Design of Solar Thermal Energy Storage Facility for 50 MW Solar Thermal Power Plant

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Design of Solar Thermal Energy Storage Facility for 50 MW Solar Thermal Power Plant

Major Project Report

Submitted in partial fulfillment of the requirements

For the Degree of

Master of Technology in Mechanical Engineering

(Energy System)

By

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DECLARATION

This is to certify that,

1. The thesis comprises my original work towards the degree of Master of Technology in Energy System at Nirma University and has not been submitted elsewhere for a degree or diploma.

2. Due acknowledgement has been made in the text to all other material used.

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UNDERTAKING FOR ORIGINALITY OF THE WORK

I, Siddhant S. Shah, Roll. No. 15MMEN04, give undertaking that the Major Project entitled "Design of Solar Thermal Energy Storage Facility for 50 MW Solar Thermal Power Plant" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (Energy System) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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This is to certify that, the Major Project Report entitled “Design of Solar Thermal Energy Storage Facility for 50 MW Solar Thermal Power Plant” submitted by Mr. Siddhant S. Shah (15MMEN04), towards the partial fulfillment of the requirements for the award of Degree of Master of Technology in Mechanical Engineering (Energy System) of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination. The result embodied in this major project, to the best of our knowledge, has not been submitted to any other University or Institution for award of any degree.

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ABSTRACT

The energy received from the sun is plentiful to satisfy every one of the prerequisites of humankind, however that energy is discontinuous, frequently capricious and diffused. Because of discontinuity of the sun oriented power, it is hard to match control delivered from this source with different burdens like residential, mechanical and business. For settling the power conveyance and to expand the day by day working hours of the plant, it can be either consolidated with ordinary power plant or separate thermal energy storage framework can be made for the plant. Thermal energy storage is not another idea; it has been utilized for quite a long time and assumes a vital part in energy preservation.

Concentrated Solar Power (CSP) plants which are as of now being used, utilizes oil as a heat transfer fluid and molten salt as the thermal energy storage fluid. As per recent developments in industrial practices, utilization of oil as heat exchange fluid (HTF) is confined, as it can burst into flames and begin contaminating over its maximum utmost temperature which is 390ºC. Additionally recent rearch proposed the utilization of liquid salt (molten salt) as heat transfer fluid (HTF) and thermal energy storage (TES) fluid. Utilization of liquid salt as a HTF and TES fluid will expand the aggregate cost of plants, as it is having a high solidification point (238ºC) contrasted with oil (12ºC). The higher cost is due to requiring special freeze protection system in sunlight based field channeling and in thermal energy storage framework.

Researchers have developed a new thermal energy storage material ($LiNO_3$-$NaNO_3$-KNO_3) which have low solidification temperature and have better thermodynamic properties at higher temperatures when contrasted with salt currently used. Use of this material in TES will help to increase operating temperature of TES system. It also have higher energy density which will be helpful to optimize the tank size and amount of storage salt required.

This thesis contains the designing of the thermal energy storage facility with liquid salt (molten salt) as heat transfer fluid and new ternary eutectic salt as thermal energy storage fluid in solar thermal power plant. Thesis principally manages the designing of storage tanks for thermal energy storage, designing of heat protection framework, heat loss estimation for various ambient conditions and tank heater sizing to maintain the minimum required temperature in the cold tank.

Keywords: Heat transfer fluid (HTF), Thermal energy storage(TES), CSP, molten salt, Freez protection, heat loss.

Contents

List of Figures

List of Tables

Nomenclature

A	Total tank area, m^2
$Cp_{storage\,salt}$	Specific heat of storage salt $kJ/kg\ °C$
D_i	Inside diameter of tank,mm
D_o	Outside diameter of tank,mm
Q'	Heat input to power block, MW
$m_{storage\,salt}$	Mass flow rate of storage salt, kg/s
$m_{solar\,salt}$	Mass flow rate of solar salt, kg/s
$M_{storage\,salt}$	Mass of storage salt,kg
V	Volume of tank,m^3
m_{FW}	Mass flow rate of feed water,kg/s
$Cp_{solar\,salt}$	Specific heat of solar salt, $kJ/kg\ °C$
t_{btm}	Tank bottom plate thickness, mm
$\triangle T_{storage\ salt}$	Diff. between HT salt temp. and CT salt temp., ^0C
$\triangle T_{solar\ salt}$	Diff. between solar field outlet. and inlet., ^0C
Q_o	Outlet nozzle volumetric flow rate, m^3/s
$\rho_{storage\,salt}$	Desity of storage salt,kg/m^3
T_{HT}	Hot tank salt temperature, ^0C
T_{CT}	Cold tank salt temperature, ^0C
ν_o	Outlet nozzle velocity, m/s
A_{req}	Nozzle area require,m^2
$D_{ID\,REQ}$	Inlet dia of nozzle req.mm
$D_{ID\,Selected}$	Inlet dia of nozzle selected.mm
$D_{OD\,Selected}$	Outer dia of nozzle selected.mm
t_{no}	Nominal thichkess of flanged nozzle pipi wall,$W/m^2.K$
H_{NO}	Min. distance from bottom of tank to center of outlet nozzle,mm
H_{NO_1}	Required distance from tank bottom to nozzle center, mm
$V_{T_{W1}}$	Volume of warnig interval fro LLL, m^3
$V_{T_{W2}}$	Volume of warnig interval fro HHL, m^3
$H_{T_{W1}}$	Height of warning interval for LLL,mm
$H_{T_{W2}}$	Height of warning interval for HHL,mm
H	Height of liquid column,mm
H_{curb}	Height of curb angle,mm
T_{amb}	Ambient temperature, ^oC
K	Conductivity of insulation, $W/m.^oK$

$\triangle X$	Insulation thickness, mm
Ra	Rayleigh No.
$Gr.$	Grashoff No.
$Re_L.$	Reynold no for length
Re_D	Renold no for diameter
h_i	Internal convective heat transfer coefficient for tank, $W/m^2.^oK$
h_C	Outside convective heat transfer coefficient for tank, $W/m^2.^oK$
h_r	Radiative heat transfer coefficient for tank, $W/m^2.^oK$
h	Total conductance, $W/m^2.^oK$
Nu_n	Natural convection nusselt no.
Nu_f	Forced convection nusselt no.
T_f	Temperature in Fahrenheit, $.^oF$
T_K	Temperature in Kelvin,$.^oK$

Abbreviations

CSP	Concentrated solar power
HTF	Heat transfer fluid
TES	Thermal energy storage
STG	Steam generator
FW	Feed water
MP	Melting point
FP	Freezing point
SF	Saftey factor
EJ	Engineering judgement
HT	Hot tank
CT	Cold tank
HHL	High-high level set point
HL	high level set point
LLL	Low-low level set point
LL	Low level set point
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
STPP	Solar thermal power plant
DNI	Direct Normal Irradiance.

Chapter 1

Intruduction

1.1 Introductory Remarks

Major input for the socio-economic development of any nation is energy. The energy sector of the developing nation assumes to have a great importance as, lack of energy will influence the welfare of the nation. Most of the nations are depend on the conventional sources of energy like coal, oil, gas etc. which are not long lasting and non dependable. In future, if there is absence of this sources it will definitely affect the development of nation. Conventional sources of energy are also the pollution making sources which are affecting the climate which is not good for long life of mankind.

1.1.1 Power scenario of India

According to international energy outlook 2016 published by U.S. energy information administration much of the world needed increase in demand of energy to have a economic growth and to deal with the problem of expanding population. Economic growth accompanying with the structural changes will surely impact energy consumption. As the nation develops, living standard of people improves resulting more demand of energy for development.

Current scenario of Indian power sector at the end of February 2017 shows that India is having total installed capacity of 315426.32 MW of which 215214.89 MW is from thermal sector, 5780.00 MW is from nuclear sector, 44413.43 MW is from hydropower and 50018.00 MW is from renewable energy sector (RES). RES include small hydro project (<25 MW), biomass power, urban and industrial west power. Installed capacity is as shown below,

Table 1.1: Power scenario[1]

Energy Sector	Installed capacity in MW
Coal	189047.88
Gas	25329.38
Diesel	837.63
Nuclear	5780.00
Hydro	44413.43
RES	50018.00
Total	315426.32

Breakup of Renewable energy sector is as follows (as on 31.12.2016)

Table 1.2: Renewable energy sector break up[1]

Renewable energy	Installed capacity in MW
Small hydro	4333.86
Wind	28700.44
Bio power	7971.02
Solar power	9012.69
Total	50018.01

Power scenario of India shows that India is mainly rely on conventional power sources as compared to renewable sources.

India is developing quick. Energy is integral to accomplishing India's improvement desire, to support a growing economy, to convey power to the individuals who stay without it, to fuel the interest for more prominent portability and to build up the framework to address the issues of what is soon expected to be world's most crowded nation. It is home to 18% of the world's population and uses only 6% of the world's primary energy. According to the special report of world energy outlook 2016, still today almost 240 million peoples of India are without access to the electricity

So, to meet the requirement of energy need and to minimize the usage of conventional power sources for cleaner environment, we need to develop the technologies which are related to renewable resources and which will be ample to stabilize the world climate.

1.1.2 Solar Energy

India has an extraordinary potential for sun based power and it is assessed such a large number of times of the energy necessity which is around 5000 trillion kWh every year. The sunlight based radiation episode over India is equivalent to 4–7 kWh per square meter every day with an annual radiation extending from 1200–2300 kWh per square meter. It has a normal of 250–300 clear sunny days and 2300–3200 hours of daylight for every year.

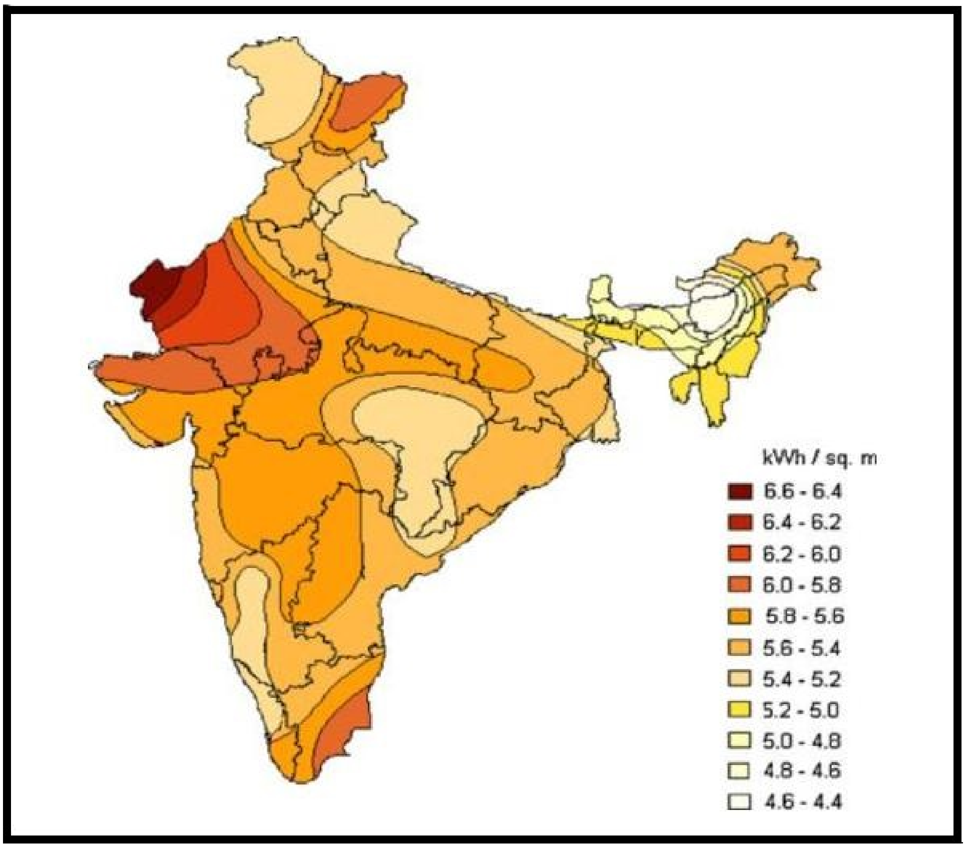

Figure 1.1: Solar radiations over India[2]

According to the survey taken by Ministry of New & Renewable Energy, Govt. of India in the year 2014-15 India is having solar power potential of 748.98 GWp with Rajasthan having the highest potential of around 143 GWp. There are mainly two ways of harnessing the solar energy as, by photovoltaic plants and by solar collector plants.

- Photovoltaic plants :- These types of plants uses solar panels that can harnesses the energy from the sun's light (photo) and convert it into direct current electricity (volts). The photovoltaic effect is closely related to the photoelectric effect in which electrons are ejected from a material when subjected to energy exposure, such as light radiation. In the photovoltaic effect however, these generated electrons are forced to flow within the material, which result in an electric current and the buildup of voltage.

- Solar thermal plants :- Sunlight based thermal systems tackle sun oriented energy by using sun oriented radiations to produce heat-as hot water, hot air, steam etc. that can be sent for meeting various applications in various divisions, for example, space heating, space cooling, community cooking, process heating and so on. These applications make utilization of sunlight based energy collectors as heat exchangers that change sun powered radiation energy to internal energy of the transport medium (or heat exchange liquid, typically air, water, or oil). The sunlight based energy accordingly gathered is conveyed from the coursing fluid either directly to the hot water, or to a thermal energy storage framework from which it can be drawn for use during the evening and additionally shady days. Sun powered thermal systems can be either non-focusing or focusing type. They may likewise be either stationary or with sun-tracking systems, contingent upon the application, temperatures required and financial reasonability.

