ENERGY AND EXERGY ANALYSIS OF SOLAR POWER TOWER PLANT BASED ON NANOFLUID

A dissertation

Submitted in the partial fulfilment of requirement for the award of degree of

Master of Technology

In

Thermal Engineering

Submitted by:

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I **Shubham Jindal**, Roll no. **2k17/the/15** student of **M.TECH** with specialisation in **"Thermal Engineering"** hereby declare that the project dissertation titled **"Energy and exergy analysis of solar power tower plant based on nanofluid "** which is submitted by me to the Department of **Mechanical Engineering**, **Delhi Technological University, Delhi** in the fulfilment of the requirement of the award of the degree **of Master of Technology** is original and not copied from any source without proper citation. This work has not previously formed the basis of the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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ABSTRACT

The evolution of nanofluid with good specific heat capacity and thermal conductivity makes it use in solar thermal powerplant. This work present the theoretical framework of energy and exergy analysis of solar tower powerplant with molten salt nanofluid as the heat transfer fluid in the central receiver. Several design parameters are also consider like direct normal irradiation (DNI), concentration ratio, receiver outlet temperature. The result show the variation of receiver efficiency, receiver exergy efficiency and overall system efficiency, receiver exergy efficiency with DNI, concentration ratio and receiver outlet temperature. And the receiver and overall system efficiency are also compared to eachother. This work also compare the energy efficiency and exergy efficiency of various solar tower powerplant subsystem of molten salt nanofluid with the pure molten salt.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

$\dot{E}_{input}$	Rate of energy input
$\dot{E}_{output}$	Rate of energy output
$\Delta\dot{E}_{system}$	Rate of change in energy of the system in steady flow
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{X}$	Exergy (kW)
$\dot{q}$	Direct normal radiation (DNI) (kW/ m^2)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ $kg^{-1}K^{-1}$)
A_h	Area of heliostat field (m^2)
d	diameter
T	temperature (K)
IR	Irreversibility
c_p	Specific heat capacity of molten salt
r	Receiver
k	Thermal conductivity

Greek letters

η	efficiency
ρ	density (Kg/m^3)
$\sum$	represents sum of
σ	Stefan's Boltzmann constant
μ	viscosity
δ	Tube thickness

Subscripts

I	First law efficiency
II	Second law efficiency
r	Receiver
l	loss
r,s	Receiver surface
conv	Convection loss
em	Emissive loss
ref	Reflective loss
con	Conduction loss
a	Ambient condition
sg	Steam generator system
s	steam
o	Outer
i	Inner
ms	Molten salt

CHAPTER 1

INTRODUCTION

1.1 World Energy Scenario

Today Global energy is dependent on fossil fuel which are depleting day by day and last for next 50 years only but energy consumption is increasing day by day due to the growth in industrialization, population and urbanization. So it becomes necessary to find some other sources of energy for our future requirement. The pattern for consumption of several. energy sources, including both conventional & renewable, will play an vital role in sustainable growth. At present-day, 80% of the energy come from fossil fuel (like coal, petroleum and natural gas) which also cause degradation of environment by emission of harmful pollutant like greenhouse gases (CO_2) which in turn causes global warming. Also, petroleum derivative vitality sources are in charge of an expanding pace of environmental change, and creating nations particularly should look for clean and renewable source of energy like solar, wind, tidal, etc.[1]

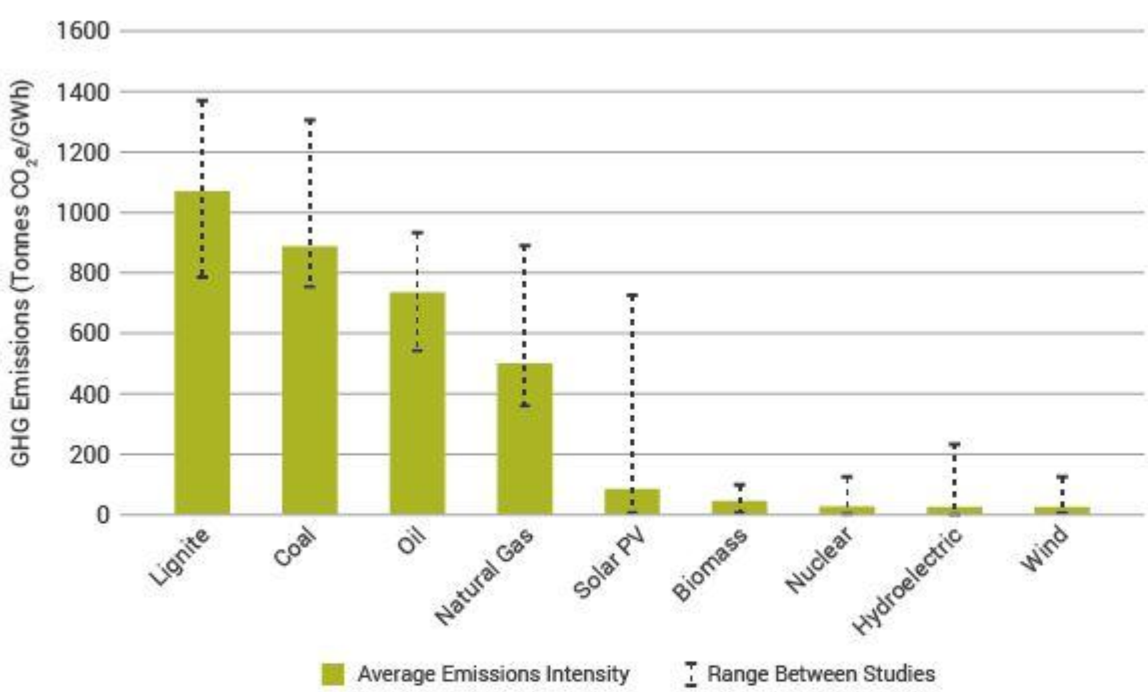

Fig 1 – Greenhouse gas emission [6]

Let we see the energy scenario of the world in the following existing energy sources –

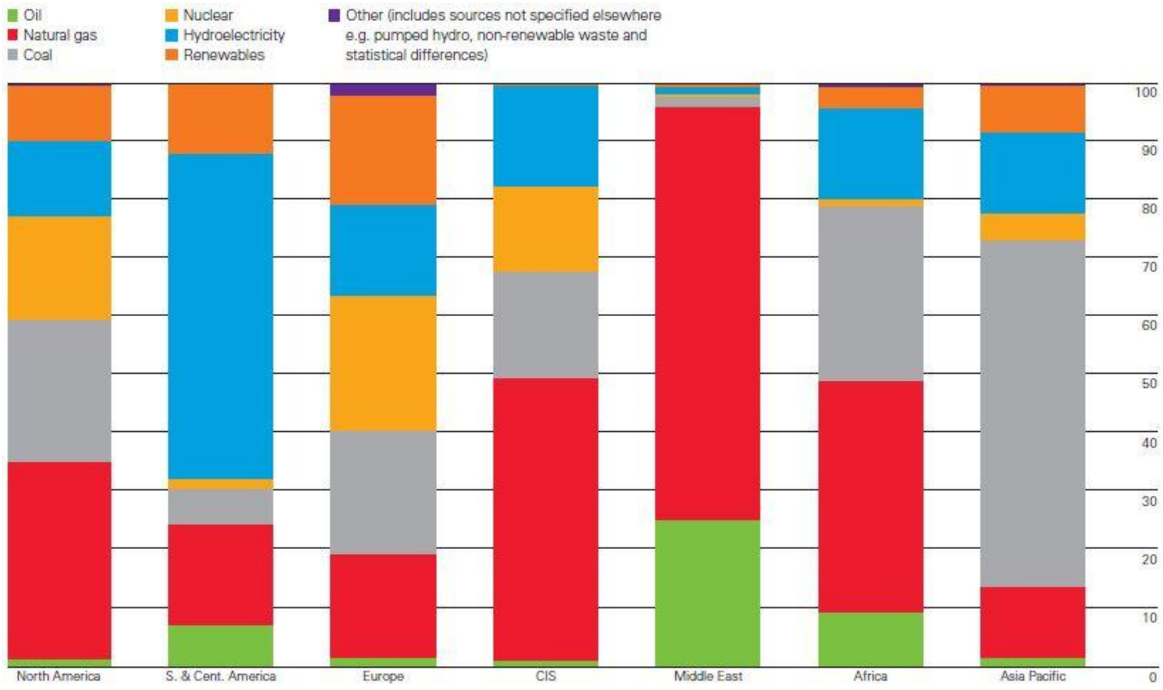

Fig 2 – World energy scenario 2019 in percentage [2]

