases the heat transfer coefficient.

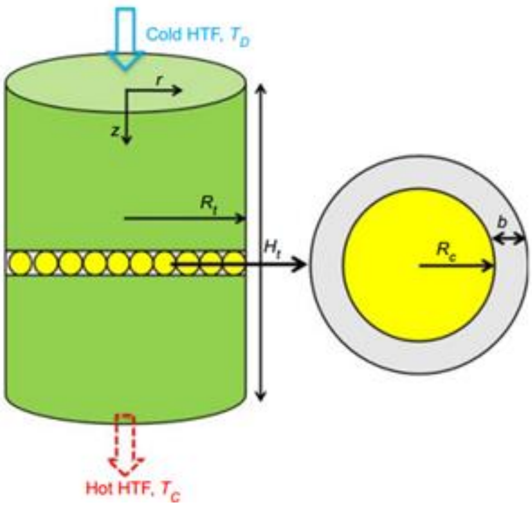



**Fig 4: Schematic of EPCM-TES**

In an EPCM-LHS, a tank of height $H_t$ and radius $R_t$ is packed with spherical capsules filled with PCM. For the sake of clarity in illustration, an ordered arrangement of capsules is in Fig. ; However, in reality, the packing could be disordered with the porosity for most packing of interest falling into the range of 0.36-0.40. The inner radius of the capsules, represented by $R_c$, is filled with PCM (shaded), while the thickness of the capsule wall is denoted by $b$ in Fig... Generally, hot HTF from the solar receiver enters the LHS from the top while cold fluid is pumped from the bottom of the LHS packed bed during discharge. Buoyancy forces ensure stable thermal stratification of hot and cold fluids within the tank during both charging and discharging processes.

## III. PURPOSE OF WORK:

Two important components of the power tower technology are the heliostats and the receiver. This technique utilizes a central power tower that is surrounded by a large array of two-axis tracking mirrors–termed heliostats–that reflect direct solar radiation onto a fixed receiver located on the top of the tower. The typical concentration ratio for this approach is in excess of 400. Within the receiver, a fluid transfers the absorbed solar heat to the power block where it is used to generate steam for a Rankine cycle steam engine/generator.

A heliostat consists of a large mirror with the motorized mechanisms to actuate it, such that it reflects sunlight onto a given target throughout the day. A heliostat array is a collection of heliostats that focus sunlight continuously on a central receiver.

The plant uses molten salt as heat transfer and storage medium. During solar operation the molten salt is pumped from the cold storage tank (at about 290°C) to the receiver where it is heated to about 565°C. The hot salt is then piped to the hot storage tank. For power generation, the hot salt from the tank is pumped to the steam generator where superheated steam at 540°C is generated to produce power. The cooled-down salt (290°C) is then pumped back to the cold storage tank. This plant concept allows decoupling of solar energy collection and electricity production.

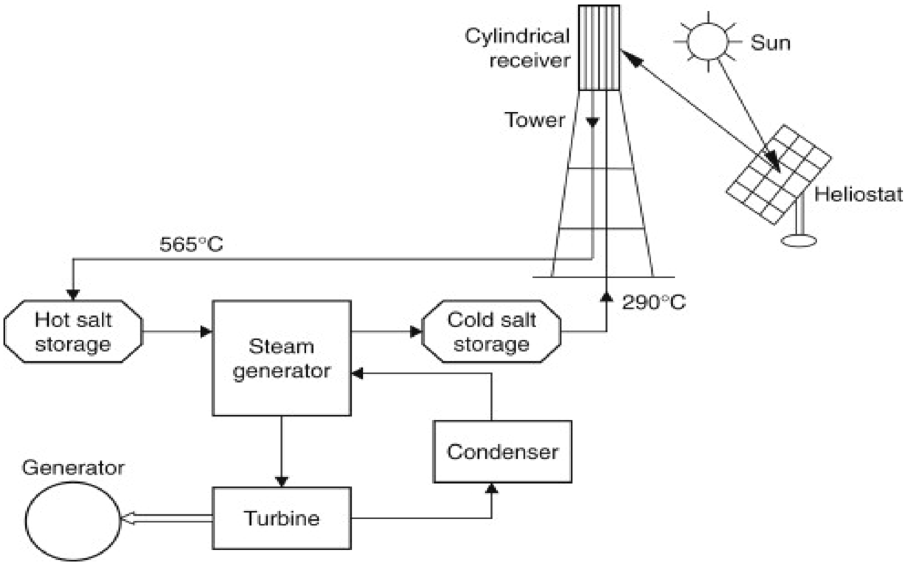



**Fig 5: Working Principle of CST plant**

During Night and cloudy weather, when power is needed from the plant, the hot salt is pumped to a generator that produces steam. The steam activates a turbine-generator system that creates electricity. From the steam generator, the salt is returned to the cold storage tank, where it is stored and can be eventually reheated in the receiver.