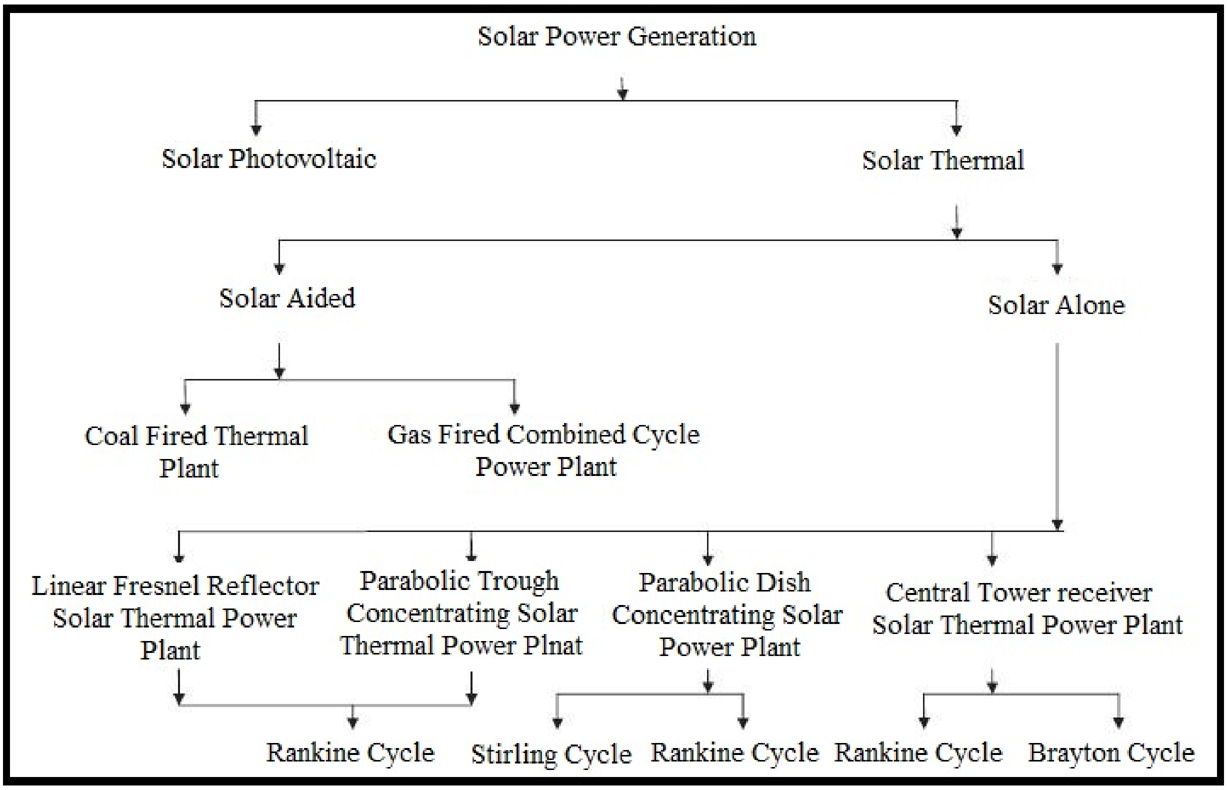

Figure 1.2: Solar power generation[2]

1.1.2.1 Concentrating solar power (CSP)

System uses various types of mirrors, lenses to concentrate the radiations received from sun to heat the heat transfer fluids which will further goes to steam generator to exchange heat with working fluid which runs the steam turbine to generate the power. There are four main types of concentrating technologies: Parabolic trough, dish Stirling, concentrating linear Fresnel reflectors and solar power towers. Each one of them has its own advantages and disadvantages according to its application and type of working. They also vary from one another in the way they focus and concentrate the sun's irradiation. Total installed capacity of CSP plants in India under JNNSM (Jawaharlal Nehru National solar mission) phase -1 is 518 MW.

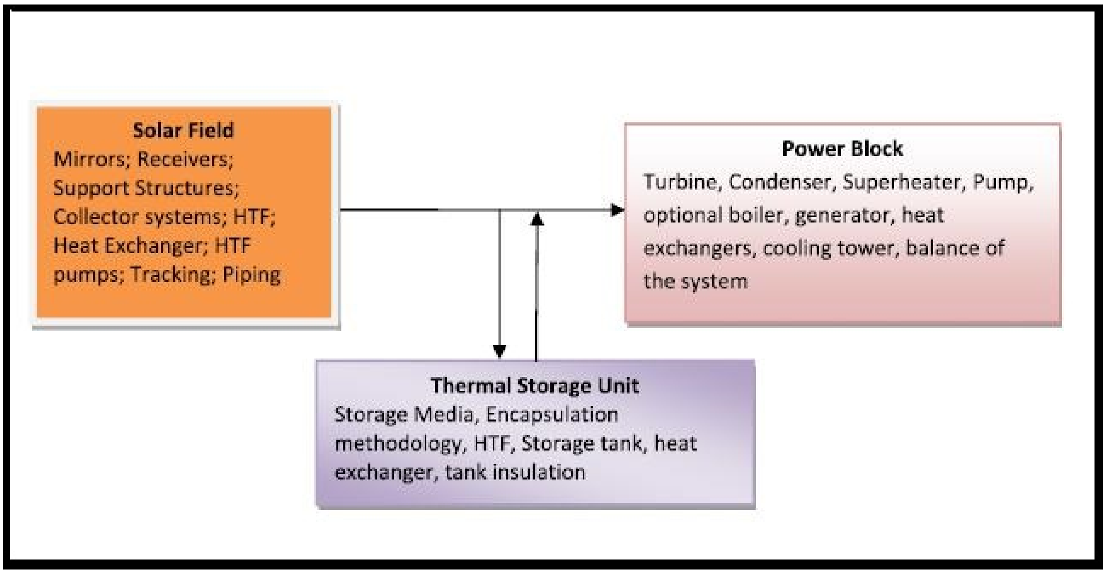

Figure 1.3: Main parts of CSP plants and their components[2]

Types of CSP power plants are as under,

- **Solar power towers :-** It consists of the collector tower which is surrounded by flat movable computer assisted mirrors called as heliostats which track the sun individually to concentrate the solar irradiation upon it, that will generate the thermal power which heats water, transforming it in steam and that steam will be used to run the steam turbine. As in this system heliostat focuses the radiations on a perticular point on a power tower this system is point focused.

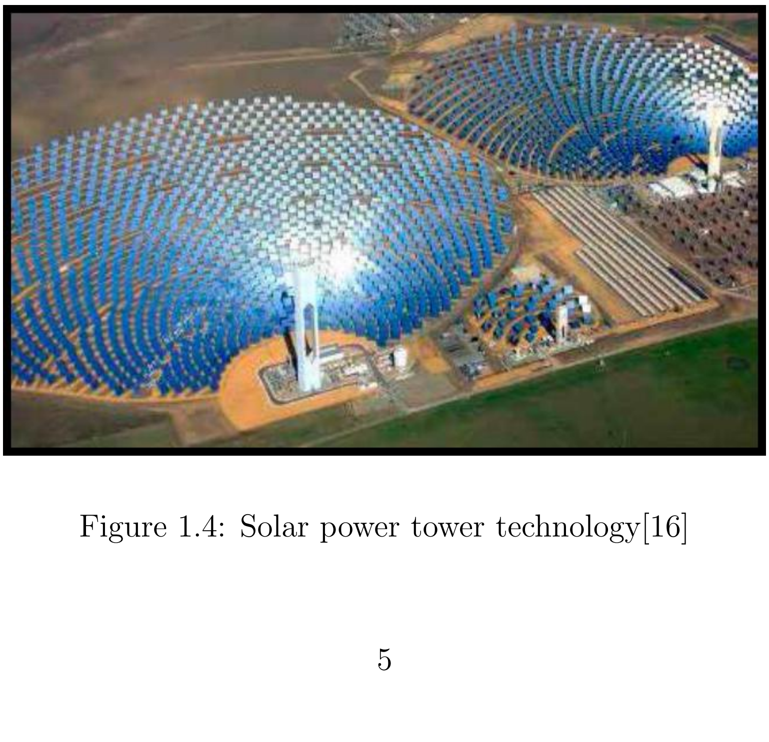

Figure 1.4: Solar power tower technology[16]

- **Fresnel Reflectors :-** It consists of the assembly of long thin mirrors that focuses the sun's irradiations approximately 30 times of its normal intensity onto a fixed absorber located at a common focal point of the reflectors. This system is line focused system.

Figure 1.5: Fresnel reflectors technology[21]

- **Dish Stirling :-** A system uses a parabolic solar dish concentrator that tracks sunlight and focuses it into a cavity receiver in which working fluid in the receiver is heated to 250-700°C.

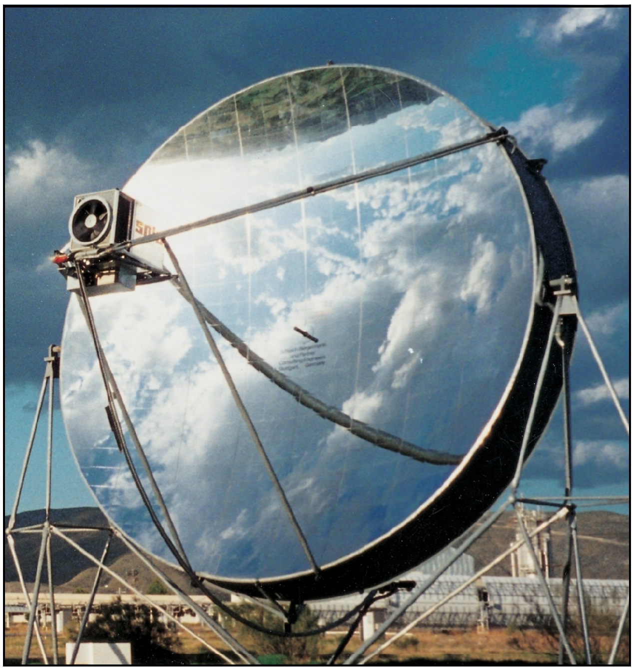

Figure 1.6: Dish stirling technology[21]

This thermal energy is transformed into power by a Stirling engine generator. Use of this technology is of great interest because Dish-Stirling systems have highest efficiency among any other solar power generation system by converting nearly 30% of DNI solar radiation into electricity after considering parasitic power losses. This is point focus system.

- **Parabolic trough :-** This System is broadly utilized as a part of all among the CSP Technologies. The framework comprises of long parabolic mirrors which concentrates the sunrays on to a tube, situated at the point of convergence of these parabolas which keeps running all through the entire length of these mirrors. Illustrative trough control plants have the greatest share of the installed concentrating solar power technology. The system is line focusing.Thi is the most commercially ready technology.

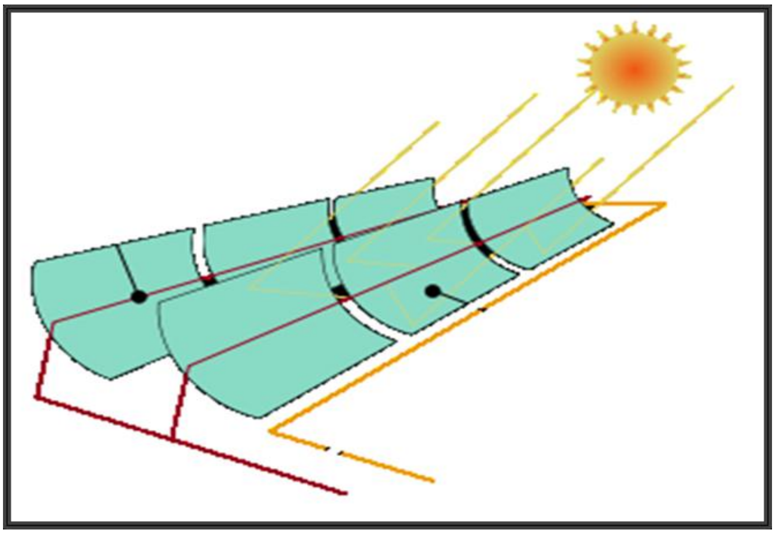

Figure 1.7: Parabolic trough technology[21]

These CSP technologies are used either with the thermal energy storage systems or without thermal energy storage systems depending upon the requirement.

1.1.2.2 Thermal energy storage.

Thermal energy storage for concentrating solar thermal power (CSP) plants can help in overcoming the irregularity of the sun powered asset and furthermore decrease the levelized cost of energy (LCOE) by using the power blocks for amplified timeframes.Thermal energy not only can be used for solar thermal power plants but it can also be used as seasonal thermal energy storage in various countries.

Addition of thermal energy storage framework with solar thermal power plant can collect energy between sunshine hours and store it with a specific end goal to move its conveyance to a later time or to smooth out plant yield during shady climate conditions. Thus, the operation of a sunlight based thermal power plant can be utilized beyond periods of no solar radiation without the need to burn fossil fuels.TES will not only helps in reducing rate mismatch between supply and demand but it aslo improves the reliability and performance of the whole system which will helps in the conservation of energy. Thermal energy can be stored in the form of sensible heat storage, latent heat storage and thermo-chemical heat storage.[3]

1. Sensible heat storage :- The term sensible heat depicts the heat which is retained or discharged by a material as a result of a change in temperature, whereupon the material does not experience a change of total state.In this system solid or liquid is heated without changing its phase i.e. only by senesible heating.The quantity of energy stored depends on temperature change of the material and can be expressed in the form ,

$$E_s = m \times \int_{T_1}^{T_2} C_p \times T$$

2. Latent heat storage :- Heating a material, which undergoes a phase change (usually melting) is called latent heat storage.The property of materials to absorb or release heat energy during a phase change is used when storing latent heat. The amount of energy stored (E) is depends upon the mass (m) and latent heat of fusion (λ) of the material.

$$E_L = m\lambda$$

3. Thermo-chemical heat storage :- In thermo-chemical energy storage frameworks, reversible reactions are utilized to store energy, which are endothermic while charging and exothermic while releasing. The useful specific reaction enthalpy of such reactions is merely one order of magnitude smaller than that in the combustion of fossil fuels and henceforth extensively bigger than that in the storage of sensible or latent heat. But this technology is currently at a very early stage.

1.2 Motivation

Current thermal energy storage system uses oil as a heat transfer fluid and molten salt as a thermal energy storage fluid in solar thermal power plant. There is another system which uses molten salt as a heat transfer fluid as well as thermal energy storage fluid. But this both mentioned systems have some restrictions as,

- System with oil as HTF and molten salt as TES have low operating temperature because oil have a boilng point of 400ºC, so it can not go beyond 390ºC. which results in storing the thermal energy at very low temoperatures which reduces the power block performance as compared to conventional system.

- Molten salt used for thermal energy storage have high solidification point of 238^{o}C which requires additional freez protection system.
- Low specific heat of molten salt
- Low energy density of molten salt
- Toxicity of oil as HTF

From the above points its clear that there is a need to develope new storage as well as heat transfer fluid so that one can improve the power block performance and storage capacity of the system. This improvement will results in higher annual solar contribution, reduction of part-load operation, power management and buffer storage.Increasing the operating temperaure will increase the power block performance by notable amount and lowering the solidification temperature in the storage system will give additional storage capacity.With the addition of the storage the security of the energy supply will be increased. This has provided the main motivation for the present project.

1.3 Aim and Scope of the work

Considering the above issues, investigation have been carried out with the following objectives.

- To study and to find the suitable material for thermal energy storage with low solidification point, high specific heat as well as high energy density compared to molten salt.
- To find suitable method for thermal energy storage and to design that system.
- To design the insulation for storage system
- To calculate cool down time with standby heat loss with refereance to various atmospheric temperatures

1.4 Methodology

In the first phase, selection of suitable heat transfer fluid and thermal energy storage material with required properties along with the basic designing of thermal energy storage system were done. In the second phase thermal insulation selection and heat loss calculation were done to find out the requirement of heater.

1.5 Outline of report

Report consists of total of six chapters. First chapter is about introductory remarks and motivation for the project. It also tells about the list of objectives, methodology used to complete this work along with the scope of project. Second chapter is about the related literature studied for achieving the objective. Third chapter presents selection of new heat transfer fluid material as well as thermal energy storage material with basic and detailed designing of storage tanks. Fourth chapter deals with the insulation system design and heat loss calculation to decide the requirement of heater. Comparative result will be discussed in chapter five. In sixth chapter conclusion and possible future scope were presented.

Chapter 2

Literature Review

2.1 Basics of thermal energy storage and heat transfer fluid

- **O. Ercan Ataer**[3] :- In this publication the author has given the brief introduction about the various storage technologies like sensible heat storage, Latent heat storage, thermochemical heat storage that can be used for the storage of thermal energy in various forms. Author also suggested some of the basic considerations that one has to take into account while going for design of storage system and selection of method for storage. He also done comparative study of some of the storage system used.

- **E. Hahne**[4]:- Brief introduction about sensible heat storage system were given by author in this publication. Sensible heat storage is well matured technique as compared to latent heat storage sysstem and thermo-chemical heat storage which is now in most of the concentrated solar thermal power plant. Author has presented basic thermodynamic consideration which one has to take into account while going for the design of sensible heat storage system.