1.1.1 COAL

It is the most inexhaustible of all petroleum derivative .The world devours around 7800 mn huge amounts of coal which is utilized by different segments like power age, iron, and steel creation and as a fluid fuel. World 33% vitality generation is subject to coal. The real piece of coal is utilized in the generation of power that uses steam coal or lignite or iron and steel creation that utilizing coking coal.

The major of world vitality extraction is subject to coal and its job is set to proceed. Coal as of now shares 40 % of the world's power and is gauge to supply vitality share for the following three decades. The biggest coal delivering nations are not restricted to one locale. The main five makers are [2]-

- China
- USA
- India

- Indonesia
- Australia

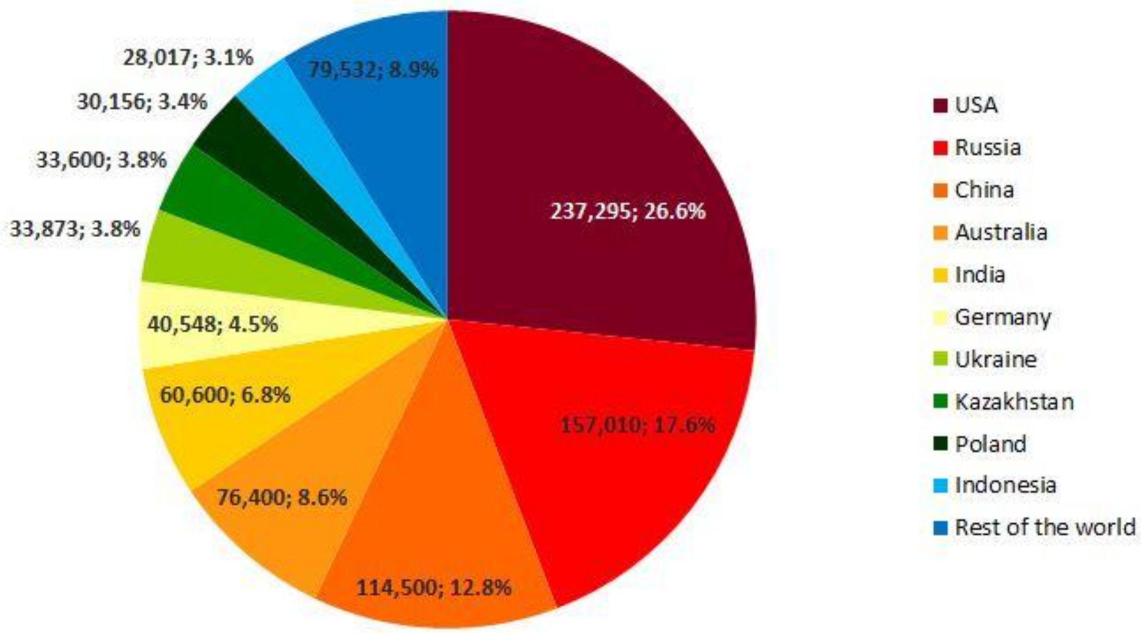

Fig 3 – World coal reserve 2019 [3]

Coal is the large emitter of greenhouse gases which causes global warming and air pollution. But despite of these coal will continue to be the largest source of extraction of power generation.

1.1.2 MINERAL OIL

It is occur under the bed of rocks and various types of fuel refined from it by the distillation process. Petroleum is the main fuel derived from it and used for electricity generation. Today electricity generation consist of 0.2% from the petroleum coke and produces 9 billion KWh of electricity annually in 2018.

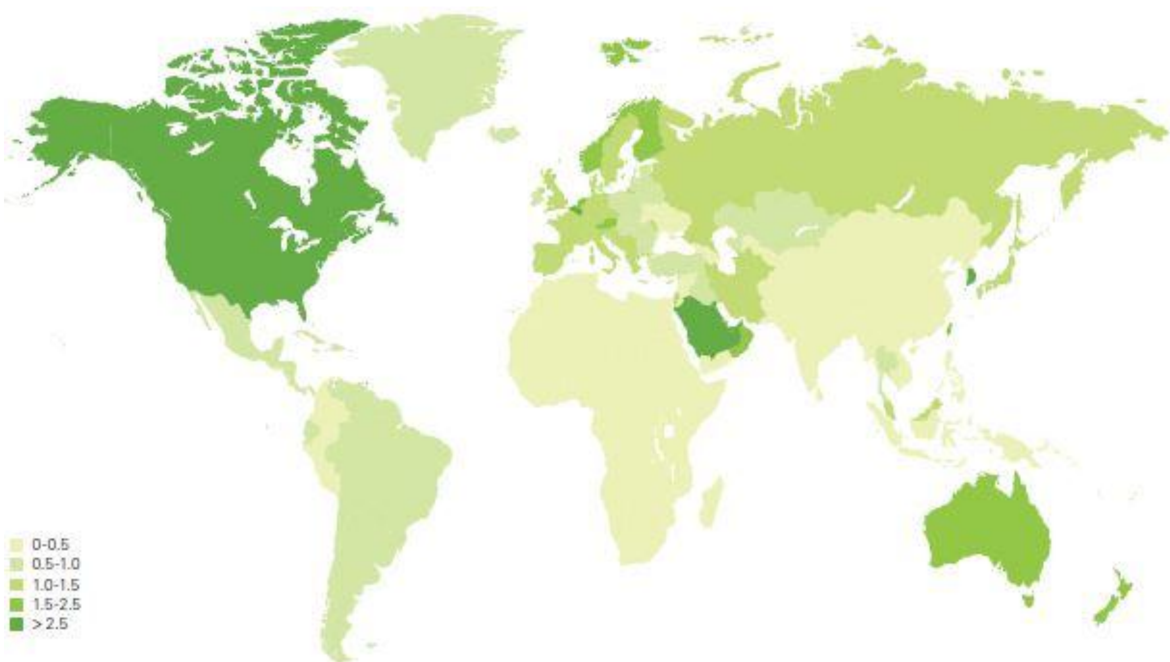

Fig- 4 Oil consumption per capita in tonnes (2019) [2]

1.1.3 Natural Gas

It is a hydrocarbon gas mixture consisting of mostly of methane. Natural gas is framed when layers of decomposition of plant and creature are exposed to extreme warmth and weight under the surface of the earth for the million of year. It is found more deeper in the earth crust than the coal. So in this way the energy obtained by the plant is stored in the form of chemical bond in the gas. It is a non – renewable form of energy and it is used as a energy source for heating, cooking and power generation .But natural gas is the major cause of global warming .There are two types of natural gas , defined by their methane content that reflect in the formation process :