### Working of Thermal Energy Storage

#### During charging

LHS in a CST power plant operates in one of the two modes, namely, charging and discharging, depending on the solar thermal energy resource at the particular hour of the day and the energy available in the LHS. Charging occurs whenever the incident solar thermal energy is in excess to that required by the operation of the power block at the rated capacity. Excess hot HTF from the solar receiver enters the LHS from one end and transfers heat to the PCM, thus effecting the melting of PCM at a constant temperature. The cooled HTF exits the tank to return to the solar field, completing a closed loop of the HTF flow (Fig. (a)). The excess hot HTF is directed to the storage system until the cooled exit temperature of the HTF reaches a certain charge cutoff temperature, $T_C$, which determines the extent to which the TES system can be charged.

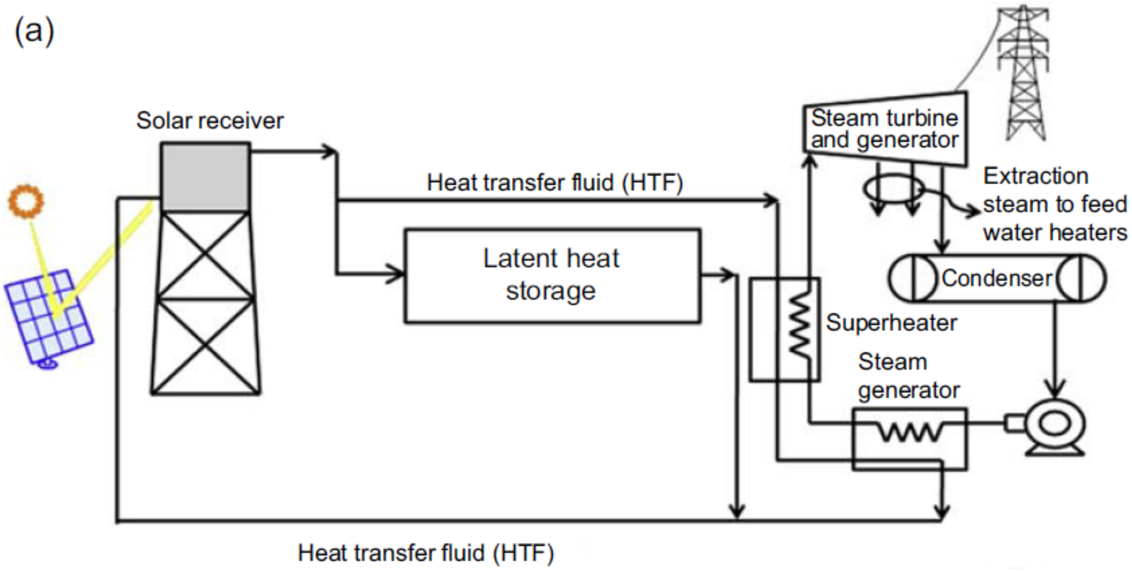



**Fig 5(a): Charging operation of LTES**

#### During discharging

As illustrated in Fig., excess hot HTF fluid from the receiver outlet is stored in the TES, which can be subsequently removed to smooth fluctuations in power output during cloud episodes and to extend power generation after sunset Fig. During discharging, cold HTF is pumped from the other end of LHS, resulting in the solidification of the PCM as heat is drawn from the PCM to the fluid, and the hot fluid exiting the tank is directed to generate steam to drive a turbine and produce electricity (Fig.). Similar to the charging process, the strong dependence of the power block cycle efficiency on the hot HTF temperature requires the termination of discharge process when the HTF exit temperature from LHS reaches a certain minimum discharge cutoff temperature, $T_D$.