- **Sarada kuravi, Jamie Trahan, D.Yogi Goswami et. all.**[5]:- In this paper authors have taken a review of various design methodologies related to thermal energy storage technologies and factors that are necessary at different levels of design consideration for CSP plants. The data related to various storage materials and storage media, which mhave the potential in terms of cycle life and stability were published by author in his paper which will be useful for further research in the field of thermal energy storage. Brief discription about exergy analysis of various systems were also presented in this paper.

- **D. Kearney, B, Kelly, U. Herrmann, R. Cable., D.Blake et. all.**[6]:- An evaluation were carried out in this paper to investigate feasibility of molten salt as heat transfer fluid in the solar field to improve the performance of the system in a large scale solar parabolic trough power plants. The investigation includes examination of known critical problems, and various approaches to deal with that problem to make it more suitable for the system. According to authors operation and maintainance is an important concern with respect to molten salt because of their high freezing point, if they were used in solar field of parabolic trough system. This paper also focuses on other related issues and their solutions with appropriate material selection for piping as well as for fittings.

2.2 Selection of thermal energy storage material

- **Robert W. Bradshaw, Nathan P. Siege**[7] :- In this paper author reported recent developements related to multicomponent molten salt mixtures which consists of common alkali nitrates as well as alkaline earth nitrate salts that have superior properties for using it as a heat transfer fluid and thermal energy storage fluids. Author carried out the experimental work for the development of new quaternary molten nitrate salt having low liquidus temperature with good chemical stability. They compared it with solar salt, ternary nitrate salts in terms of nitrite formation in the form of graph. Author also compared the viscosities of different nitrate salt and cost of various constituents in the nitrate salt. Author concluded that this quaternary salt displays much lower liquidus temperature and may be used as HTF. Working temperature range for this salts is upto $500^0 C$ and viscosity is higher than binary salt.

- **R.W. Bradshaw and D.E. Meeker** [8]:- In this paper author determined chemical stability of low melting, ternary molten salt mixtures [$Ca(NO_3)_2 - NaNO_3 - KNO_3$and $LiNO_3 - NaNO_3 - KNO_3$ in different temperatures for various compositions] and determined types of decomposition products formed under equilibrium conditions. According to them initial decomposition reaction is approximately same in ternary mixtures as in equimolar binary mixtures. Mixtures containing lithium nitrate were more stable than that of calcium nitrate. Author also studied the effect of various compositions on high temperature stability and melting point of two systems presented in paper. He suggested that $LiNO_3 - NaNO_3 - KNO_3$ component is having better thermal stability up to 550ºC with melting point of 120ºC in presence of oxygen as cover gas at higher temperatures and will be used as thermal energy storage material.

- **Rene I. Olivares, William Edwards** [9]:- In this paper the author has done the experimental work to carry out thermal stability evaluation of $LiNO_3 - NaNO_3 - KNO_3$ salt with composition (30-18-52 Wt %) in blanket gas atmospheres of argon, nitrogen, air, oxygen between room temperature and 1000ºC. They found that the stability of gas, measured by gases evolving from melt were affected by atmosphere. Evolution of main gaseous species NO were detected at 325ºC, 425ºC, 475ºC, 540ºC for above atmosphere respectively. Author also suggest that for long term stability one can use the mixture in presence of air up to 600ºC for extended period of time but has to change the relative concentration of constituents which affect the composition of eutectic.

- **Satish Mohapatra, Alparslan Oztekin, Sudhakar Neti**[10] :- Current heat transfer fluid and thermal energy storage fluid used in the CSP plants have certain limits for their use. Various literatures have suggested newly formed ternary salts for use as a heat transfer fluid and thermal energy storage fluid but there is very less data available for thermophysical properties. Author in this paper had done a experimental work to found some of the thermophysical properties and effect of addition of new nitrates on to properties of molten salts and his work is closer to whatever the data available in the literatures. They found the properties such as viscosity, specific heat and latent heat of ternary salts. Viscosity is found to behave like room temperature water. Viscosity experiences an exponential decrease at higher temperatures from melting point to 550ºC.Specific heat have been measured for pure components from highest to lowest in order of ($LiNO_3 > NaNO_3 > KNO_3$) . They found that there is an increase of 10-25% from solid state to liquid state. In molten state salts were insensitive to temperature changes and its found to increase with increase of lithium nitrate composition.

2.3 Tank material selection

- **D.W. Jeppson, J.L. Ballif W.W., Yuan B.E. Chou.**[11] :-In this report authors discussed about chemical and physical properties of lithium as well as its interaction with various gases, metals, non-metals.. Author also discussed about effect of lithium on corrosivity of various materials. As lithium is highly reactive, they presented the guidelines about handling of lithium and safety majors that one should take into account when working with lithium.

- **Wei-Jen Cheng, Ding-Jhih Chen, Chaur-Jeng Wang.**[12] :- In this paper author studied the effect of using eutectic ternary nitrate salt at high temperature of about 550^0C on various alloy steel grades. Author has done corrosion test on various alloy steel which have different amount of chromium content and found that corrosion behavior of alloys in nitrate salt is predominantly controlled by oxidation. By the various tests and reaction analysis, author concluded that when one could use the steel with higher chromium content it will form $(Fe, Cr)_3O_4$ which retards the outward diffusion of iron making it less susceptible to corrosion.

- **Dr. Ramana G. Reddy** [13]:- This is the research work carried out by author and his co-workers with the funding of US department of energy. Author had done various experimental work and found various salt mixtures which have potential for thermal energy storage. They have done melting point determination, heat capacity determination, density determination, thermal conductivity determination on developed salts. Author presented determination of corrosivity of low melting point salts with cost analysis and effect of system integration modelling . According to author SS316L is the material which is suited for storage of low melting point salts developed. Various cost analysis were also done by author to check the fesibility of newly developed salts to be used as HTF and TES system.

- **Dr. Ramana G. Reddy** [14]:- Research on development of low melting point (LMP) molten salt thermal energy storage media with high thermal energy storage density for sensible heat storage systems were presented by author in this work. The required properties of the selected LMP molten salts for thermal storage in solar energy applications including heat capacity, melting point, density, and thermal energy storage capacity were determined by experimental work in this research. They used thermodynamic modeling calculations to estimate eutectic compositions of the salt mixtures, heat capacities and densities to develop candidate low melt point salt materials.

2.4 Heat loss and cooling process

- **Christian Suarez, Alfredo Iranzo, F.J. Pino, J Guerra**[15] :-Transient analysis of the cooling process of molten salt thermal storage due to standby heat loss were done by author. The transient analysis were carried out for variuos charging levels by developing the CFD model for the cooling process. According to author maximum heat loss and risk of local solidification were at minimum charging level of tank. On the other hand at maximum charging level the risk is minimum.

- **Mr. Joseph E. Kopp** [16]:- Report consists of a two tank indirect thermal energy storage designs for solar parabolic trough power plants. Author proposed an alternate indirect two tank molten salt thermal energy storage system in which molten salt were utilised as the heat source for steam generation. A base case with no storage were modelled by taking input parameters from one of the working plant and the effect of same on solar field size were analyzed in this report. Various operating strategies with respect to alternate storage design were also discussed.

2.5 Conclusion from Literature review

Use of oil as heat transfer fluid has some restricted properties, such as restrictions on operating temperatures, toxicity of oil, fire saftey etc. Oil have highest operating temperature of 390ºC which limits its use in high temperature applications. Molten salt were successfully demonstrated as heat transfer fluid which will increase the operating temperatures of solar field upto 550ºC. It is also used as a thermal energy storage fluid. Using molten salt as HTF fluid and TES fluid has only one problem i.e. its high freezing point which increases the total system cost. Direct thermal energy storage is the technique in which same salt is used as heat transfer fluid as well as thermal energy storage fluid. Indirect thermal energy storage is well matured and industry ready technology in which HTF is different and TES fluid used is different. If molten salt (Solar salt) is used in direct thermal energy storage system will increase its cost because of its freez protection system. To replace high freezing point molten salt and to increase operating temperature of storage system to higher level, there is a need to develope new materials with low freezing point and which have better thermodynamic properties than molten salts. Research is showing that there is lot of developement in HTF and TES materials, with various compositions and better properties than currently used molten salts.

$LiNO_3 - NaNO_3 - KNO_3$ salt is having better properties than molten salt (solar salt) and have low melting point ranging between 116-127ºC for various compositions. It is suggested that it can be used as heat transfer fluid and thermal energy storage fluid. $LiNO_3 - NaNO_3 - KNO_3$ salt is having thermal stability upto 540ºC in presence of oxygen. Two tank indirect thermal energy storage system is commercially well proven technology than direct thermal energy storage system. According to research, atmosphere affects the thermal stability of nitrate/nitrite salts than its compositions. Research done for various cover gas atmospheres shows that ternary eutectic salt is said to be stable at a perticular temperature when main gaseous species NO were detected to be evolved at that temperature and rapid weight loss were detected after that perticular temperature. Ternary salt were stable at 325ºC, 425ºC, 475ºC, 540ºC temperatures for atmospheres of argon, nitrogen, air, oxygen gas respectively[9]. literature study concludes that $LiNO_3 - NaNO_3 - KNO_3$ salt is suitable to use as TES material with oxygen as a cover gas. Use of $LiNO_3 - NaNO_3 - KNO_3$ will increase the operating temperature of TES system as it is having a higher temperature stability upto 540ºC in presence of oxygen. So, if molten salt is used as HTF and $LiNO_3 - NaNO_3 - KNO_3$ is used as TES fluid it is possible to increase solar field output temperature to 550ºC and thereby storing the heat energy in TES system at higher temperatures

Chapter 3

Selection of storage material with system design

3.1 Introduction

Consumption of energy by human civilization is increasing at very fast pace over the years, as new technologies for the betterment of human life are getting invented. Every new technology invention directly or indirectly relates to the need of energy. According to international energy outlook 2016 published by U.S. energy information administration much of the world needed increase in demand of energy to have a economic growth and to deal with the problem of expanding population. Economic growth accompanying with the structural changes will surely impact energy consumption. As the nation develops, living standard of people improves resulting more demand of energy for development.

Conservation of energy is that much important as developing a new source of energy. The concept of thermal energy storage will help very well in that case. India is having abundunt of solar energy which can be used in solar thermal power plant. TES system coupled with solar thermal power plant will use solar energy in day hours to store it for later use (i.e. when solar energy is not available or in case of peak power demand etc.). Addition of TES system to solar thermal power plant will increase reliability of power plant and will reduce the burden on conventional fuels.

TES can be mainly done in three ways as sensible heat storage, latent heat storage and thermochemical heat storage[3]. Use of sensible heat storage is very much used concept now a days and other two concepts are at developing stage. As the concept of sensible heat storage is very well proven, in the current work system is designed with the concept of sensible heat storage[4]. Sensible heat storage system can be coupled directly or indirectly with the CSP plants. Indirect thermal energy storage technique of thermal energy storage is commercially proven and widely used in solar power plants[16]. With indirect thermal energy storage system it is possible to increase the solar field outlet temperature to a higher level which will reduce the physical size of thermal energy storage and possibly storing the more energy at higher temperatures. In case of direct thermal energy storage system it is difficult to use high freezing point fluid because freeze protection of whole system is difficult. So indirect thermal energy storage as shown below is better option for thermal energy storage. Economical consideration were not taken into account for this system. The system selected is In-direct thermal energy storage system which is with reference to the document provided by the L&T, S&L as a reference for carrying out this thesis work. The system selected is with parabolic trough system as this is most commercially ready technology.

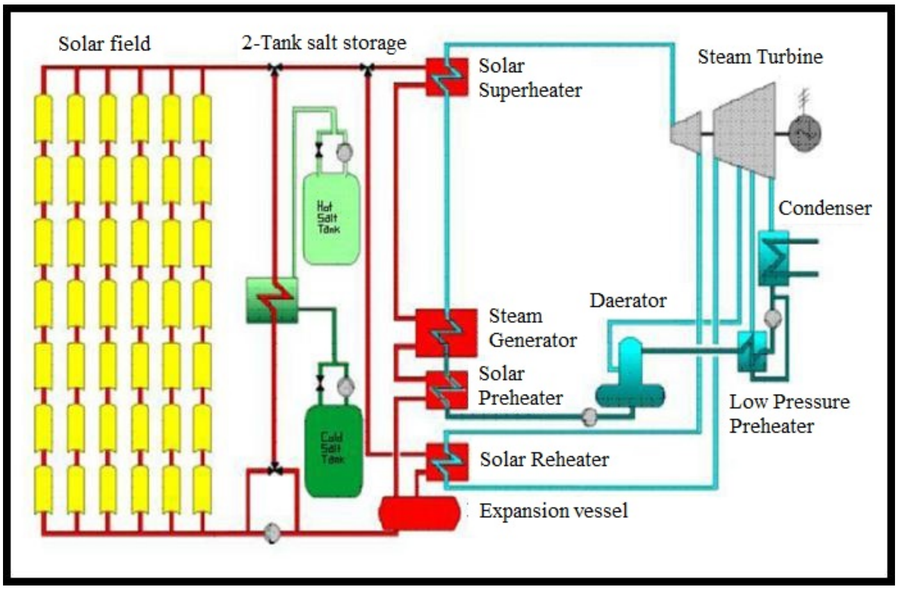

Figure 3.1: Indirect thermal Energy storage system[16]

3.2 Thermal energy storage fluid selection

Most of the CSP plants uses oil as a heat transfer fluid and molten salt as the thermal energy storage material, but from the experiences of various working plants, the use of oil as heat transfer fluid (HTF) is restricted as it can catch fire above its upper limit temperature which is 390ºC. So there is continuous research going on for better heat transfer fluid. Some have also suggested the use of molten salt as heat transfer fluid[6] and for thermal energy storage, but use of molten salt as a heat transfer fluid and thermal energy storage will increase the total cost of plant, due to its higher solidification point (239ºC) as compared to oil which results in requiring a special freeze protection system in solar field piping and in thermal energy storage system.

Researchers [8, 13] have developed new storage as well as heat transfer fluid material ($LiNO_3 - NaNO_3 - KNO_3$) which has low melting point and has potential to store more amount of energy as compared to solar salt. The new eutectic material developed has low melting point ranging from 116ºC -127ºC for various compositions both theoretically and experimentally in various literature. No literature is having a fixed composition of this newly developed salt. Various researchers have found the properties of this salt with different compositions. Satish Mohapatra et. al.[10] have found the eutectic point i.e. melting point as 127ºC with the composition of 38 mol. % $LiNO_3$, 15 mol. % $NaNO_3$ and 47 mol. % KNO_3. They suggested that there is an increase in the melting temperature of the mixture when the composition of $LiNO_3$ in the mixture goes beyond 38 mol. %. they also stated that with $LiNO_3$ compositions between 35 mol % to 38 mol. % and KNO_3 compositions between 40 mol. and 50 mol. % have similar melting temperature of 127ºC.

R.W. Bradshaw and D.E. Meeker[8] suggested the composition as 37 mol. % $LiNO_3$, 14 mol. % $NaNO_3$ and 49 mol. % KNO_3. and having melting point of 120ºC. According to Bradshaw and Meeker[8] high temperature thermal stability of eutectic salt mixture depends on formation of oxide ions at high temperatures. When one will increase the $LiNO_3$ concentration up to 40 mol. % the oxide ion concentration in the mixture increases but a further addition of $LiNO_3$ results in much smaller increase in oxide ion concentration. They also suggested that concentration of oxide ions were depend on temperature and not on composition of the mixture. Thermal stability of this new ternary salt is up to 550ºC in presence of oxygen.