- Biogenic Gas
- Thermogenic Gas

The top three countries which have largest reservoir of natural gas –

- Russia
- Iran
- Qatar

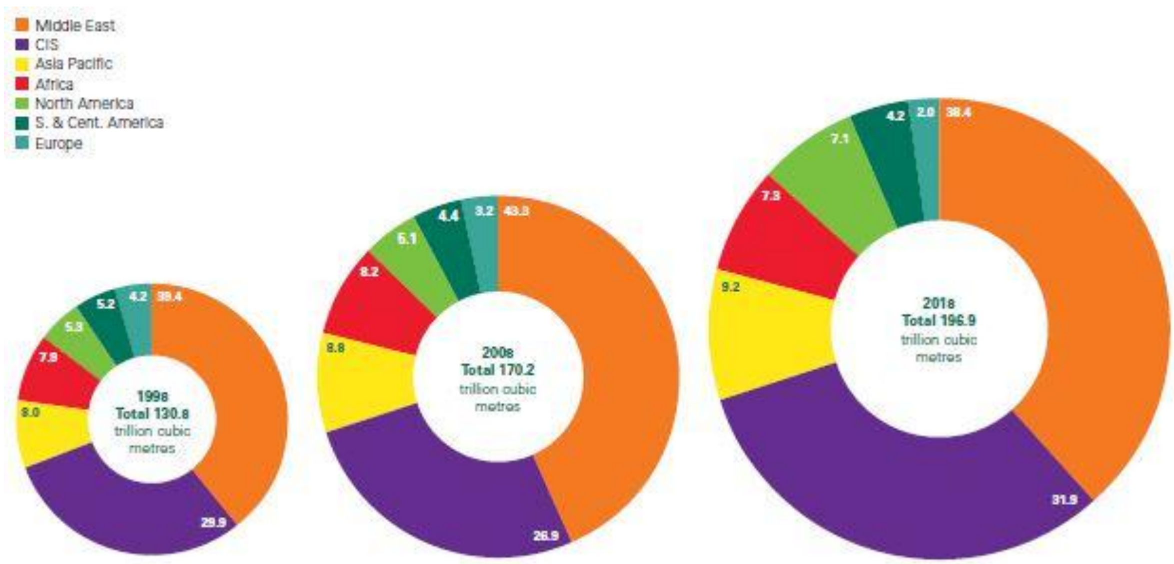

Fig 5 – Natural gas scenario [2]

1.1.4 Nuclear power

It is a clean & efficient way to produce electricity. The nuclear reaction emit high heat which is used to heat the water and produces steam ,than this steam is used to run the turbine which generate electricity. Nuclear energy provided 17% share of the total electricity generation. The main problem associated with nuclear power generatiom is the dumping of the radioactive waste which is now a big concern for all the countries.

The leading nation in nuclear power generation are-

1.) USA
2.) France
3.) Russia

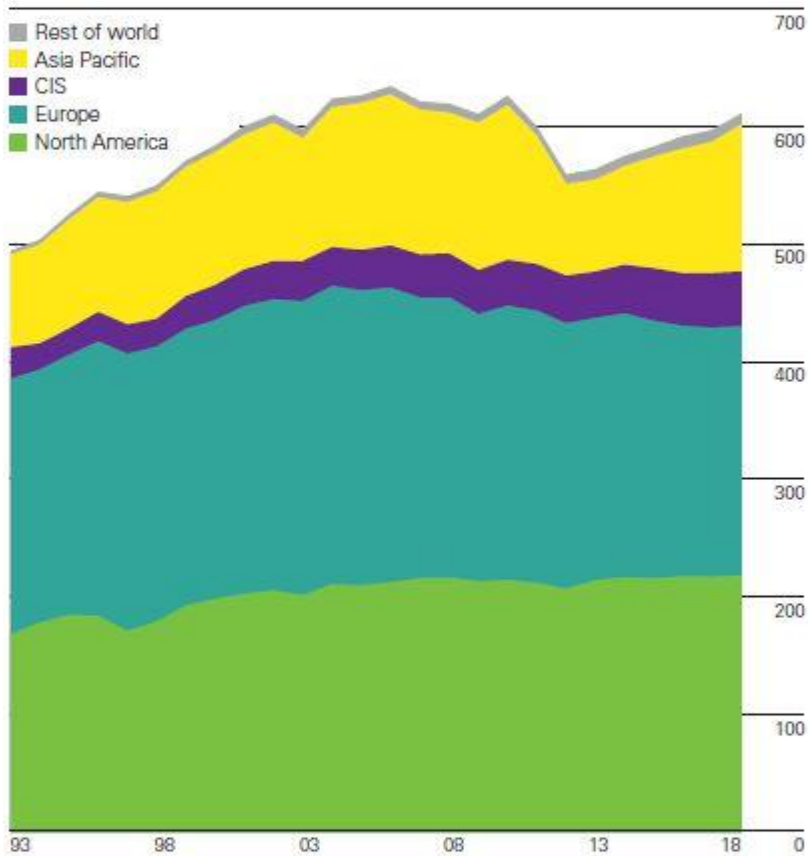

Fig 6 – Nuclear energy consumption in million tonnes oil equivalent [2]

1.1.5 Hydroelectric Power

In this the stored energy of water (by the construction of dams) i.e. potential energy is converted into kinetic energy of the turbine by passing it through the blades. It is renewable form of energy and doesn't produces any greenhouse gases. In 2017, electricity generated by hydropower is 4185 terawatt (TWh)[2].

The top three countries which produces electricity by hydropower are –

a.) China

b.) Brazil

c.) Canada

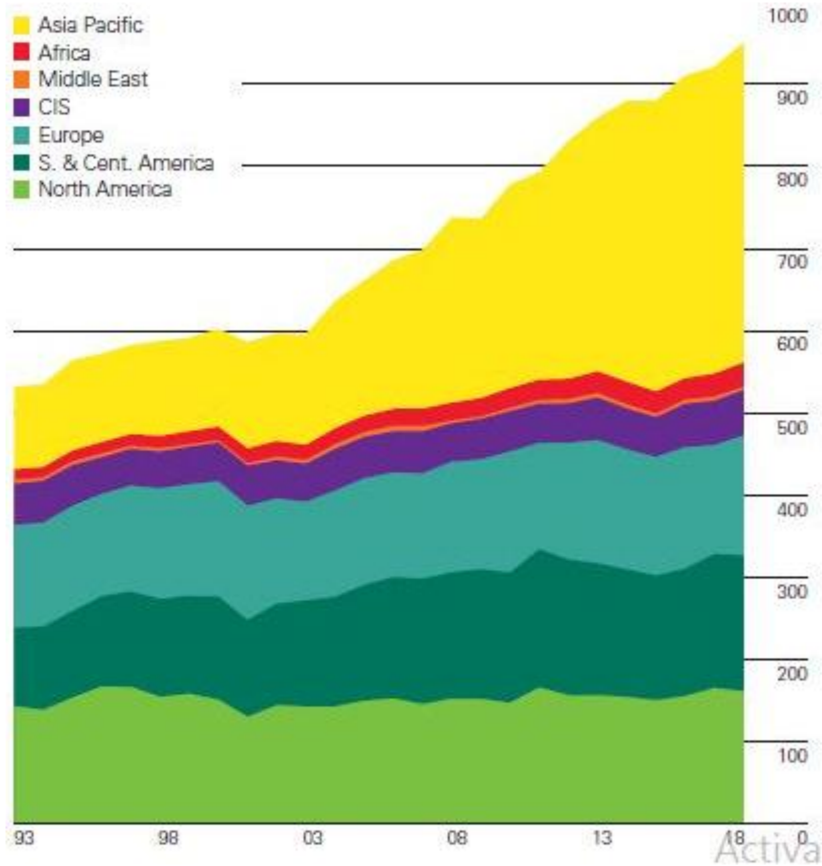

Fig 7 – Hydroelectric consumption in million tonnes oil equivalent [2]