### IV. RESULTS AND DISCUSSIONS

#### Solar collector characteristics

| Parameters | Symbol | Value | Units |
|---|---|---|---|
| Collector aperture width | w | 0.05 | m |
| Collector length | L | 0.05 | m |
| Concentration ratio | CR | 500-550 | - |
| Aperture Area | A | 0.025 | $m^2$ |
| Collector reflectance | γ | 0.9 | - |
| Receiver absorbance | ρ | 0.88 | - |
| Number of mirror in each row | M | 90 | |

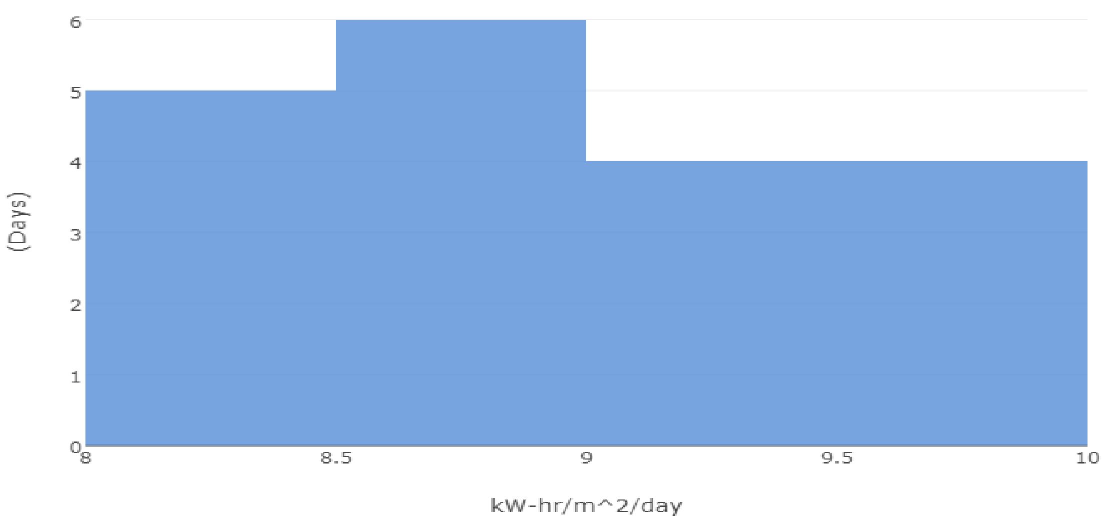
Location Name: Nagpur_Maharashtra_IND Design Conditions
Latitude {N+ S-}: 21.10°
Longitude {W- E+}: 79.05°
Elevation {m}: 310.00

**Thermal infrared radiation flux**

| Date: (DD/MM/YYYY) | Thermal infrared radiation flux ($kW\text{-}hr/m^2/Day$) |
|---|---|
| 07/03/2020 | 8.41 |
| 08/03/2020 | 8.04 |
| 09/03/2020 | 8.64 |
| 10/03/2020 | 9.86 |
| 11/03/2020 | 9.37 |
| 12/03/2020 | 9.16 |
| 13/03/2020 | 9.69 |
| 14/03/2020 | 9.12 |
| 15/03/2020 | 8.24 |
| 16/03/2020 | 8.43 |
| 17/03/2020 | 8.78 |
| 18/03/2020 | 9.53 |
| 19/03/2020 | 8.93 |
| 20/03/2020 | 8.77 |
| 21/03/2020 | 8.94 |
| 22/03/2020 | 8.39 |
| 23/03/2020 | 8.86 |
| 24/03/2020 | 9.21 |
| 25/03/2020 | 9.61 |