According to experiment carried out by Rene Oliver and William Edward[9] the salt with the same composition is said to be stable when main gaseous species NO were detected to be evolved from the mixture. They have carried out an experiment with the salt present in different atmospheres to check thermal stability and found that, in argon atmosphere NO were detected at 325ºC, in nitrogen atmosphere NO were detected at 425ºC, in air atmosphere NO were detected at 475ºC, and in oxygen atmosphere NO were detected at 540ºC without measurable weight loss. Further they added that for long term stability in presence of air system can be used upto 600ºC but the relative concentration of constituents have to be changed which will affect the composition of the eutectic.

Satish Mohapatra [10]and their co-workers determined the specific heat of this newly developed salt and salt specific heat depends on specific heat of $LiNO_3$, as specific heat of $LiNO_3$ is higher as compared to other two nitrate salts in the mixture. Comparision of currently used storage fluids with ternary eutectc salt is shown below.

Table 3.1: Lithium eutectic Ternary salt comparison

Properties	Solar salt	Lithium eutectic salt	Hitec XL	Hitec
$LiNO_3$% wt.	60	12-40	7	7
$NaNO_3$% wt.	40	15-40	45	53
KNO_3% wt.	-	40-70	-	-
$Ca(NO_3)_2$% wt.	-	-	48	-
$NaNO_2$, % wt.	-	-	-	40
Solidification point, ^{0}C	220	116-127	120	142
Upper temp, ^{0}C	600	550	500	535
Density, Kg/m^3	1743	1785	1827	1714
Energy density, MJ/m^3	756	1056	-	-
Viscosity, cp.	3.26 @300^0C	1 @ $> 500^0C$	-	-
Heat capacity, J/Kg-K	1530	1630	1447	1560

Above comparison shows that lithium nitrate eutectic salt is better candidate for the case of thermal energy storage. Specific heat for various combination of nitrate salts is in the range of 1.53-1.70 kJ/kg.K. The data related to specific heat were limited in the literature for selected salt. Eutectic salt with specific heat equal to 1.63 kJ/kg.K and density equal to 1785 kg/m^{3}were selected. System is designed with $LiNO_3 - NaNO_3 - KNO_3$as thermal energy storage and molten salt (solar salt) as heat transfer fluid with two tank indirect thermal energy storage system. Molten salt will be selected as heat transfer fluid because by using molten salt its possible to increase the opoerating temperature of the system and possible storing the thermal energy at higher temperatures.

3.3 Basic terminologies and methodology related to tank sizing

3.3.1 Basic terminologies related to tank sizing

Storage tanks are nothing but the containers that stores liquids or mediums that can be used for the short- or long-term storage. Storage tanks are classified based on their fabrication place either at field or at shop. Place of operations will vary based on transportation facility, availability and manufacturing capacity at shop.Basically tanks are of following types,

1. Vertical and Horizontal,
2. Aboveground and Underground,
3. Atmospheric and Pressurized
4. Field Fabricated and Shop Fabricated.

Terminologies related to vertical aboveground field fabricated tank are as follows,

- High-High Level Set Point – The level at which the tank inlet would be shut off to prevent the tank overflow from being reached. This is also the maximum allowable fluid level in a tank.
- High Level Set Point – The level at which a signal or alarm is sent to indicate that the tank inlet is approaching shut-off. This is also the maximum level for calculating working volume.
- Low Level Set Point – The level at which a signal or alarm is sent to indicate that the tank outlet is approaching shut-off. This is also the minimum level for calculating working volume.
- Low-Low Level Set Point – The level at which the tank outlet will shut off to prevent air from entering the suction system. This is also the minimum allowable fluid level in a tank.
- Minimum Tank Capacity – The minimum amount of fluid a tank can hold to satisfy the requirement.
- Minimum Working Volume – The minimum amount of fluid the tank can hold to satisfy a required design margin.
- Warning Interval (High or Low) – The change in fluid level (ft.) from the time a warning signal is sent until an operator or control system can take corrective action. Typical reaction times ranges from 2 to 5 minutes. The warning interval should reflect the reaction time based on required specific values such as flow into and out of the tank.

3.3.2 Methodology and formulas used

Purpose

Storage tank sizing will provide the thermal energy which is stored in the storage salt and which is used to heat the heat transfer fluid first and that heat transfer fluid will heat working fluid in the power block to generate power when solar energy is unavailabe or less available. Whenever there is absence of solar energy and during the night operation of power plant. It will be helpful in matching the supply and demand at the load side with increasing the reliability of power plant. Storage tank sizing and its related calculations covers the following attributes.[17]

1. Heat input to the power block.
2. Mass flow rate of heat transfer fluid to the power block.

3. Mass flow rate of heat transfer fluid to the thermal energy storage system.
4. Thermal capacity required for 16 hrs. storage.
5. Total heat transfer fluid flow rate from solar field .
6. Storage tank inlet nozzle sizing .
7. Storage tank outlet nozzle sizing.
8. Net working capacity .
9. Height and diameter of tank.
10. Distances from bottom of tank to various liquid levels.

3.3.2.1 Methodology

Methodology of calculation adopted while designing of a tank is as follows,

1. Initially heat input required to power block from solar field were calculated with reference to HBD of power block.
2. After calculation of aggregate heat input required to power block, mass flow rate of HTF (solar salt) required to heat working fluid in power block were figured.
3. Calculation for thermal energy storage capacity were finished with the assistance of aggregate heat input required for 16 hr. storage time.
4. Mass flow rate required for storage salt to charge storage system in 8 hrs. were computed from mass flow rate of HTF.
5. Amount of total storage salt required will be calculated from storage salt flow rate for 16 hr. storage time.
6. After deciding storage salt quantity, volume of tank required computed..
7. Inlet and outlet nozzle sizing were done after volume estimation.
8. Calculation of total height of tank with Various liquid level sizing calculations were done.

General strategy which will be used for designing of TES system is shown in the fig below,[3]

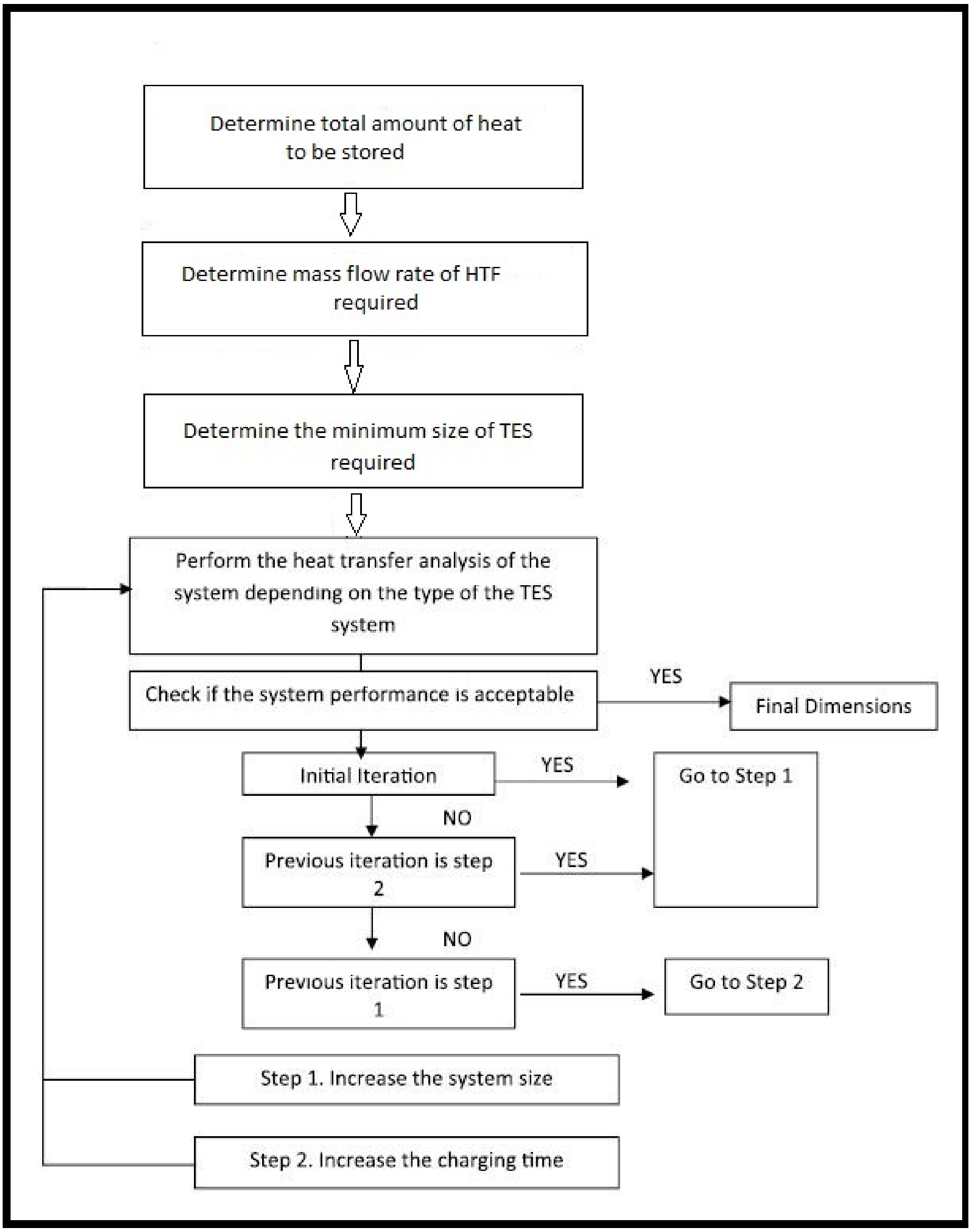

Figure 3.2: Schematic of tank sizing procedure

3.3.2.2 Formulas

1. Heat input required to power blocks

$$Q' = m_{feedwater} \left(h_2 - h_1\right)$$

2. Mass flow rate of solar salt required to heat working fluid in power block

$$m_{solar\ salt} = \frac{Q}{Cp_{solarsalt} \times \triangle T_{solarsalt}}$$

3. Thermal capacity of thermal energy storage

   $MWhr = Heat\ input\ to\ power\ block\ in\ MW\ \times Required\ storage\ time\ in\ hrs.$

4. Mass flow rate of storage salt to charge system in 8 hrs.

   $m_{storage\ salt} = \frac{m_{solar\ salt} \times C_{p_{solar\ salt}} \times \Delta T_{solar\ salt}}{C_{p_{storage\ salt}} \times \Delta T_{storage\ salt}}$

5. Amount storage salt required

   $M_{storage\ salt} = m_{storage\ salt} \times 3600 \times No.of\ hrs.of\ storage$

6. Volume of tank required

   $V = \frac{M_{storage\ salt}}{Density\ of\ storage\ salt} = \frac{\Pi}{4} \times D^2 \times height$

7. High-High set point :-

   The High-High level is determined from the following expression.

   $High - High\ tank\ level(ft.) = E_{overflow} – Nominal\ margin$

   Where:

   $E_{overflow}$ = Bottom of the Overflow Nozzle Elevation (ft.)

   Nominal Margin = Small margin below the bottom of the overflow nozzle (or point at which the overflow will begin draining) based on specific requirements.

8. High Level Set Point :-

   This level is used as the height for calculating the usable volume of the tank,

   $High\ Level = (HHL) – Warning\ Interval(high) – Required\ specific\ interval.$

   Where the Required Specific Interval covers any additional fluid level clearance needed from the overflow nozzle based on specific requirements.

9. Low Level Set Point :-

   This level is used as the height for calculating the usable volume of the tank.

   $Low\ Level = Low – Low\ level + Warning\ Interval(low) + Required\ Specific\ Interval$

   Where,

   Required Specific Interval covers any additional fluid level clearance needed from the outlet nozzle based on specific requirements.

10. Tank Design Capacity (minimum working volume) :-

    The tank shall meet the minimum tank capacity requirement based on specific requirements. The minimum working volume is set as the minimum tank capacity plus a design margin. Therefore, the design capacity (minimum working volume) of the tank should be a minimum of the following,

$Minimum\ Working\ Volume = Minimum\ Tank\ Capacity \times (1 + Design\ Margin)$.

Where,

The design margin is a percentage of capacity.

The useable portion of the tank is as follows and is used for calculating the minimum working volume based on the tank configuration.

$Usable\ Height(ft.) = Elevation\ of\ HL\ Set\ Point(ft.) – Elevation\ of\ LL\ Set\ Point(ft.)$.

11. Low-Low Level Set Point :-

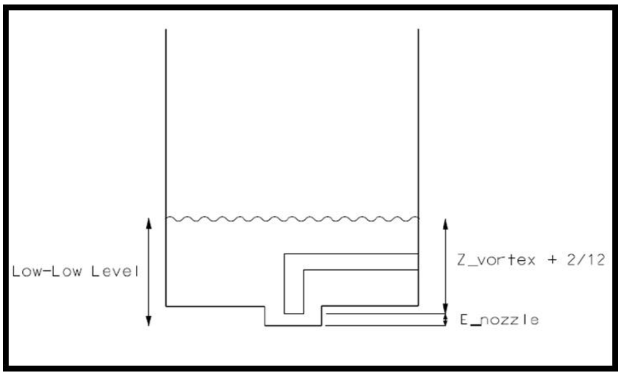

Figure 3.3: Low-Low tank level for design 1

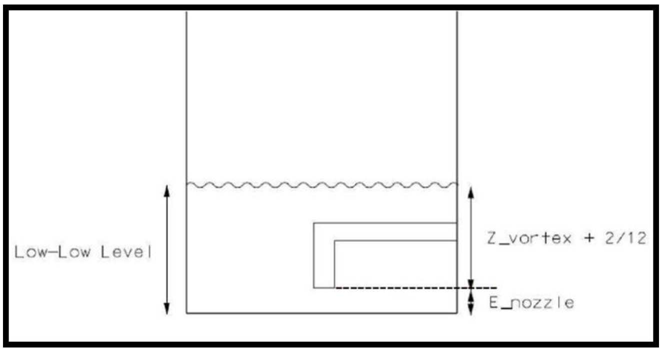

Figure 3.4: Low-Low tank level for design 2

The low-low tank level setting is determined from the following equation:
$Low - Low\ tank\ level(ft.) = E_{nozzle} + Z_{vortex} + 2/12$
Where:
E_{nozzle} = Top of the Suction Nozzle Elevation (ft.)
Z_{vortex}(vortex head)=(velocity of liquid entering tank discharge piping)^2 /(2*g) (ft.)
2/12 = a safety factor of 2-inches.
The fig. above shows how to find the Low-Low tank level for different tank designs.

3.4 Computation of design parameters with reference to above methodology

3.4.1 Design input parameters

Following parameters were considered as an input while sizing of storage tanks from the referance HBD of power block provided for carrying out this thesis work. This input parameters were chosen because solar field output temperature of HTF considered for designing system is 550ºC and which is directly fed into the steam generator. Assumption made here was, in steam generator HTF (enters at 550ºC and leaves at 290ºC) and feed water enters to the steam generator and exits from steam generator at following mentioned parameter.