1.1.8 WIND ENERGY

The dependence on energy scenario is increasing day by day in coastal countries. The future scenario i.e. by 2030,of wind energy is given in table below

	Installations (GW)			Generation (TWh)			EU electricity demand met by wind energy (%)		
	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total
Low Scenario	206.3	44.6	250.9	440.2	164.2	604.5	13.8%	5.2%	19%
Central Scenario	253.6	66.5	320.1	533.1	244.5	777.7	16.7%	7.7%	24.4%
High Scenario	294.0	98.1	392.1	627.5	360.8	988.3	19.7%	11.3%	31%

Fig 8 – Wind energy scenario [1]

1.1.6 OCEAN ENERGY

However extraction of electricity from ocean shares a very small percentage. The present scenario is given below

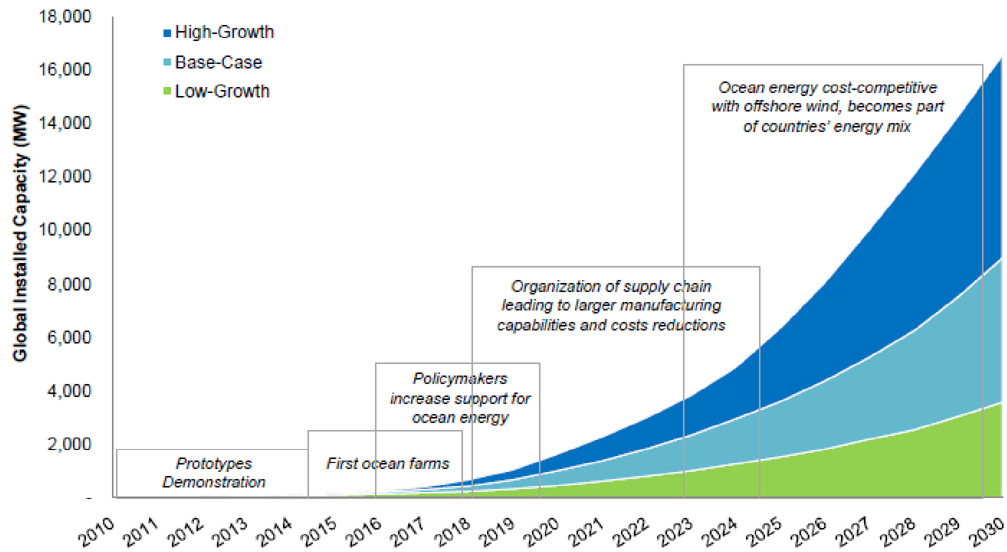

Fig 9 – Ocean energy scenario [2]

1.1.7 SOLAR ENERGY

The overall scenerio of all the electricity producing sources are given below inculding solar thermal electricity generation

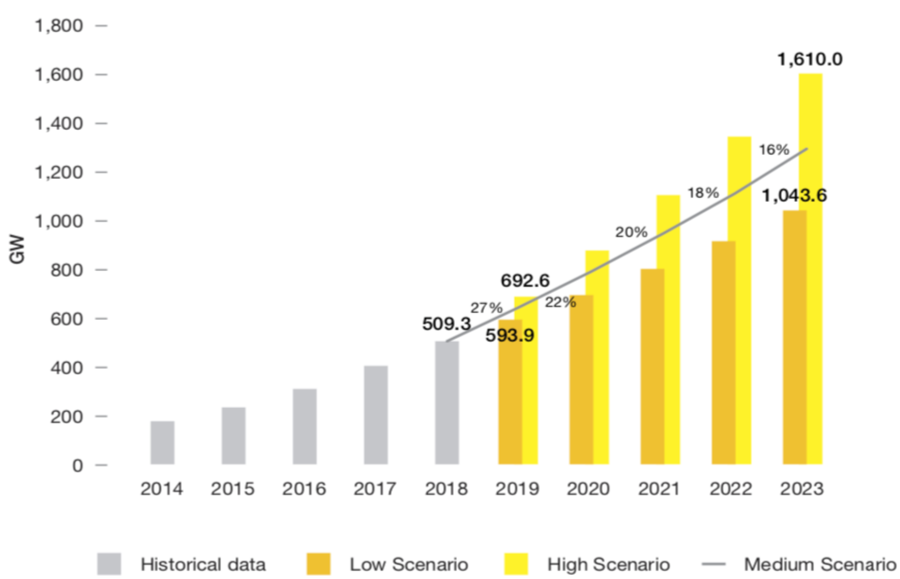

Fig 10 – Solar energy scenerio [4]

1.2 INDIA ENERGY SCENERIO

India is the third largest electricity producer in the world . The total electricity generation till may 2019 is 356.8 GW. The electricity generation (GW)from the various sources are-

	Coal-	194.44
India	Oil –	0.637
hold	Natural Gas-	25
7th	Nuclear -	6.78
rank	Hydropower-	45.4
in	Renewable energy-	78.36

hydropower generation. India has 111 gigawatt (32%) installed capacity of renewable energy and set a target for renewable energy of 175GW by 2022. This would comprise 100 GW capacity from solar energy, 60GW from the wind power ,10GW from the biopower and 50 GW from the small hydropower.[5]

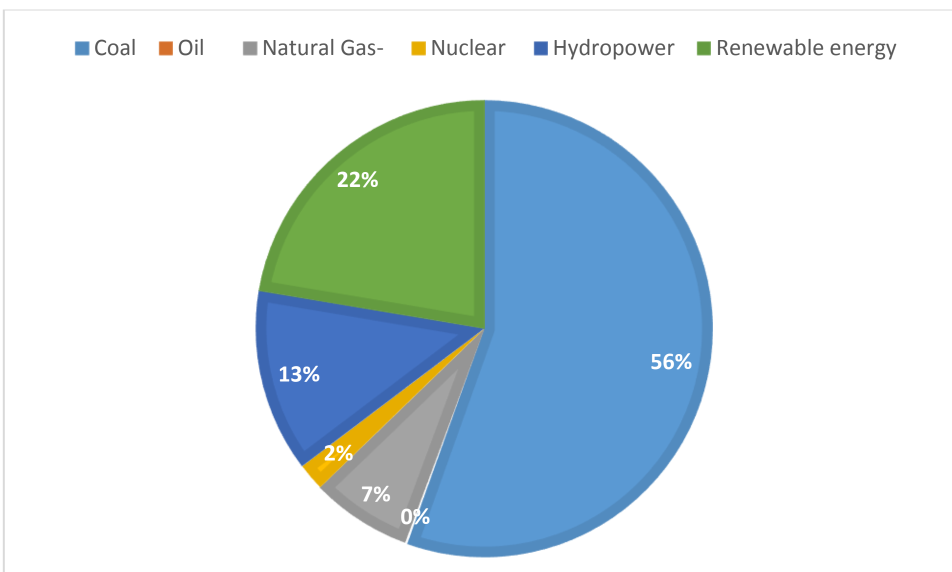

Fig 11 – Electricity generation percentage share by various sources

1.3 FUNDAMENTAL OF SOLAR ENERGY

All substance in any state (solid, liquid or gas), at temperature beyond absolute zero emit energy in form of the electromagnetic waves. This energy is called a radiation. The sun is the source of radiation for earth and several fusion reaction on sun are the reason for these radiation .The black body temperature of sun is 5762 K.