**Line Graph:**


**Histogram:**

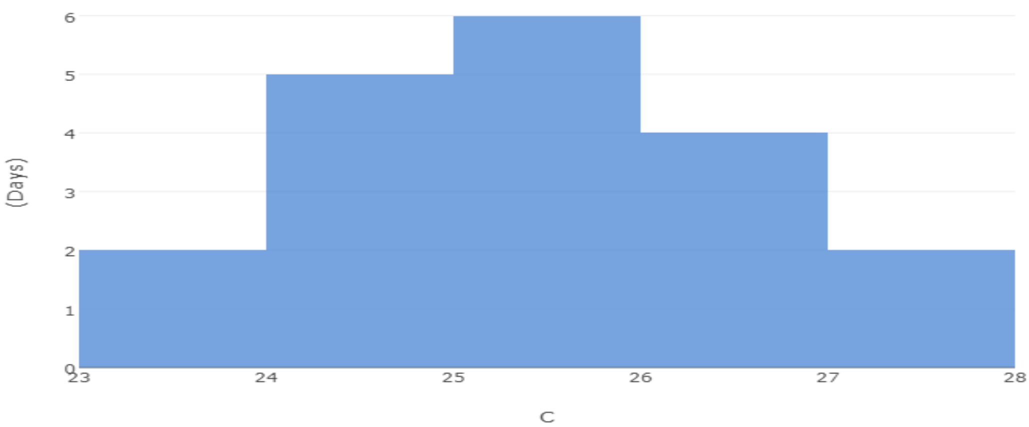


**Temperature at 2 meters:**

| Date: (DD/MM/YYYY) | Temperature (°C) |
|---|---|
| 07/03/2020 | 24.69 |
| 08/03/2020 | 24.74 |
| 09/03/2020 | 24.48 |
| 10/03/2020 | 26.31 |
| 11/03/2020 | 25.81 |
| 12/03/2020 | 26.59 |
| 13/03/2020 | 26.84 |
| 14/03/2020 | 25.21 |
| 15/03/2020 | 23.76 |
| 16/03/2020 | 23.57 |
| 17/03/2020 | 25.71 |
| 18/03/2020 | 24.01 |
| 19/03/2020 | 25.98 |
| 20/03/2020 | 24.94 |
| 21/03/2020 | 25.49 |
| 22/03/2020 | 25.39 |
| 23/03/2020 | 26.28 |
| 24/03/2020 | 27.28 |
| 25/03/2020 | 27.92 |