1. T_1= Feed water temperature at the inlet of steam generator is 245ºC
2. T_2= Feed water temperature at the outlet of steam generator 535ºC
3. h_1= Enthalpy of feed water entering steam generator is 1062 kJ/Kg
4. h_2= Enthalpy of feed water leaving steam generator is 3459 kJ/Kg
5. m_{FW}= Mass flow rate of feed water entering the steam generator 60.4 kg/s
6. $Cp_{psolars\,alt}$= Sp. heat of molten salt entering the steam generator 1.53 kJ/kg. K
7. $Cp_{storage\,salt}$= Specific heat of storage salt 1.63 kJ/kg. K
8. $\rho_{storage\ salt}$= Density of storage salt 1785 kg/ m^3

3.4.2 Assumed parameters

Following are the parameters which were assumed during the designing of system.

(EJ) = Engineering Judgement = Engineering perspective based on the previous experience and knowledge.(provided by company).

1. $T_{cold\,tank}$= Storage salt temperature in a cold storage tank 230ºC
2. $T_{hot\,tank}$ =Storsge salt temperature in a hot storage tank 530ºC
3. Melting point temperature of storage salt 116ºC
4. Velocities at the inlet and outlet of hot and cold storage tanks 1 m/s
5. Inside diameter of tank is assumed as 34000 mm.
6. Number of inet nozzles and outlet nozzles considered are 2 for each tank.

7. $H_{Freeboard}$= Minimum Free board provided above High-High level for cold and hot Storage Tanks is about 200 mm.(EJ)

8. H_{in}= Height between Bottom of Inlet nozzle & High-High Level for cold and hot Storage Tank is about 30 mm (EJ)

9. H_{CL}= Clearance between top of Inlet nozzle and Curb angle/ Wind girder for cold and hot Storage Tank is 150 mm according to API 650

10. T_{w1}= Warning interval time low to low-low level is 5 minutes.(EJ)

11. T_{w2}= Warning interval time high to high-high level is 5 minutes.(EJ)

12. t_{btm}= Tank bottom plate thickness is 20 mm (EJ)

13. $\Delta T_{storage\,salt}$= Difference between hot tank salt temperature and cold tank salt temperature.

14. $\Delta T_{solar\,salt}$= Differnce between temperature of solar salt as a inlet to system from solar field and outlet from system to expansion vessel

15. Safety factor 50 mm for low-low liquid level

16. Distance from inlet nozzle bottom to high-high level 30 mm (EJ)

3.4.3 Computation of design parameters

3.4.3.1 Tank volume

Basic tank volume sizing and basic designing of tank will be based on HBD of power block provided by Larson & Toubro, Sargent & Lundy Ltd. Vadodara for completion of this thesis work, which is attached. In power block instead of boiler there will be a heat exchanger to heat the working fluid by HTF. Temperature drop will be considered as 1% which is shown in HBD. Part of power block and input parameters were represented in below fig.

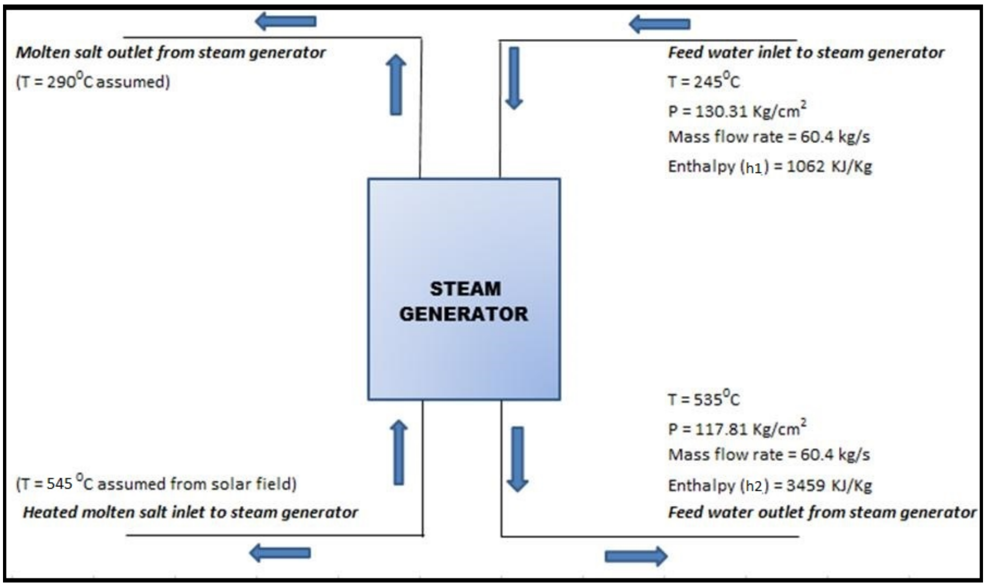

Figure 3.5: Power block diagram

$$Q' = m_{feedwater}\,(H_2 - H_1)$$

$$Q' = 60.4 \times (\ 3459 - 1062\ )$$

$$Q' = 144.778\ MW \approx 145\ MW \tag{3.1}$$

$$Q' = m_{solar\ \ salt}\ \times Cp_{solar\,salt} \times \triangle T_{solar\,salt}$$

$$m_{solar\ \ salt} = \frac{145}{1.53 \times (\,545 - 290\,)}$$

$$m_{solar\ \ salt} = 371.65\ Kg/sec \tag{3.2}$$

$$Capacity\ in\ MWhrs. = Q' \times No\ of\ hrs\ of\ storage.$$

$$Capacity\ in\ MWhrs = 145 \times 16$$

$$Capacity\ in\ MWhrs = 2320\ MWhe.$$

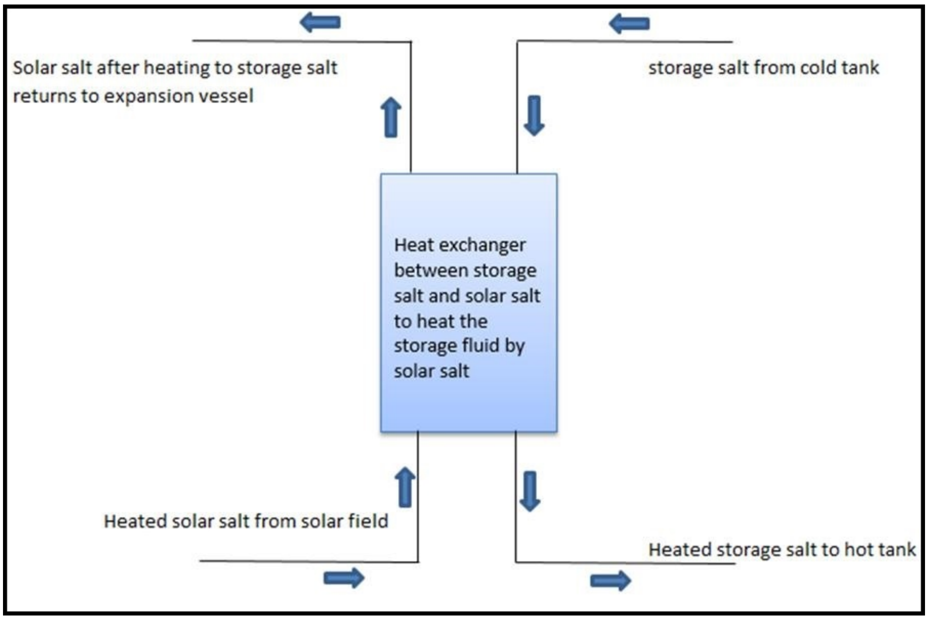

Figure 3.6: Storage salt heating by solar salt

$$Mass\ flow\ rate\ of\ storage\ salt\ to\ charge\ system\ in\ 8\ hrs.$$

$$m_{storage\ salt} = \frac{m_{solar\ salt} \times C_{p_{solar\ salt}} \times \Delta T_{solar\ salt}}{C_{p_{storage\ salt}} \times \Delta T_{storage\ salt}}$$

$$m_{storage\ salt} = \frac{730 \times 1.53 \times (545 - 290)}{1.63 \times (530 - 230)}$$

$$m_{storage\ salt} = 583.56\ Kg/sec\ \approx 584\ Kg/sec \tag{3.3}$$

$$M_{storage\ salt} = m_{storage\ salt} \times 3600 \times storage\ hrs.$$

$$M_{storage\ salt} = 584 \times 3600 \times 16$$

$$M_{storage\ salt} = 33580\ Tonnes\ \approx 35000\ Tonnes \tag{3.4}$$

$$Volume = V = \frac{M_{storage\ salt}}{Density\ of\ storage\ salt}$$

$$V = \frac{35000 \times 10^3}{1785}\ \frac{Kg}{Kg} \times m^3$$

$$V = 19607\ m^3 \approx 20000\ m^3. \tag{3.5}$$

3.4.3.2 Outlet nozzle sizing

$$Q_o = (m_{storage\,salt}/\rho_{storage\,salt})$$

$$no\,of\,nozzles\,used\,2$$

$$Q_o = (m_{storage\,salt}/\rho_{storage\,salt})/2$$

$$Q_o = (584/1785)/2$$

$$Q_o = 0.1636\,m^3/sec$$

$$velocity = v_o = 1\,m/s\ (assu.)$$

$$A_{REQ} = Q/v_o$$

$$A_{REQ} = 0.1636/1$$

$$A_{REQ} = 0.1636\ m^2\ for\,single\,nozzle$$

$$D_{ID\,REQ} = \sqrt{(\frac{A_{REQ} \times 4}{\Pi})} \times 1000$$

$$D_{ID\,REQ} = \sqrt{(\frac{0.1636 \times 4}{\Pi})} \times 1000$$

$$D_{ID\,REQ} = 456.38\,mm\,for\,single\,nozzle$$

$$D_{ID\,SELECTED} = 500\,NB\quad (ASME\,36.10) \tag{3.6}$$

$$D_{OD\,OF\,SELECTED} = 508\,NB\quad (ASME\,36.10) \tag{3.7}$$

$$t_{no} = 12\ mm\ \ (API\ 650) \tag{3.8}$$

$$H_{NO} = 600\ mm\ \ (API\ 650) \tag{3.9}$$

As volumetric flow rate from cold storage tank to hot storage tank were same the size of inlet nozzle is same as outlet nozzle. In case of inlet nozzle no of nozzles used also will be 2, as single nozzle will be higher in size.

3.4.3.3 Storage liquid level sizing

Various liquid level sizing in storage tank is as follows,

$$H_{NO1} = H_{NO} + t_{btm}$$

$$H_{NO1} = 600 + 20$$

$$H_{NO1} = 620\,mm \tag{3.10}$$

$$Z_{vortex} = (v_o^2/(2 \times 9.81))x1000$$

$$Z_{vortex} = (1^2/(2 \times 9.81))x1000 = 51\,mm$$

$$H_{LLL} = H_{NO1} + (D_{OD\,OF\,SELECTED}/2) + Z_{vortex} + SFs$$

$$H_{LLL} = 620 + 254 + 51 + 50 = 975\,mm \tag{3.11}$$

$$Outlet\,nozzle\,flow = (\,Q \times 3600 \times 2\,) \qquad (for\,2\,nozzles)$$

$$Outlet\,nozzle\,flow = (0.1636 \times 3600 \times 2) = 1177.92\ m^3/hr.$$

$$V_{T_{W1}} = (Q/60) \times T_{w1}$$

$$V_{T_{W1}} = (1177.92/60) \times 5 = 98.16\ mm$$

$$H_{T_{W1}} = (V_{T_{W1}}/(\Pi/4) \times (Di/1000)^2)) \times 1000$$

$$H_{T_{W1}} = (98.16/(\Pi/4) \times (34000/1000)^2)) \times 1000$$

$$H_{T_{W1}} = 108.11\ mm \approx 109\ mm$$

$$H_{LL} = H_{LLL} + H_{T_{W1}}$$

$$H_{LL} = 975 + 109$$

$$H_{LL} = 1084\ m \tag{3.12}$$

$$H = (V/(\Pi/4) \times (Di/1000)^2)) \times 1000$$

$$H = (20000/(\Pi/4) \times (34000/1000)^2)) \times 1000$$

$$H = 22028\ mm \approx 22030\ mm$$

$$H_{HL} = H_{LL} + H$$

$$H_{HL} = 1084 + 22030 = 23114\ mm \tag{3.13}$$

$$Inlet\,nozzle\,flow = (\,Q \times 3600 \times 2\,) \quad (for\,2\,nozzles)$$

$$Inlet\,nozzle\,flow = (0.1636 \times 3600 \times 2) = 1177.92\ m^3/hr$$

$$V_{T_{W2}} = (Q/60) \times T_{W2}$$

$$V_{T_{W2}} = (1177.92/60) \times 5$$

$$V_{T_{W2}} = 98.16\ m^3$$

$$H_{T_{W2}} = (V_{T_1}/(\Pi/4) \times (Di/1000)^2)) \times 1000$$

$$H_{T_{W2}} = (98.16/(\Pi/4) \times (34000/1000)^2)) \times 1000$$

$$H_{T_{W2}} = 108.11\ mm \approx 109\ mm$$

$$H_{HHL} = H_{HL} + H_{T_{W2}}$$

$$H_{HHL} = 23114 + 109 = 23223\ mm \tag{3.14}$$

$$H_{curb} = Curb\,angle = 75\,mm\ \ (API\,650)$$

$$H_{HHL\,to\,top\,of\,tank} = MAX\ ((H_{curb} + H_{CL} + D_{OD} + H_{in}), H_{Freeboard})$$