The energy produce in the interior of the solar space gave rise to a temperature of numerous million degrees and this energy is radiated out to the surface and radiated into space .The radiation in sun core may be in the x-ray and gamma ray portions of the spectrum with wavelength of the radiation increases as the temperature drops.

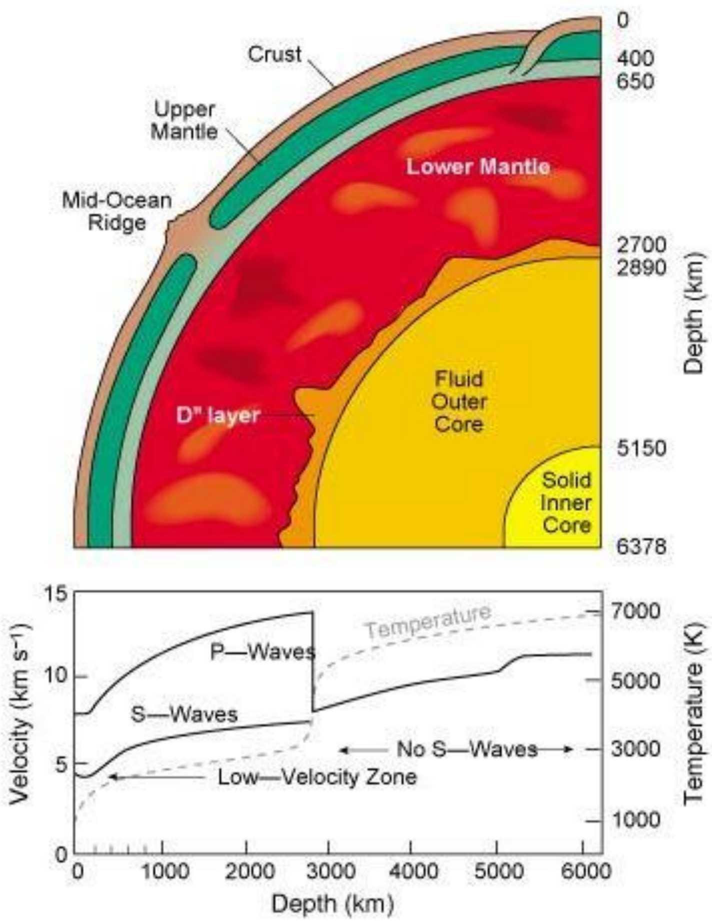

Fig 12 – Structure of sun [9]

The eccentricity of the earth's orbit is such that the distance between the sun & earth varies 1.4% .At a distance of one astronomical unit $1.495x10^{11}$m, the sun projects an angle of 32' on the earth. The sun discharged radiation and its spatial relationship to the earth bring about nearly fixed power of radiation outside the earth air. The solar constant I is the energy per unit time got on a unit region of the surface opposite to the bearing of spread of the radiation at the world's mean good ways from the sun outside the environment [8]

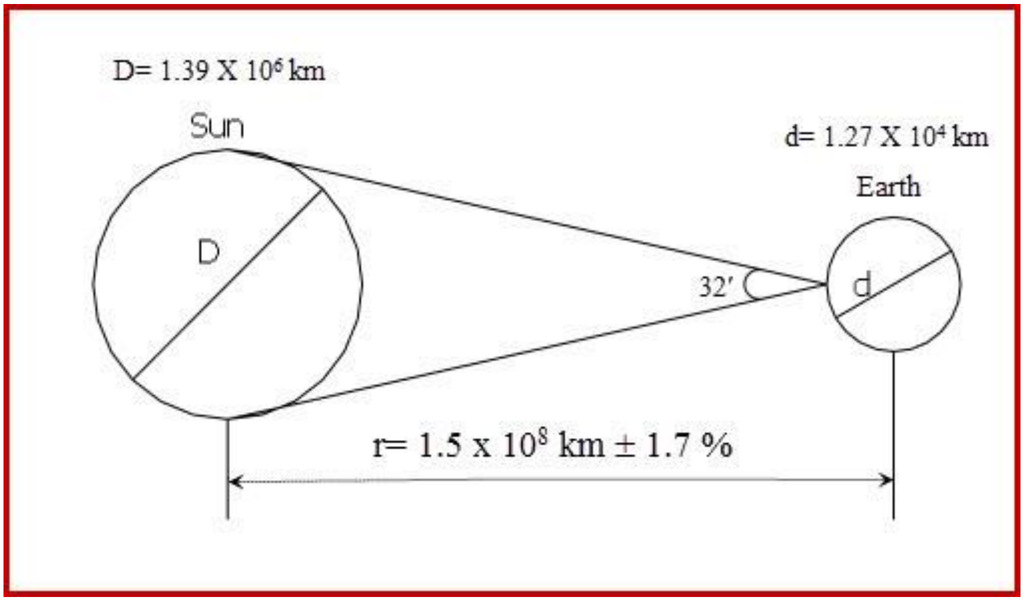

Fig 13 – Sun-earth relationship [10]

1.3.1 Spectral distribution of extraterrestrial radiation-

So in addition to the total energy received by the earth surface it is necessary to know the extraterrestrial radiation, i.e. radiation received by the earth in the absence of the atmosphere.

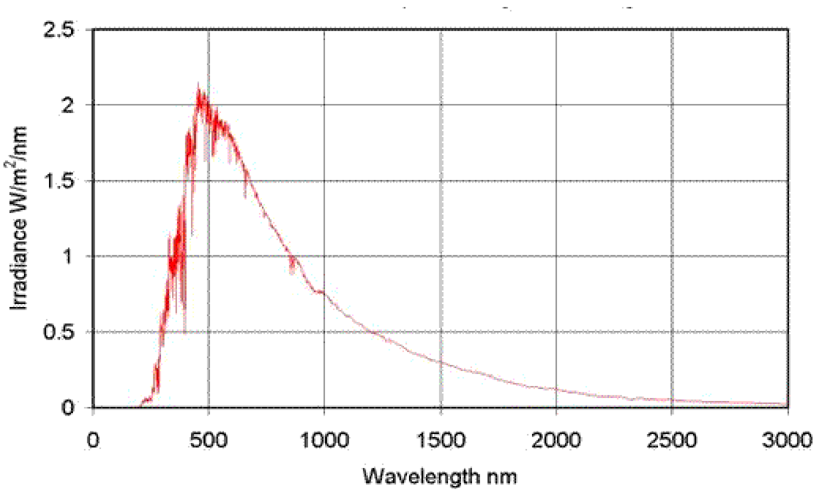

Fig 14- Extraterrestrial solar spectrum [11]

1.3.2 Variation of Extraterrestrial radiation

There are 2 causes for variation in the extraterrestrial radiation-

- Variation in the radiation emitted by sun. According to various report the radiation variation are very low ,approximately (less than $\pm$ 1.5percent)
- The second cause is variation in the earth-sun distance which lead to variation in extra-terrestrial radiation flux in the range of $\pm$ 3 percent.[8]