**Line Graph:**

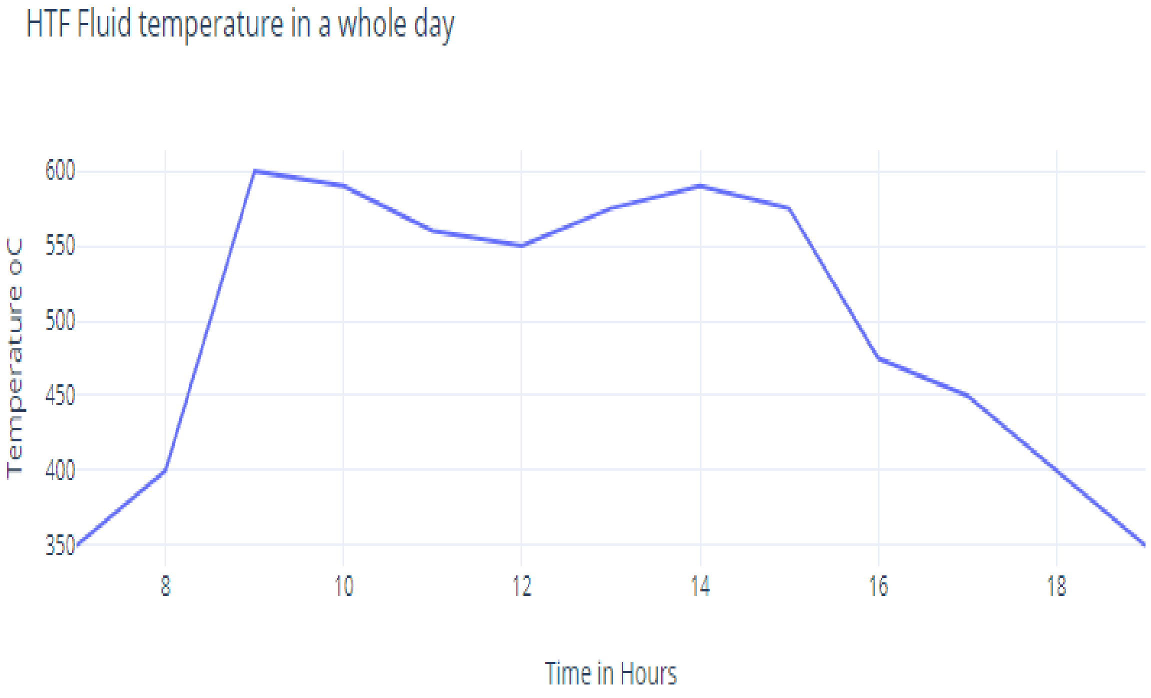

**Histogram:**



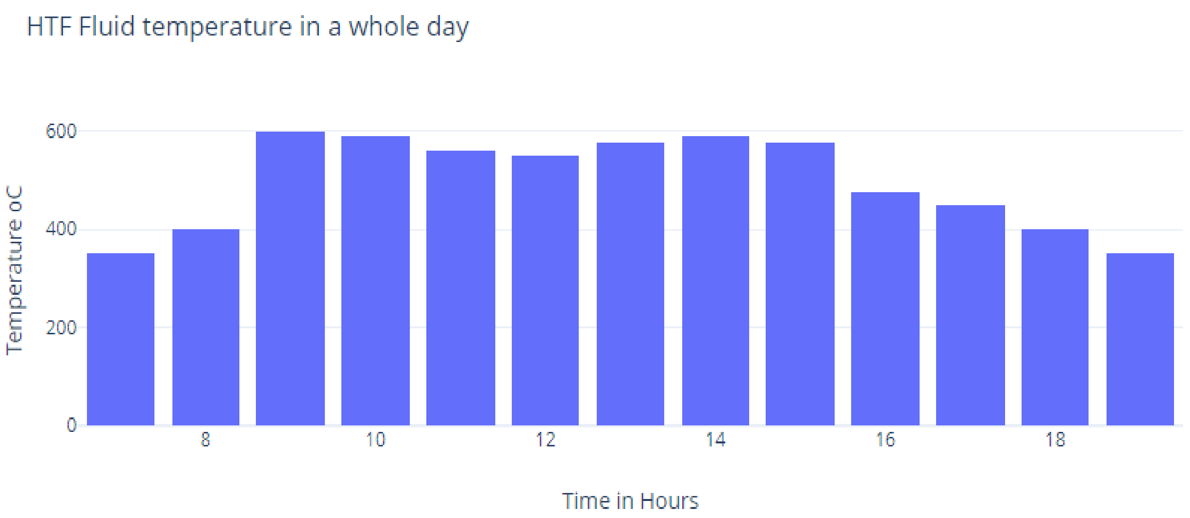
**Calculated HTF Temperature:**

| Time (hr) | HTF Temperature (ºC) |
|---|---|
| 7 | 350 |
| 8 | 400 |
| 9 | 600 |
| 10 | 590 |
| 11 | 560 |
| 12 | 550 |
| 13 | 575 |
| 14 | 590 |
| 15 | 575 |
| 16 | 475 |
| 17 | 450 |
| 18 | 400 |
| 19 | 350 |

**Line Graph:**




**Bar Graph:**



**Steam turbine cycle parameters:**

| Parameters | Calculation value |
|---|---|
| Steam Turbine inlet pressure | 121 bar |
| Steam Turbine inlet Temperature | 560 ºC |
| Steam Turbine outlet Temperature | 378 ºC |
| Output Power Generated ($P_{out}$) | 81 W |

**CALCULATIONS**

We are using 90 heliostat of size 0.05m *0.05m flat plate mirror that track radiation from sun and reflect that radiation to the central tower receiver.

Calculation of Area used by the Heliostat

Area acquired by one Solar flat plate mirror is A =0.05*0.05

A =0.0025 $m^2$

Number of Solar flat Mirror used (n) = 90

Total Area acquired by 90 Solar flat plate mirror ($A_{total}$) =90*0.0025

=0.225 $m^2$

To estimate the direct component of solar irradiation (DNI) and the amount of solar energy collected by Central tower receiver based on the selected site and available climate data.

Number of days (n) =69 days i.e. 10 mar 2020

DNI in (W/$m^2$) can be calculated by defining extraterrestrial radiation ($Iso$) as

$$I_{so} = I_{sc}\left(1 + 0.033\cos\frac{360}{365}n\right)$$

Where $I_{SC}$ is the solar constant ($Isc$ = 1367 W/$m^2$).

$$I_{so} = 1367 * \left(1 + 0.033\cos\left(\frac{360}{365} * 69\right)\right)$$

$$I_{so} = 1389.043 \text{ W/m}^2$$

$$\text{Elevation angle}(\alpha) = 90 + \phi - \delta$$

$$\text{declination angle}(\delta) = 23.45 * \sin\left(\frac{360}{365} * (284 + n)\right)$$

$$\text{declination angle}(\delta) = 23.45 * \sin\left(\frac{360}{365} * (284 + 69)\right)$$

$$\text{declination angle}(\delta) = 12.30^o$$

$$\text{Elevation angle}(\alpha) = 90 + 21.10 - 12.30$$

$$\text{Elevation angle}(\alpha) = 98.80$$

$$\text{Zenith Angle}(\theta_z) = 90 - \alpha$$

$$\text{Zenith Angle}(\theta_z) = 90 - (98.80)$$

$$\text{Zenith Angle}(\theta_z) = -8.8^o$$

DNI is given by

$$DNI = I_{so} * \tau * \cos(\theta_z)$$

Where τ is the atmospheric transmittance and θz is a zenith angle (deg.)