$$H_{HHL\,to\,top\,of\,tank} = 763\,mm \tag{3.15}$$

$$H_{top\,of\,tank} = H_{High-High} + H_{HHL\,to\,top\,of\,tank}$$

$$H_{top\,of\,tank} = 23986 = 24000\,mm \tag{3.16}$$

$$H/D\ Ratio = 24000/34000 = 0.7059$$

3.4.3.4 Results

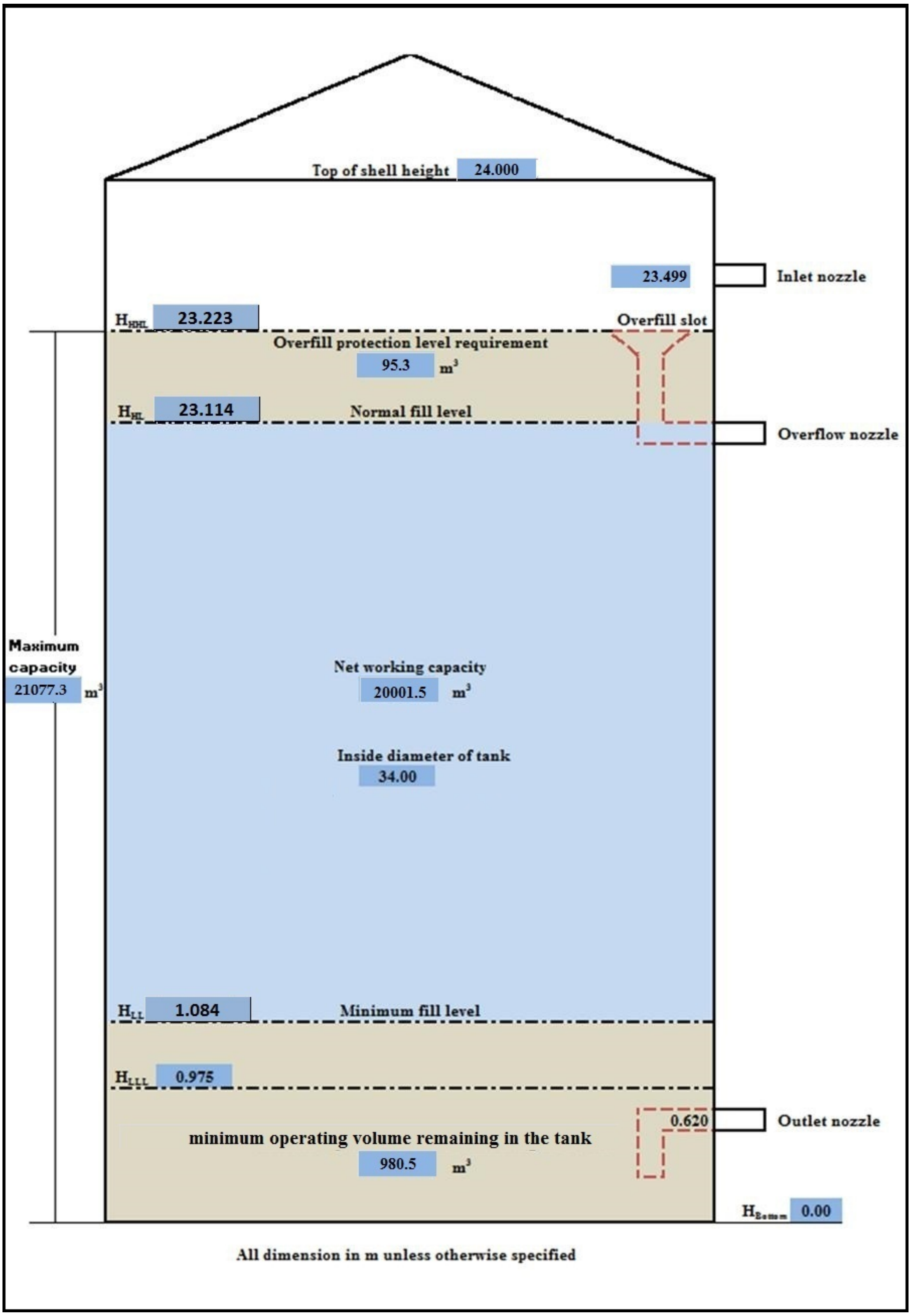

Figure 3.7: Dimentional sketch of storage tank

Table 3.2: Result of various liquid levels

Symbol	Value	Unit
Di	34	m
$H_{top\,of\,tank}$	24	m
H_{LLL}	0.975	m
H_{LL}	1.084	m
H_{HL}	23.114	m
H_{HHL}	23.223	m
$H_{overflow}$	23.223	m
$H_{HHL\ to\ top\,of\,tank}$	0.763	m
$H_{top\,of\,tank}$	23.986	m

3.5 Storage tank material selection

Newly selected thermal energy storage material contains lithium in ternary mixture which is corrossive in nature as compared to other two components in mixture. As lithium is corrosive, material selected to store this ternary eutectic salt should have good resistance to corrosion in high temperature conditions. Report by Hanford Engineering developement laboratory on lithium literature contains study done on the various materials in contact with lithium and their effect, which shows that serious attack on materials is mainly due to formation of comparatively stable but highly corrosive lithium oxide, nitrides, carbides.

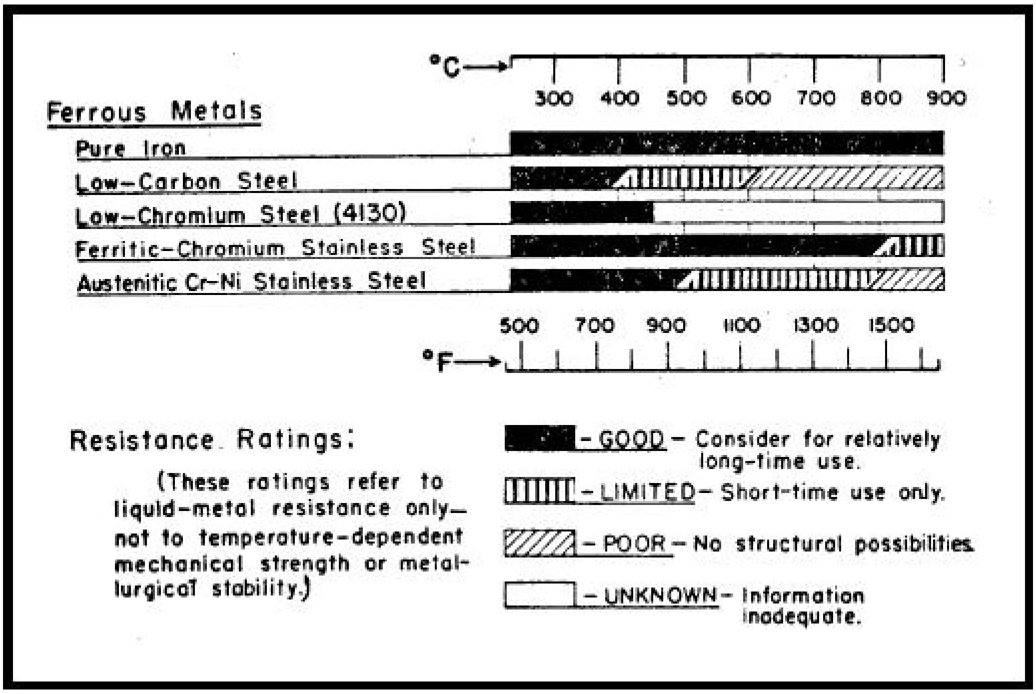

Figure 3.8: Resistance of lithium to various materials[11]

Compatibility of storage tank material is highly dependent upon lithium purity, alloy treatment, flow rates and lithium handling procedures. Rate of corrosion decrease with decrease in temperature in high purity systems and show less intergranular attack. Austenitic and ferritic stainless steel with less than 0.12 wt. %Carbon exhibit good resistance to lithium attack. Resistance of various materials to lithium is shown above.[11]

Wei-Jen Cheng et. al[12]. studied the effect of corrosion of these eutectic ternary nitrate salt $LiNO_3 - KNO_3 - NaNO_3$ at high temperature on Cr-Mo steel for thermal energy storage system in presence of nitrogen as a cover gas, as this low alloy steels are widely used in process industry for high temperature applications because of their good oxidation resistance and higher creep strength. However few have addressed this and suggested that, this low alloy steels must have been checked for their long term corrosion resistance at high temperature to confirm their compatibility.Wei-Jen Cheng et. all reviewed it with alloy steels of various chromium content and found that corrosion behavior was governed mainly by oxidation at higher temperatures. Study shows that in presence of dry and humid conditions, formation of oxide scales on steels with outer layer of Fe_2O_3 and inner layer of$(Fe,Cr)_3O_4$.were formed. Study done by Wei-Jen Cheng et. ll.[10] examined the oxidation of Cr-Mo steels which were exposed to new storage salt shows outer layer of $LiFeO_2$and inner layer of $(Fe,Cr)_3O_4$. Their study leads to the conclusion that $LiNO_3$ is more basic than other two components in the mixtures and hence shows the greatest activity in $LiNaKNO_3$.It suggest that corrosion of steels were due to lithiumization and oxidation and steels were mainly attacked by $LiNO_3$. Schematic illustration of formation of corrosion scales were shown in below figure.

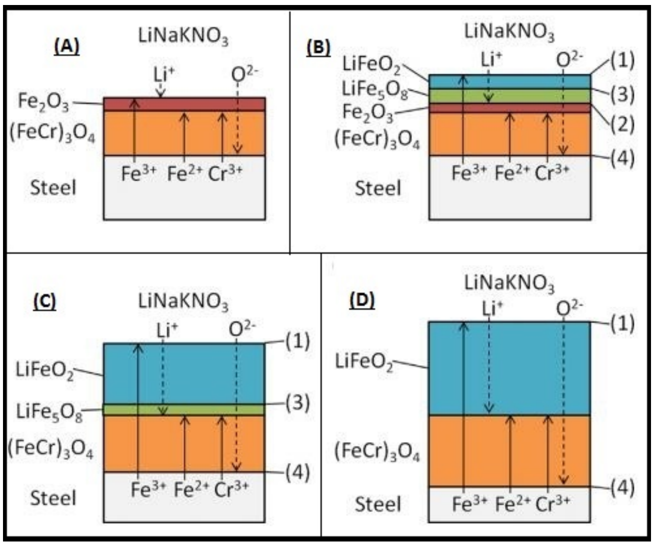

Figure 3.9: Growth stages involved in the formation of corrosion scales[10]

At initial stage steels were oxidized by O^{2-} ions in the salt and forms scales as outer layer of Fe_2O_3 and inner layer of $(Fe,Cr)_3O_4$in air or moist atmospheres shown in fig. 3.9 (A). Fe^{3+} diffused outward through the oxide scale while Li^+ and O^{2+} ions diffused into the oxide scales to the surface of the Fe_2O_3 layer and $LiFeO_2$ formed at the $Fe_2O_3/LiNaK$ interface, according to reaction (1).

$$Fe^{3+} + Li^{+} + 2O^{2-} = LiFeO_2 \tag{3.17}$$

Further as Li^{+} diffused into the oxide scale, at the interface between Fe_2O_3 and $LiFeO_2$via the lithiumization ofFe_2O_3 formation of $LiFe_5O_8$ starts, according to reaction (2),

$$6Fe_2O_3 + 2Li^{+} = 2LiFe_5O_8 + 2Fe^{3+} + 2O^{2-} \tag{3.18}$$

On the other hand, $LiFe_5O_8$ were also consumed at the interface between $LiFe_5O_8$ and $LiFeO_2$, according to reaction (3) and shown in fig 3.9 (B),

$$LiFe_5O_8 + 3Li^{+} = 4LiFeO_2 + Fe^{3+} \tag{3.19}$$

at last again $LiFe_5O_8$ is consumed further with Fe_2O_3 as,

$$3Fe^{2+} + 4Cr_2O_3 = 3(Fe, Cr)_3O_4 + 2Cr^{3+} \tag{3.20}$$

According to reaction (2) total consumption of Fe_2O_3 stopped the formation of $LiFe_5O_8$and according to reaction (3) and fig. 3.9 (C) $LiFe_5O_8$ were continuously consumed by inward growth of $LiFeO_2$. Both the layers of Fe_2O_3 and $LiFe_5O_8$ consumed in the early stages of corrosion in a short period of time. As a result the growth of outer $LiFeO_2$ and inner$(Fe, Cr)_3O_4$ controls the corrosion of the steel shown in fig 3.9 (D). Accumulation of chromium were mainly in the inner portion of $(Fe, Cr)_3O_4$ immediately adjacent to steel which is more than chromium content in the steel and increases with an increase in chromium content in the steel. Low chromium content will result in outward diffusion of$Fe^{2+}$and Fe^{3+}, leaving inert chromium distributed in the scale next to steel subtrate. Higher chromium content will retard this outward diffusion of iron which results in less corrosion of steel.

Study shows that specifically for $LiNO_3 - NaNO_3 - KNO_3$ eutectic salt for thermal energy storage SS316L is most suitable material with corrosion rate of 21.42 µm/yr. and this would imply less than 450 µm/yr. corrosion rate over a 20 years lifetime. Hence it is selected as storage tank material for this thesis work.

3.6 Thickness of tank material required

3.6.1 Design procedure and design inputs

Shell thickness for storage tank will be calculated on the basis of formula given in API 650. Two thickness were calculated as design shell thickness and hydrostatic test shell thickness. Highest of them will be selected as required shell thickness of storage tank. The method is called as one-foot method.[17]

1. Diameter of tank is 34000 mm
2. Height of tank 24000 mm
3. Volume of tank 20000 m^3
4. Specific gravity of storage fluid is 1.785
5. Tensile stress for SS316L 485 MPa
6. Yield stress for SS316L is 170 MPa
7. According to API 650 design stress is minimum of $2/3^{rd}$ of yield sress and $2/5^{th}$ of tensile stress. $2/3^{rd}$of yield stress in minimum i.e 114 MPa.
8. According to API 650 hydrostatc test stress is minimum of $3/4^{th}$ of yield stress or $3/7^{th}$ of tensile stress. $3/4^{th}$ is minimum i.e. 127.5 MPa
9. Corrosion allowance to be asssumed 3 mm.

3.6.2 Tank shell course thickness calculation

$$t_d = Design\ stress = \frac{4.9 \times D(H - 0.3) \times G}{S_d} + CA$$

$$t_d = \frac{4.9 \times 34(24 - 0.3) \times 1.785}{114} + 3$$

$$t_d = 64.82 \approx 65\, mm \tag{3.21}$$

$$t_t = Hydrostatic\ test\ stress = \frac{4.9 \times D(H - 0.3)}{S_t}$$

$$t_t = \frac{4.9 \times 34(24 - 0.3)}{127.5}$$

$$t_t = 30.96\, mm \tag{3.22}$$

Design Shell thickness is maximum of t_d and t_t i.e.$t_d = 65\ mm$ hence will be selected as shell thickness of storage tanks for further calculation. This shell thickness is for first shell course of 2400 mm width. for height of 24 m requires 10 shell course of 2400 mm thickness. Thickness for remaining shell course is calculated in a simmilar way and is shown in below fig.

No. of course	t_t (mm)	t_d (mm)	Widht of shall course (mm)	Min nom. Thk as per IS 803 Cl	$t_{required}$ (mm)	Provided Thk. (mm)
1st shell course (Bottom of tank)	30.787	64.824	2400.000	6	64.824	65
2nd shell course	27.669	58.563	2400.000	6	58.563	63
3rd shell course	24.552	52.303	2400.000	6	52.303	56
4th shell course	21.434	46.042	2400.000	6	46.042	50
5th shell course	18.316	39.781	2400.000	6	39.781	40
6th shell course	15.199	33.521	2400.000	6	33.521	36
7th shell course	12.081	27.260	2400.000	6	27.260	28
8th shell course	8.963	20.999	2400.000	6	20.999	22
9th shell course	5.846	14.739	2400.000	6	14.739	16
10th shell course	2.728	8.478	2400.000	6	8.478	10

Figure 3.10: Shell course thicknesses for height of 24 m tank

3.7 Basic operating strategy of STPP and storage tank

3.7.1 STPP basic operating strategy

The basic flow diagram (attached) of solar thermal power plant is discussed below. The flow diagram is shown in Appendix.The system basically works as,

1. Initially HTF will be filled in HTF storage tanks, from where it is transferred to expansion vessel. Expansion vessel expands HTF to required temperature, pressure and sends it to solar field via HTF main pumps. solar radiations received in solar field, where HTF gets heated and goes to power block to heat working fluid and goes to TES to heat storage fluid. Solar radiations received are not constant, hence flow rate of HTF is very much depends on solar radiations received. If solar field outlet temperature is fixed the mass flow rate varies according to the solar radiations. HTF after exchanging heat in power block and TES system returns to expansion vessel via HTF filters and cycle repeats.

2. If it is considerd that after completion of first cycle, some amount of TES is available and flow rate of HTF is less due to less DNI. In such case generation of power is not possible.So, if heat from TES system is used to take HTF to required flow rate and temperature, it is possible to generate some amount of power. Extraction of TES will depends on availability of TES.

3. If solar energy is available and power block is under maintainance, in such case some HTF will store excess heat into TES and remaining HTF will be circulated in piping. To deal with such situation we can use two seperate power blocks.