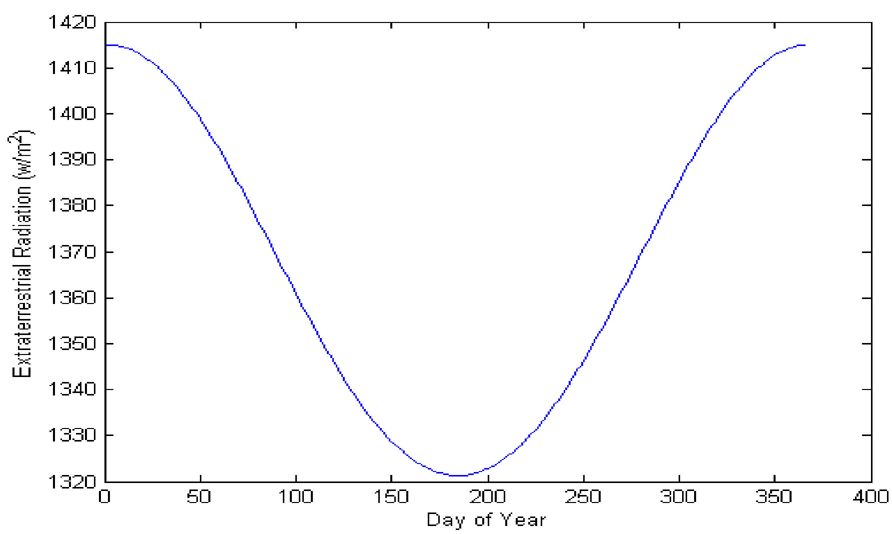

Fig 15 – Annual variation of extra-terrestrial radiation [12]

1.3.3 Basic Earth – Sun Angles

The solar radiation vary during the daytime and also along with the year.So it is necessary to have a knowledge of sun position in the sky at a particular time, we define two angles namely, solar altitude and solar azimuth angle.

The altitude (β) is the angle between the sun rays and the horizontal projection of the sun rays.

The azimuth angle (ϕ) is an angle in the horizontal plane which is measured from south to the horizontal projection of the sun rays.

The zenith angle (z) is the angle between the line perpendicular to the plane and the sun rays.[8]

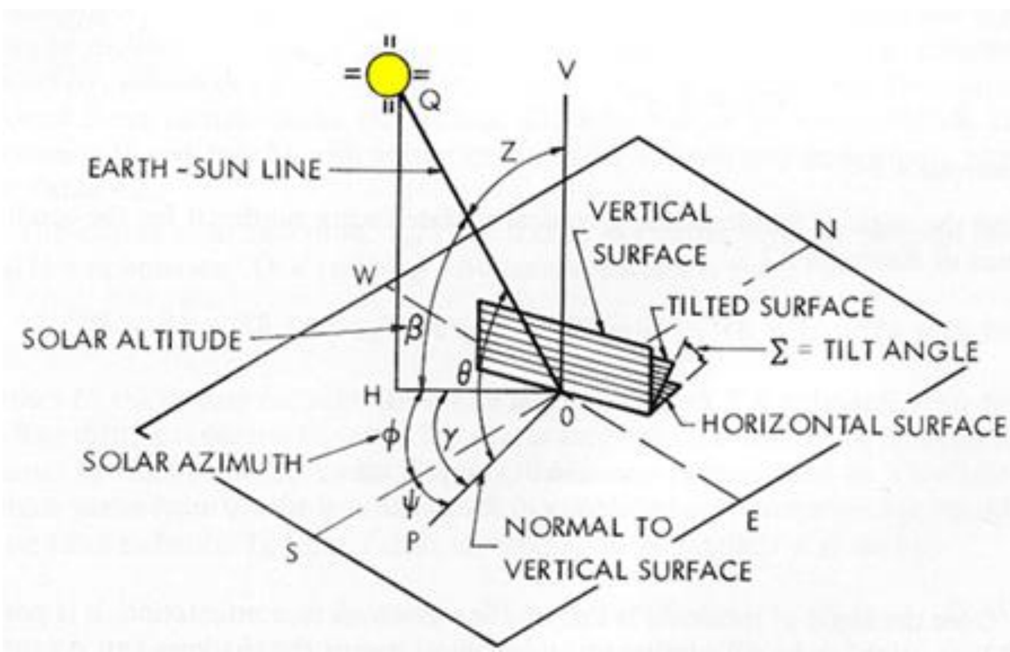

Fig 16 – Basic earth-sun angle [13]

1.3.4 Solar Time And The Equation Of Time

Solar time is normally estimated w.r.t. solar noon, which is a time when sun is crossing the observer's meridian and the difference between two successive solar noon defines a solar day. Because of the precession of the earth's axis, orbital and rotational variations. The solar day is not always of 24 hours, so one can't use a clock conferring to the solar time.

$$Solar\ time = Standard\ time \pm 4(L_{st} - L_{loc}) + E$$

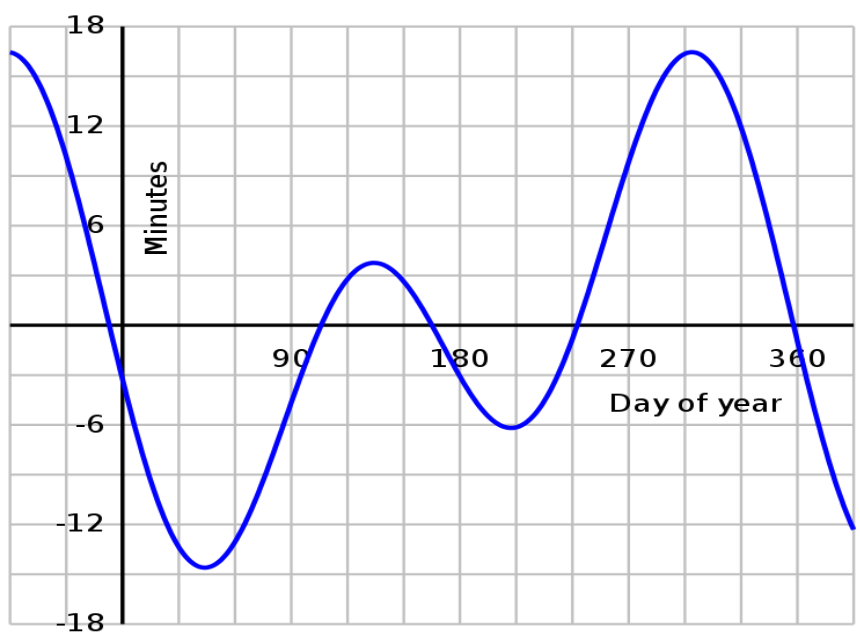

Fig. 17 – Extraterrestrial solar radiation variation with time of year [14]

1.3.5 Solar Radiation depletion by the Atmosphere

While travelling to earth surface solar radiation is absorbed or reflected by earth's atmosphere due to presence of suspended particle, gaseous constituent and other solid and liquid minute particle.