$\tau$=0.7

$\theta_z$=-8.8º

$$DNI = I_{so} * \tau * \cos(\theta_z)$$

$$DNI = 1389.043 * 0.7 * \cos(-8.8)$$

$$DNI = 960.884 \text{ W/m}^2$$

The heat losses from the Central tower receiver solar field from pipes ($Q_{loss,\,pipe}$) can be determined from

$$Q_{loss,\,pipe} = 1.693*10^{-2}(\Delta T) - 1.683*10^{-4}(\Delta T)^2 + 6.78*10^{-7}*(\Delta T)^3$$

$$(\Delta T) = (T_r - T_a) = (565 - 30) = 535^o\text{C}$$

$$Q_{loss,\,pipe} = 1.693*10^{-2}(535) - 1.683*10^{-4}(535)^2 + 6.78*10^{-7}*(535)^3$$

$$Q_{loss,\,pipe} = 64.70 \text{ W}$$

where $Q_{absorbed}$ is the total solar energy absorbed by the central tower reciever solar field (W/m$^2$)

$$Q_{abosorbed} = DNI.K(\theta)*\cos(\theta)$$

$$K(\theta) = 1 - 2.23073*10^{-4}\theta - 1.1*10^{-4}\theta^2 + 3.18596*10^{-5}\theta^3 + 4.85509*10^{-8}\theta^4$$

$$\theta = \text{Incidence angle in radian}$$

$$\theta = 20*\frac{\Pi}{180} = 0.349$$

$$K(\theta) = 1 - 2.23073*10^{-4}*0.349 - 1.1*10^{-4}*0.349^2 + 3.18596*10^{-5}*0.349^3 + 4.85509*10^{-8}*0.349^4$$

$$K(\theta) = 0.999$$

$$Q_{abosorbed} = DNI.K(\theta)*\cos(\theta)*\eta_{rowshading}$$

$$Q_{abosorbed} = 960.88*0.999*\cos(20)$$

$$Q_{abosorbed} = 902.089 \text{ W/m}^2$$

$$Q_{abosorbed} = 902.089*0.225$$

$$Q_{abosorbed} = 202.97 \text{ W}$$

Overall solar field efficiency is given by

$$\eta_{solar} = \frac{Q_{aborbed} - Q_{loss}}{Q_{aborbed}}*100$$

$$\eta_{solar} = \frac{202.97 - 64.70}{202.97}*100$$

$$\eta_{solar} = 68.12\%$$

Overall thermal efficiency of power plant

$$\eta_{th} = \frac{P_{out}}{Q_{abosorbed}}*100$$

$$\eta_{th} = \frac{81}{202.97}*100$$

$$\eta_{th} = 39.90\%$$

## V. CONCLUSIONS

The main drawback of sub-critical solar thermal plants is Thermal energy storage, lower efficiency and higher cost per MWh. To reduce these challenges it is necessary to use High temperature supercritical solar thermal plants based on high temperature HTF and advanced Latent Thermal Energy Storage.

More than 50% of the energy needed in CSP solar plants is for water evaporation. Therefore, the development of reliable and cost-effective latent heat storage systems could benefit a wider deployment of this type of CST systems. Current research follows two paths, the search of new PCMs on one hand, including adequate design of LTES containers with higher heat transfer capabilities, and on the other hand the design of equipment to transport the latent heat storage material during charging discharging processes.

## VI. RECOMMENDATION FOR FUTURE WORK

Non renewable energy sources such as coal, diesel and Hydro are limited in the world. They cannot use again if they are used. So it is necessary to use renewable energy sources such as solar, wind energy and tidal energy for producing power. Apart from all renewable energy sources solar is one that can have large amount of energy that is used for producing electricity.

Energy produced by the sun is abundant and cheap. One of greatest advantages of CSP technology is that solar thermal energy can be stored in thermal energy storage for later use. So CSP based power plant can be used as 24 h a day and during bad weather conditions.

By replacing Coal fired plants by CSP technology, we can produce electricity in large scales and it also help to preserve non renewable energy sources. CSP technology can also be used as combined power plants for increasing efficiency and reduce overall cost.

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