4. In case of winter condition some amount of TES will be used for freez protection and some will be used for power generation depending upon the availability of TES. This will also be depends on the sitution, i.e. if situation needed is freez protection then all TES will be used for freez protection and if power generation is needed TES will be used to generate minimum amount of power. If no TES will be available HTF heaters will be used for freez protection. Solar system will be having seperate freez protection system.

3.7.2 TES system basic Operating strategy

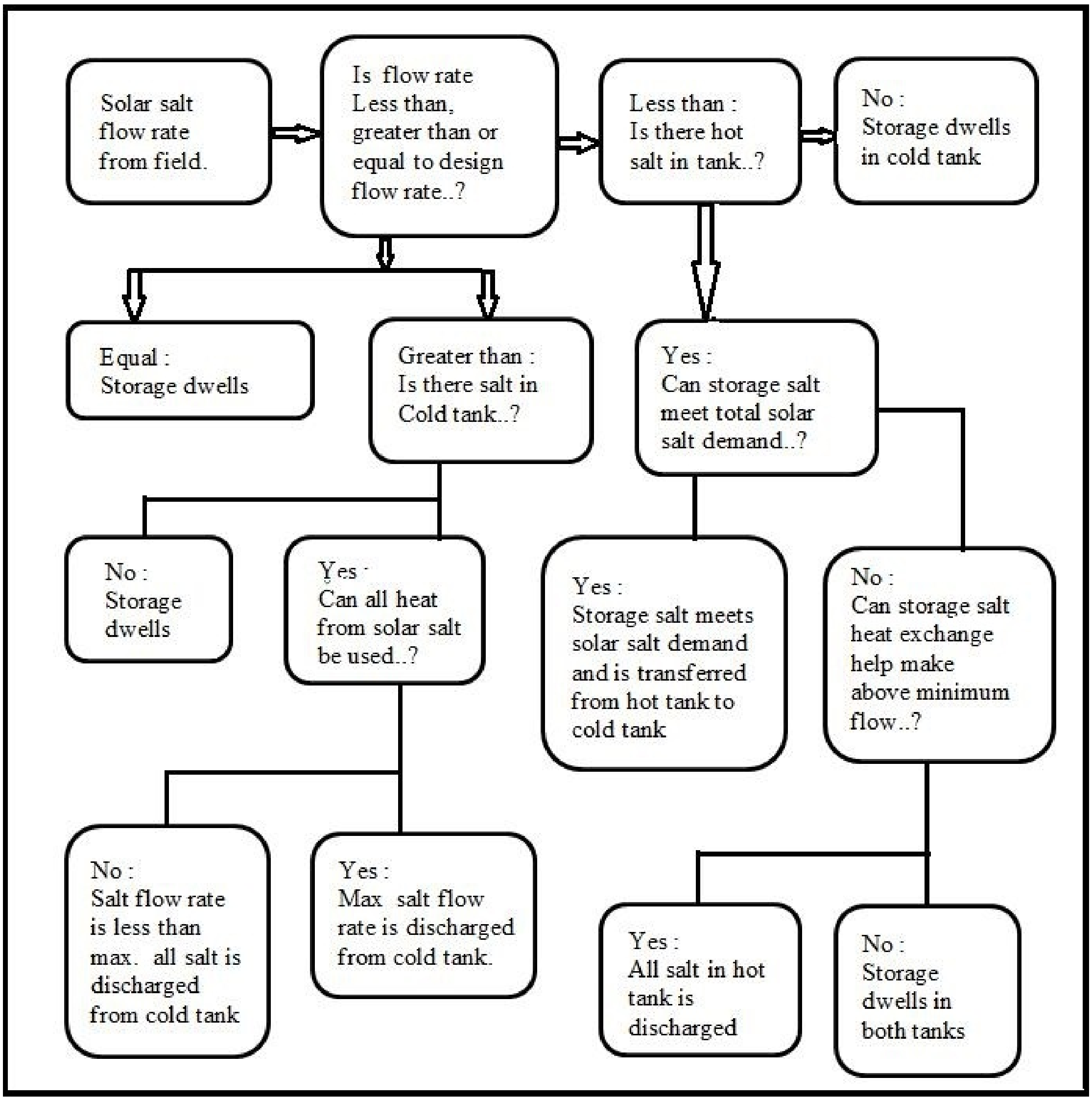

Figure 3.11: Operating strategy of designed storage system [16]

The basic operating strategy for indirect thermal energy storage tank containing eutectic ternary nitrate salt as thermal energy storage fluid and molten salt (solar salt) as heat transfer fluid is depends on the flow rate of HTF from the solar field.

Chapter 4

Insulation design and heat loss calculation

4.1 Thermal Insulation

One of the major concern in case of thermal equipments is gaining of heat or loosing of heat due to effect of atmosphere, which will reduce the performance of the system and losses energy. Provinding insulations for thermal energy equipments will help very well to reduce heat loss or heat gain by the equipment. In case of large storage vessels used for thermal energy storage in solar thermal power plants, providing proper thermal insulation will help to reduces heat transfer between storage vessel and atmosphere providing more time for storing energy in thermal energy storage system. As storage vessels always exposed to atmosphere, designing of proper insulation system will be very essential. For storage tanks, designing of thermal insulation is mainly based on surface operating temperature criteria where selected insulation grade is always exposed to high temperature conditions providing outside surface temperature of insulation not more than 60^0C according to standards used for designing insulation system.Also the selected insulation grade have to minimise heat loss from the vessel to atmosphere as it is amajor concern in case of storage vessel.

Mineral wool is less costly, is best suited for indian conditions and widely used in Indian industrial insulations, therefore mineral wool will be selected as thermal insulation for energy storage tanks in this work. Thickness of insulation required will be calculated considering steady state. Insulation system for various equipments will be designed considering various design considerations for satisfactory performance of the overall system.. Various design considerations for designing thermal insulation were shown in below fig.

CONSIDERATION.	ACTION.
Surface Operating Temperature	Choose insulation grade capable of operating continuously at maximum expected design temperature.
Surface Size and Shape	Choose insulation in appropriate form; semi-rigid board, flexible blanket, pipe insulation.
Heat Transfer and Thermal Conductivity	Select material with low thermal conductivity at design operating temperatures.
Process Control Requirements	Understand the type of process and the control requirements
Economic Thickness of Insulation	Design insulation thickness based on operating temperature, ambient conditions, thermal conductivity of insulation, external surface cladding type.
Personnel Protection	Design for maximum safe temperature of cladding surfaces.
Condensation Control	Design with respect to dew point at expected atmospheric conditions.
Noise Control	Choose insulation of sufficient density and thickness for required noise attenuation to be achieved.
Minimisation of Stress Corrosion Cracking Risk	Use insulation deemed suitable for use with Austenitic Stainless Steel
Fire Protection	Select material with suitable fire resistance for protection of people and equipment.
Moisture Resistance & Water Repellency	Select material with low water absorption.
Mechanical Properties	Ensure dimensional stability, compressive strength, vibration resistance, rigidity or flexibility are satisfactory for purpose.
Durability	Select suitable product for the application and operating conditions.
Environmental and Biological Aspects	Choose environmentally friendly insulation products for ecologically sustainable development.
Installed Cost	Select insulation products and systems for ease of installation and low maintenance.

Figure 4.1: Insulation design cosiderations

4.1.1 Economic thickness of insulation

Thickness of insulation will be calculated by considering steady state condition. Economic thickness is defined as the thickness of insulation which produces the minimum total cost for the period of evaluation i. e. for respective estimated service life of insulation system. Total cost is sum of net present value of heat loss cost and cost of insulation system. These two costs will be shown in graphical way as follows,

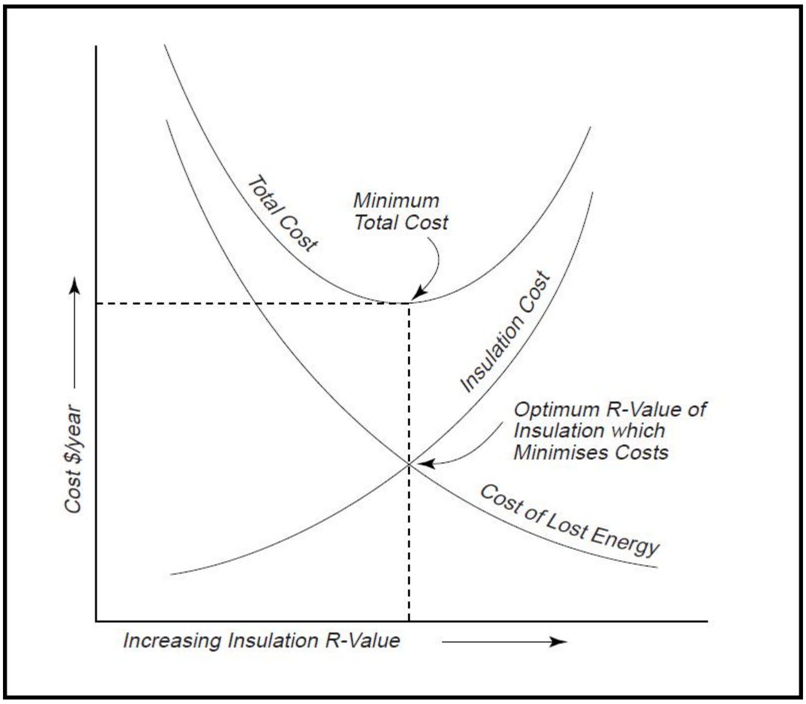

Figure 4.2: Economic thickness of insulation

4.1.1.1 Estimation of thickness of insulation and saving in energy.

Input Parameters

1. Tank outside diameter is equal to 34130 mm
2. Tank outside surface area without insulation 2564 m^2
3. Discouting factor for calculating NPV is 23%
4. Storage salt temperature is 530^0C
5. Ambient temperature 13^0C
6. Heat transfer coefficient assumed for bare surface 25 $W/m^{2\,0}K$
7. Cost of heat energy asssumed 4.325 Rs/kWhr
8. Heat transfer coefficient assumed for insulated surface for three different surface temperatures of 60^0C,55^0C,50^0C is 6.45, 6.2 , 5.9 $W/m^{2\,0}K$
9. Thermal conductivity of mineral wool insulation is 0.17 $W/m\,^0K$
10. Annual working hrs. assumed 8700 hrs.
11. Cost of insulation for 30 mm thickness, 100 kg/m^3 density is about 140 Rs/m^2. The cost of insulation will varywith respect to thickness and density of insulation.

Calculations :- To calaculate economic thickness of insulation three various surface temperatures as 60^0C,55^0C,50^0C were assumed for which thickness of insulation were calculated. Economic thickness of insulation is the thickness of insulation for which total cost i.e. cost of insulation and cost of energy lost will be minimum. For smaller thickness of insulation it is easy to calculate economic thickness because standard thicknesses are available in market. If single layer insulation is considered and thickness of insulation is also high then some assumptions has to be made for calculating economic insulation thickness. Assumption made in current work is, standard thickness of insulation is kept constant as 30 mm and density of insulation varied which results in cost variation.Calculation for the same are shown below,

$$Heat\,loss\,without\,insulation = h.A. \triangle T$$

$$Heat\,loss\,without\,insulation = 25 \times 2564 \times (530 - 13)$$

$$Heat\,loss\,per\,m^2 without\,insulation = 33140\,kW \tag{4.1}$$

$$At\,steady\,state$$

$$Conduction\,heat\,transfer = Convective\,heat\,transfer$$

$$K.A\frac{\triangle T}{\triangle X} = h_{ins}.A. \triangle T$$

$$\triangle X = \frac{0.17 \times (530 - 60)}{6.45 \times (60 - 13)}$$

$$\triangle X = 0.264\,m = 264\,mm \tag{4.2}$$

$$New\ Radius\ of\ tank\ after\ insulation = thickness\ of\ insulation + tank\ radius$$

$$New\ Radius\ of\ tank\ after\ insulation = 17328.7\ mm$$

$$Isulated\ area\ of\ tank = 2 \times \Pi \times r \times h$$

$$Isulated\ area\ of\ tank = 2613\, m^2$$

$$Isulated\ surface\ loss = 6.45 \times 2613 \times (60 - 13)$$

$$Isulated\ surface\ loss = 792\ kW \tag{4.3}$$

$$power\ saved = (33140 - 792) = 32348\ kW$$

$$power\ saved\ per\ yr = 28.14 \times 10^7\ kWhr/yr \tag{4.4}$$

$$Total\ cost\ of\ insulation = \frac{264 \times 140}{30} \times 2564$$

$$Total\ cost\ of\ insulation = \frac{264 \times 140}{30} \times 2564$$

$$Total\ cost\ of\ insulation = 32\ lakhs\ approx \tag{4.5}$$

$$Annual\ cost\ of\ energy\ lost = 792 \times 8700 \times 4.325$$

$$Annual\ cost\ of\ energy\ lost = 3\ Cr. \tag{4.6}$$

$$NPV\ of\ annual\ cost\ of\ energy\ losses\ for\ 5\ yrs. = 82\ Lakhs\ approx \tag{4.7}$$

$$Total\ cost = NPV\ of\ annual\ cost\ of\ energy\ losses + .Total\ cost\ of\ insulation$$

$$Total\ cost = 32\ Lakhs + 82\ Lakhs = 1.1\ Cr \tag{4.8}$$

Values will be calculated for all the three cases in a simillar way as shown in the calculation above and it is found that the thickness of 264mm is having the lowest total cost as compared to value for other thicknesses. According to defination of economic thickness of insulation the thickness which have total cost (cost of NPV of heat loss+cost of insulation)minimum is the economic thickness of insulation. Thus here in this work 264 mm thickness is economic thickness of insulation and will be selected for further work.

4.2 Standby heat losses from storage tanks

Standby heat loss[20] from thermal energy storage tanks and heater size for tank will be calculated using following methodology.

4.2.1 Methodology

1. To calculate the standby heat loss from thermal energy storage tanks, per three hour atmospheric temperature data were selected for Nokh, Rajsthan, India considering winter condition.
2. Air properties were calculated for respective temperatures according to ASTM C680
3. With the help of air properties convective heat transfer coefficient were calculated for respective temperatures.
4. Heat loss for tank wall, tank bottom and tank roof were calculated.
5. Total heat content in the tank for specific tank fluid temperature calcxulated
6. From difference between total heat content and heat loss new tank fluid temperature were calculated.
7. Same procedure is followed to calculate the time required for tank fluid to drop upto certain marginal temperature kept above freezing point temperature..
8. Time caculated will decide whether tank requires heater or not.
9. This heat loss is calculated considering tank is full.