The depletion in solar radiation is occur by 3 different process if atmosphere is very clear –

- Absorption by water vapor, carbon dioxide, oxygen in certain wavelength.
- Rayleigh scattering of molecule of dissimilar gases & dust particle that create the atmosphere.
- Mie scattering[8]

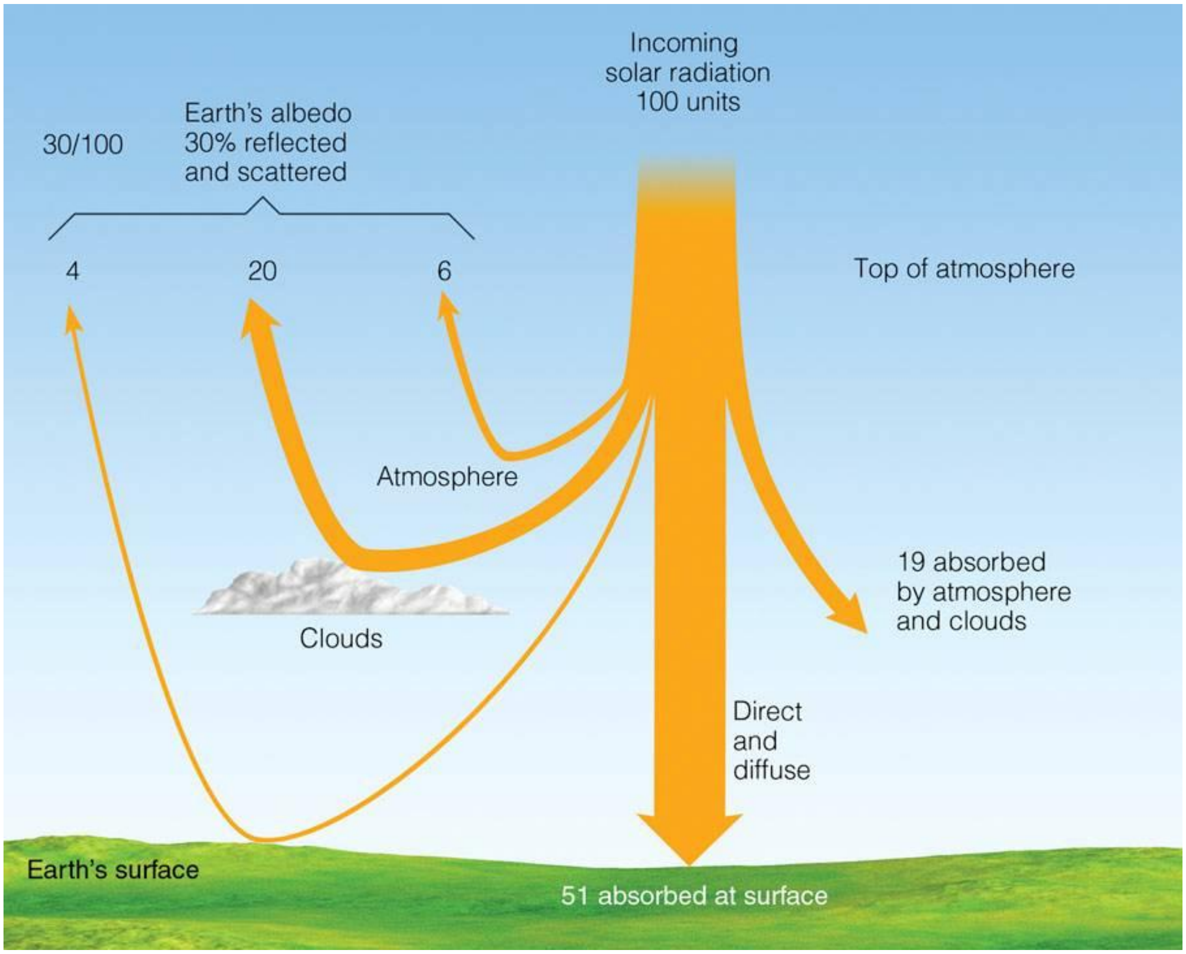

Fig 18 - Depletion of Solar Radiation by the Atmosphere [16]

CHAPTER-2

LITERATURE REVIEW

2.1 Summarization of various authors work

Unmadisingu et al consider the Potential of CSP in India & states that in India, rajasthan and Gujarat have the space for extensive application of CSP in India and also feed-in tariffs as incentive, government policy & industry-university associations have a vital role in installing CSP for power generation.[1]

Bijarniya JP ,also studied the CSP in India and states that absence of technological data, economic barriers, & intricate administrative & bureaucratic problems in India are real inhibitor of large-scale CSP application and solar PV is the challenger of CSP due to intense reduction in cost.[7]

Ho work to increase the efficiency of CSP by using high temperature particle receiver and states that in different types of Direct particle receiver which are listed below fluidized bed is good as in this the highest temperature attain is > 1000^{o}C -

- Free falling
- Obstructed
- Rotating kiln
- Fluidized bed[20]

Pramanik, study different type of hybrid technologies to increase the dependence on solar power and for its continuous operation in dark hours also states the Various CSP-hybrid system(high, medium, low) are studied in detail, and following point are concluded-

- CO_2 emission is highest in low CSP-Hybrid system.
- For capacities less than 50 MW, CSP-wind, and CSP m.

- A capacity of more than 100MW can be achieved by using CSP-biomass hybrid system. CSP-wind systems undergo from low capacity factor due to the inherent fluctuation is wind and solar resource.[27]

Baharoom DA, study the various CSP technology and state that, CSP of LFR type may work more efficiently if cosine effect is reduced than worldwide commercialized PTC technology. And SPT CSP plant can be a great contender of PTC if cost of the heliostats & receiver are decreased.

Ho studies the performance of high temperature receiver particle and states that the particle receiver are more useful than the conventional molten salt .There are basically two sorts of particle receiver, one is direct receiver which has the highest efficiency because it receive direct radiation whereas second one is gravity driven particle flow through the enclosures and while fluidized particle flow through the tubes are two kinds of indirect particle receiver.[26]

Kommalapati R study the life cycle of GHG emission from the CSP and states that Life-cycle of greenhouse gases emissions for the PTC, central receiver, SPD were computed as 79.8g CO_2 e/kW h, 85.67g CO_2e/kW h, 41g CO_2e/kW h. PTC and central receiver CSP emitted about 50% additional GHGs than the SPD.

Pelay U et al. study the thermal storage system for CSP and states that Prospect of latent storage is remarkable and needs research in the area-

- Properties augmentation of PCMs.
- Process of eliminating solid debris.
- TES assembly and its management needs development.
- Augmentation in heat transfer of thermal reactions
- We need to optimize the latent heat storage system with respect to its charging and discharging time.

Chen et al. study the thermo-physical property of molten salt nanofluid , basically they study the nanofluid of spherical SiO_2 particle of diameter 20nm suspension in molten salt . They states various property correlation like specific heat, viscosity, thermal conductivity, and density.[23]

Xu et al, study the solar power tower plant and gave the energy & exergy analysis of solar powerplant working on molten salt as HTF in receiver. And several conclusion are make for the improvement of solar tower powerplant efficiency.[18]

Li et al, consider the thermal model & thermodynamic performance of molten salt cavity receiver in solar tower powerplant. They consider all the heat losses from the absorber i.e, convection loss, emission loss, reflection loss, and conduction loss . They also show the various of various loss with receiver surface temperature, concentration ratio, solar radiation, etc.[21]

Gupta et al, summarizes the improvement of the thermal properties of nanofluid. The impact of various parameters like particle's size, shape and material used are consider and also various important parameters like, base fluid type, temperature, additives and pH value has been deliberated. There are several contradictory reports on the impact of parameters on thermo-physical properties.[25]

2.2 Research Gap

As from the previous work various studies are make regarding ,the enhancement of heat transfer fluid using nanoparticle and various type of receiver were introduce to increase the heat absorbing capacity of HTF. Exergy and energy analysis are also study of molten salt receiver, to calculate the efficiency of receiver and overall efficiency of the system and various factors affecting efficiency & second law efficiency but the energy and exergy analysis is not study on nanofluid as heat transfer fluid in cavity receiver.