4.2.2 Heat loss estimation

4.2.2.1 Internal convective heat transfer coefficient

Table 4.1: Tank internal convective heat transfer coefficient[20]

Properties	formula	Value	Value	Unit
		$Cold\,tank$	$Hot\,tank$	
ρ		0.9463	0.6875	kg/m^3
Cp		944.24	995.48	J/$kg.K$
K		0.03560	0.04714	$W/m.K$
μ		2.85×10^{-5}	3.33×10^{-5}	$Kg/m.s$
ν		2.81×10^{-5}	4.85×10^{-5}	m^2/s
Pr		0.7019	0.7030	
β		0.00242	0.00176	
Ra	$\frac{g\times\beta\times\rho\times Cp\times\triangle T\times L^3}{\nu\times K}$	1.38×10^{14}	9.88×10^{13}	
Nu_n	$0.15 \times Ra^{(1/3)}$	7154.26	6933.85	
h_i	$(Nu_n \times K)/D$	11.043	8.12	$W/m^{2\,0}K$

4.2.2.2 Properties of air according to ASTM C680

Here calculation were shown for 17^0C i.e 290^0K i.e.62.4^0F, atmospheric temperature.[19]

Thermal conductivity

$$K = \{\frac{6.325 \times 10^{-6}\sqrt{(T_k)} \times 241.77}{[1 + (245.4 \times 10^{12/T_k})/T_k]}\}/0.57782$$

$$K = 0.02334\ W/m.K \tag{4.9}$$

Dynamic Viscosity

$$\mu = \{\frac{145.8T_k \times \sqrt{(T_k)} \times 241.9 \times 10^{-7}}{T_k + 110.4}\}/2419.1$$

$$\mu = 1.80 \times 10^{-5}\ kg/m - s \tag{4.10}$$

Volumetric coefficient of expansion

$$\beta = \frac{1}{1.8 \times T_k}$$

$$\beta = 0.00178 \tag{4.11}$$

Density

$$\rho = \frac{22.0493}{T_k} \times 14.62$$

$$\rho = 1.11159\ kg/m^3 \tag{4.12}$$

Specific heat

$$Cp = \{0.24008 - T_f[1.247 \times 10^{-6} \times T_f(4.0489 \times 10^{-8} - 1.6088 \times 10^{-11} \times T_f)]\}/0.23885$$

$$Cp = 1.00547\ kJ/kg.K \tag{4.13}$$

Prandtl No.

$$Pr. = 0.7189 - T_f[1.6349 \times 10^{-4} - T_f(1.8106 \times 10^{-7} - 5.6617 \times 10^{-11} T_f)]$$

$$Pr. = 0.7093 \tag{4.14}$$

Kinematic Viscosity

$$\nu = \frac{\mu}{\rho}$$

$$\nu = 1.62 \times 10^{-5}\ m^2/s \tag{4.15}$$

Table 4.2: Convective heat transfer coefficient[19]

Properties	formula	Value	Unit
Re_l	$\frac{V \times H}{\nu}$	3.09×10^6	
Re_D	$\frac{V \times D}{\nu}$	4.25×10^6	
Ra	$\frac{g \times \beta \times \rho \times Cp \times \triangle T \times L^3}{\nu \times K}$	3.48×10^{10}	
Gr	$Ra * Pr$	4.91×10^{10}	
Nu_n	$\{0.825 + \frac{0.387 Ra^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\}^2$	149.3	
Nu_f	$0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}[1 + (\frac{Re_D}{282000})^{5/8}]^{4/5}$	4448.41	
Nu	$0.3 + ((Nu_f - 0.3)^4 + (Nu_n - 0.3)^4)^{(1/4)}$	4448.42	
h_c	$\frac{Nu \times K}{L}$	4.154	W/m^2K
h_r	$\epsilon \times б \times 4 \times T_f \times (1 + ((Ts - Ta)/(Ts + Ta))^2)$	1.338	W/m^2K
h	$h_c + h_r$	5.53	W/m^2K

4.2.2.3 Heat loss and temperature drop estimation

Input Parameters.

1. Per three hour atmospheric temperature data for Nokh, Rajsthan.
2. Tank fluid temperature is 530ºC
3. Tank wall thickness is 65 mm and tank internal diameter is 34 m
4. Thickness of insulation and conductivity of insulation material is 264 mm and 0.17 W/m.ºK respe.
5. Thickness and conductivity of sand used at bottom is 75 mm and 0.4 W/m.ºK
6. Internal convection heat transfer coefficient at mean temperature$8.12\, W/m^2\, ^oK$
7. Area of tank $3622\, m^2$.

Heat loss through wall of the tank

$$Q_{wall} = \frac{(T_{tank\, fluid} - T_{amb})}{R_{isulation} + R_{convection}}$$

$$Q_{wall} = \frac{(230 - 17)}{\frac{0.264}{0.17} + \frac{1}{5.53}}$$

$$Q_{wall} = 122.854\, W/m^2 \tag{4.16}$$

Heat loss through bottom of tank

$$Q_{bottom} = \frac{(T_{tank\, fluid} - T_{ground})}{R_{inultion} + R_{sand}}$$

$$Q_{bottom} = \frac{(230 - 20)}{1.7404}$$

$$Q_{bottom} = 120.687\, W/m^2 \tag{4.17}$$

Heat loss through roof of tank

$$Q_{roof} = \frac{(T_{tank\, fluid} - T_{amb})}{R_{internal\, convection} + R_{conduction} + R_{outside\, convection}}$$

$$Q_{roof} = \frac{(230 - 17)}{1.8243}$$

$$Q_{roof} = 116.945\, W/m^2 \tag{4.18}$$

Total heat loss

$$Q_{total} = Q_{wall} + Q_{bottom} + Q_{roof}$$

$$Q_{total} = 360.159\ W/m^2 = 360.159 \times 3564 = 1283.60\ kW = 13862918.81\ kJ \tag{4.19}$$

Total heat content in tank in kJ at 230ºC

$$Heat\,content\,in\,tank = 1.368 \times 10^{10} kJ \tag{4.20}$$

After 3 hrs. heat content in tank

$$After\ 3\ hr\ heat\ content = (heat\ content\ in\ tank)_{at\,fluid\,temp} - Heat\,loss$$

$$heat\ content\ after\ loss = 1.367 \times 10^{10}\,kJ \tag{4.21}$$

$$New\ storage\ salt\ temperature = \frac{heat\ content\ after\ loss}{m_{storage\ salt} \times Cp_{storage\ salt}}$$

$$New\ storage\ salt\ temperature = \frac{1.367 \times 10^{10}}{35000000 \times 1.63}$$

$$New\ storage\ salt\ temperature = 229.74^0C \tag{4.22}$$

$$Drop\ in\ temperature = (230 - 229.74) = 0.26^0C\ per\ 3\,hrs.$$

Above temperature drop is for every three hours as heat loss were calculated for every three hours. Generally heat loss will vary according to the atmospheric temperatures. If atmospheric temperature is too low heat loss will be more resulting higher daily temperature drop and vice versa. Similar calculations were performed on excel to find out time required to drop temperature from 230^0C to 127^0C i.e cooling down time upto solidification temperature of storage salt of cold storage tank. In the same way calculation can be done for hot storage tank. Calculation performed here are considering tank is fully filled. Time required is around 59 days which is little more than the time calculated in literature for another system because time calculated in literature is calculated by considering tank is filled half of its capacity and time calculated in this work is considering tank is fully filled upto its capacity. Heater will be used to maintain the minimum required temperature in the cold storage tank in case of standby mode due to various conditions which causes temperature drop in the tank. Heat loss calculations carried out in this work shows that there is no any requirement of heater as temperature drop which is calculated considering weather data is not major. Though heater will be placed in the storage tank for saftey purpose. 1.3 MW is the maximum heat loss calculated with respect to weather data and that will be the size of the heater. Heater will also be used if storage salt in the tank solidifies due to long standby period of tank.

Chapter 5

Result and Discussion

- **Result comparison**

  The hot and cold thermal energy storage tanks used in solar thermal power plant will be identical with only the temperature of salt varying. Each storage tank is assumed to be fully mixed thermally. Fluid contained in the tank have capability to completely fill and empty the tank but in real case salt neither fully discharge nor fully fill the storage tanks.[23]. For relative increase in thermal energy storage tank volume and tank area will change. Andasol 1 CSP project working in spain having gross turbine capacity of 50 MW with 7.5 hrs of thermal energy storage in which molten salt is thermal energy storage fluid and dowtherm A is HTF will be compared with our result. our result shows good confirmity with Andasol 1 and the comparative result is as shown in below table.

Table 5.1: Result compoarison with Andasol 1 CSP Project

Property	Andasol 1 [24]	Current thesis work
Gross turbine capacity	50 MW	50 MW
Storage salt	Solar salt	$LiNO_3 - KNO_3 - NaNO_3$
HTF	Dowtherm A	Solar salt
Operating temp. (HTF)	$12^0C - 400^0C$	$238^0C - 600^0C$
Operating temp.(Storage)	$293^0C - 393^0C$	$230^0C - 530^0C$
Storage method	Two tank indirect	Two tank indirect
Storage time	7.5 hrs.	16 hrs.
Amount of salt	28,500 Tonnes	35,000 Tonnes
Height of tank	14 m	24 m
Diameter of tank	36 m	34 m

- **Discussion**

  Comparative results were shown in above table. Our system is different in aspect of HTF used and Storage salt used. Storage salt used for designing the system in this work is having higher energy density and better thermodynamic properties than solar salt. Energy density is defined as amount of energy stored per unit volume. Higher the energy density less will be the storage volume of the system which results in reduced amount of storage material. Diameter and height of tank will vary according to storage capacity and volume of the tank required. Heat loss and other data related to Andasol one were not accessable. Cool down time calculated in our currently designed system is around 59 days for fully filled tank of capacity of 16 hrs. storage. The data in the literature is 46 days for a half full tank with capacity of 7 hrs.[16]

Chapter 6

Conclusion and Scope for future work

Conclusions

Sensible heat storage with two tank indirect thermal energy storage system is well matured and industry ready technology. Current system using solar salt as TES material and oil as HTF have high freezing point and low operating range of temperatures which leads to developements of new HTF as well TES material. Many developements were done with respect to HTF and TES materials. Ternary eutectic salt $LiNO_3 - KNO_3 - NaNO_3$with low melting point and better stability at higher temperatures ranging from 116^0C-127^0C for various compositions were developed by researchers with potential for HTF and TES. As TES system is one of the prominant part of STPP its designing plays vital role in designing of whole system. Here basic designing of tank with various liquid level sizing were done. Design is based on guidelines provided in API 650 and own standards of company provided for carring out this work. Results will be compared with the currently working plant and are in good agreement. Insulation requirement and heat loss calculation were done to find requirement of heater in the tank. Heat loss calculations carried out in this work are with respect to atmospheric temperatures of winter conditions for Nokh, Rajsthan. Size of heater will be decided by calculating cool down time of storage salt from its minimum required temperature in the cold storage tank to its solidification temperature. Heat loss will be changed according to weather conditions and cool down time is based on heat loss. Whichever is the maximum heat loss for atmospheric temperature that will be the size of heater.

- Use of $LiNO_3 - KNO_3 - NaNO_3$ salt as TES material and solar salt as HTF material will increase the operating temperature of TES system.
- Higher energy density of selected salt optimizes the design parameters of tank and amount of storage salt required for 16hr. thermal energy storage.

- Tank diameter calculated is 34 m and height is 24 m with amount of salt required as 35000 Tonnes.
- Economic thikness of insulation is about 264 mm if single layer of mineral wool insulation is considered.
- Cool down time for cold storage tank salt were computed from 230ºC -127ºC. Cool down time is calculated by considering standby heat losses for fully filled cold storage tank. Cool down time is around 59 days.
- Heater will be used to maintain minimum required temperature in cold storage tank. No heater will be required for current perticular case as temperature drop is not major. Even though heater will be placed in a tank for saftey purpose.

Possible future work

1. Review of various thermal energy storage materials developed.
2. Detail study of charging and discharging system in storage tanks.
3. Economic analysis of storage system designed.
4. Design optimization of system.
5. Solar field designing for currently designed system.
6. Calculation of heat loss and cool down time to decide size of heater when tank is filled 75% or less.

Bibliography

[1] Central Electricity Authority, India website.

[2] Atul Sharma," A comprehensive study of solar power in India and World", Renewable and Sustainable Energy Reviews-15, pp 1767-1776, Elsevier, 2010

[3] O. Ercan Ataer, "Storage of thermal energy", Energy storage system,Vol-I

[4] E. Hahne, "Storage of sensible heat", Energy storage system, Vol-I

[5] Sarada Kuravi, Jamie Trahan, D. Yogi Goswami, Muhammad M. Rahman, Elias k. Stefanakos, "Thermal energy storage technologies and systems for concentrating solar power plants". Progress in energy and combustion science, pp. 285-319, Elsevier, March 2013.

[6] D. Kearney, B. Kelly, U. herrmann, R. Cable, J. Pacheco, R. Mahoney, H. Price, D. Blake, P. Nava, N. Potrovitza. "Engineering aspects of molten salt heat transfer fluid in a trough solar field", Energy-29, pp 861-870, Elsevier, 2003

[7] Robert W. Bradshaw, Nathan p. Siegel, "Molten nitrate salt development for thermal energy storage in parabolic trough solar power system", Energy Sustainibility, ASME, 2008

[8] R.W. Bradshaw, D. E. Meeker, "High temperature stability of ternary nitrate molten salts for thermal energy systems", Solar energy materials-21, pp.51-60, Elsevier, 1990

[9] Rene I. Olivares, William Edwards, "$LiNO_3$-$NaNO_3$-KNO_3 salt for thermal energy storage : Thermal stability evaluation in different atmospheres", Thermochimica Acta-560, pp.34-42. Elsevier, March 2013.

[10] Satish Mohapatra, Alparslan Oztekin, Sudhakar Neti, "Thermophysical properties of $LiNO_3$-$NaNO_3$-KNO_3 mixtures for use in concentrated solar power", Solar energy engineering, ASME, August 2013

[11] D.W. Jeppson, J.L. Ballif, W.W. Yuan, B.E. Chou., "Lithium literature review: Lithium's properties and interactions", Hanford engineering development laboratory, April 1978

[12] Wei-Jen Cheng, Ding-Jhih Chen, Chaur-Jeng Wang. "High-temperature corrosion of Cr-Mo steel in molten $LiNO_3$-$NaNO_3$-KNO_3 eutectic salt for thermal energy storage", Solar energy materials and solar cells-132, pp 563-569, 2015.

[13] Dr. Ramana G. Reddy, "Novel molten salt thermal energy storage for concentrating solar power generation", Technical report, US DOE, 2013.

[14] Ramana G. Reddy, "Molten salt thermal energy storage materials for solar power generation".2013

[15] Christian Suarez, Alfredo Iranzo, F.J. Pino, J Guerra, "Transient analysis of the cooling process of molten salt thermal storage tanks due to standby heat loss", Applied energy-142, pp 56-65, January 2015

[16] Mr. Joseph E. Kopp, "Two tank indirect thermal storage design for solar parabolic trough power plants".,Thesis, University of Nevada Las Vegas, 2004.

[17] API Standard 650, "Welded Tanks for Oil Storage", Twelfth edition, March 2013.

[18] IS 803, "Code of practice for design, fabrication and erection of vertical mild steel cylindrical welded oil storage tanks", 1976

[19] ASTM C680, "Standard practice for estimate of the Heat Gain or Loss and the Surface Temperatures of Insulated Flat, Cylindrical, and Spherical Systems by Use of Computer Programs", 2014

[20] Yunus A. Cengel, Afshin J. Ghajar,"Heat and Mass transfer : Fundamentals And Applications, 5Th Edition", Mc Graw Hill, India

[21] S.P. Sukhatme, "Solar Energy: Principles Of Thermal Collection and Storage".

[22] ASTM A240, "Standard Specification for Heat-Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels", ASTM , 2001.

[23] Schulte-Fischedick, Jan, et al., 2008, "CFD Analysis of the Cool Down Behaviour of Molten Salt Thermal Storage Systems," ASME, Proceedings of ES2008, Jacksonville, FL.

[24] https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3.

Appendix

1. Power block HBD
2. Flow diagram for STPP with two tank indirect thermal energy storage system.