2.3 Objective

The objective of this thesis is to make energy and exergy analysis of molten salt nanofluid in cavity receiver. The purpose is also to study the various factor affecting the energy & exergy efficiency of the system like –

- To study the influence of incident solar radiation
- To study the influence of concentration ratio
- To study the influence of mass flow rate
- To study the influence of Receiver surface temperature
- To study the influence of mean temperature of the fluid

CHAPTER 3

SOLAR TOWER POWER PLANT

3.1 Concentrating Solar Powerplant (CSP)

In CSP electricity is generated by concentrating the solar radiation which increases the temperature of the working fluid and this working fluid is used to heat the gases in the work producing cycle and also for storage media. There are various part of CSP-

I. Solar field
    - Mirrors
    - Receivers
    - Support structure
    - Collector system
    - Heat exchanger
    - Pumps
    - Tracking system
    - Piping

II. Thermal Storage unit
    - Storage media
    - Encapsulation
    - Heat exchanger
    - Tank insulation

III. Power Block
    - Turbine
    - Condenser
    - Superheater
    - Pump
    - Optional boiler
    - Generator
    - Cooling tower
    - Heat exchanger

3.1.1 Parameters affecting Solar concentrators

There are numerous factors used to state solar concentrators are –

- Aperture Area –

  It is the area at which solar radiation is incident on the central receiver.

- Acceptance Angle-

  It is the angle over which beam radiation may deviate from the normal to the aperture plane and yet reach the absorber. Collector with large acceptance angle require only occasional alteration, while collector with small acceptance angle have to be adjusted continuously.

- Absorber Area-

  It is the total area of the receiver that receives the concentrated radiation.

- Concentration Ratio-

  It is defined as ratio of the effective area of the aperture to the surface area of the absorber.

- Intercept Factor-

  It is the fraction of radiation which is reflected or refracted from the concentrator is incident on the absorber. The value is almost close to one.

- Optical Efficiency-

  It is defined as the ratio of the energy absorbed by the absorber to the energy incident on the concentrator aperture.[15]

3.1.2 Thermodynamic Limits to concentration

The main function of solar concentrator is to increase the flux density of solar radiation. So it is necessary to find out that to what value we can increase the flux density. The radiation incident on aperture are A_a is to be concentrated on receiver area A_r . So the maximum possible value is given by

$$C_{ideal,3D} \leq \frac{1}{sin^2\phi}$$

$$C_{ideal,2D} \leq \frac{1}{sin^2\phi}$$

The angular diameter of the sun is 32 minutes, so maximum possible concentration in a perfectly cylinder (2-D) geometry is obtain by putting ϕ = 16 minutes, $C_{ideal,2D}$ comes out to be 215 and for 3D case is approximately 40000.[8]

3.1.3 Solar Concentrator Mountings

3.1.3.1 Point focus mountings

The concentrators in point focus mountings in full tracking mode because the image formed at the receiver is very small, so to possess the image focused on absorber requires accurate modification of the reflecting or refracting surface. The fully tracking mountings have several geometries.

The simplest of all the mountings is the polar monting. In this one axis is kept parallel to the earth's axis and second axis is perpendicular to it.

The non-polar mountings requires motion about its two axis which are non-linear in nature. The most common is azimuth mountings in which one axis is vertical and other is horizontal.

3.1.3.2 Line Focusing Mounting

The line focusing require one axis tracking, so several geometries are available. The three important mountings are-

- Polar mounting

In this the axis of rotation of system is pointed towards the pole of the earth. The minimum value of cosine factor is .92, so the difference between summer, euinox and winter will be small.

- NS Horizontal – EW tracking

The axis is mounted in NS horizontal direction with east-west tracking to follow the sun. But in this seasonal performance is considerably different as in winter the cosine fator is small.

- EW Horizontal – NS tracking

This mounting gave better performances in winter in comparison to NS horizontal configuration.[8]

3.2 TYPES OF CSP

In CSP technology solar radiation is used to heat the working fluid which in turn used to run the turbine which generated electricity .CSP power generation plant are of four type

3.2.1 Solar Parabolic dishes (SPD)

A CSP-SPD system, concentrate the radiation fall onto receiver to the focal point of the parabolic dish .They are employed in a assembly thru 2-axis tracking system that tracks the sun. And the concentration ratio of the parabolic dish is around 2000 at the focal point of the SPDs, the temp. & the pressure of the HTF can reach about 750^{o}C and 200 bar, respectively. The diameter of dish varies from 5 to 10m & surface area varies from 40-120m^2.

The performance of SPDs can be improved when a glass is used with a coating of silver of 1µm thickness. A certain percentage of iron is also used to enhance the reflection of the surface. A single unit of SPDs system may have a electricity generation capacity variable from 0.01 to 0.5 MW. The solar to electric efficiency is highest in SPDs as compare to the other solar technologies. [1]

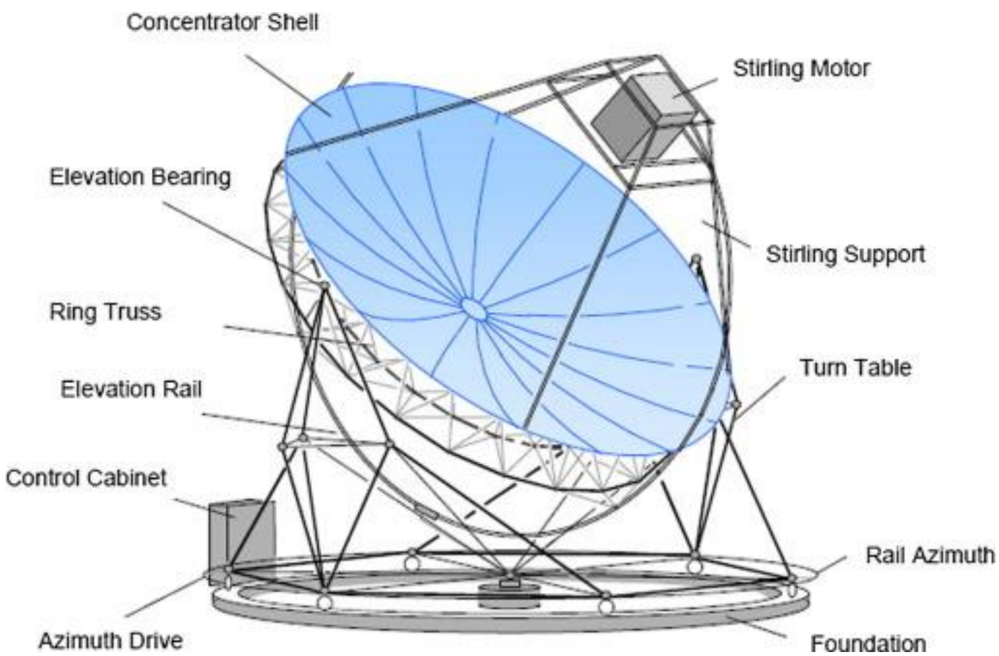

Fig 19 – Solar dish collector [1]

3.2.2 Parabolic trough collectors (PTC),

In the PTC-CSP framework, enormous mirrors shape like a mammoth U is used to focus the sun oriented radiation onto a recipient. The collector field involve various hundred troughs that are situated in parallel columns adjusted on a north-south pivot. This compliance empowers the single-pivot troughs to follow the sun from east to west for the duration of the day. The collector or the retention tube is painted with dark so as to accomplish the most extreme sunlight based radiation and reduction in warmth misfortune. The effectiveness is relied upon two components, initial a high assimilation coefficient of the ingestion cylinder and, second is its situation in the point of convergence of the trough.

The working liquid can achieve the temperature of 400oC relying upon the fixation proportion, sun oriented force, working liquid rate and different parameters. The sun oriented to electric effectiveness is 15% .[1]

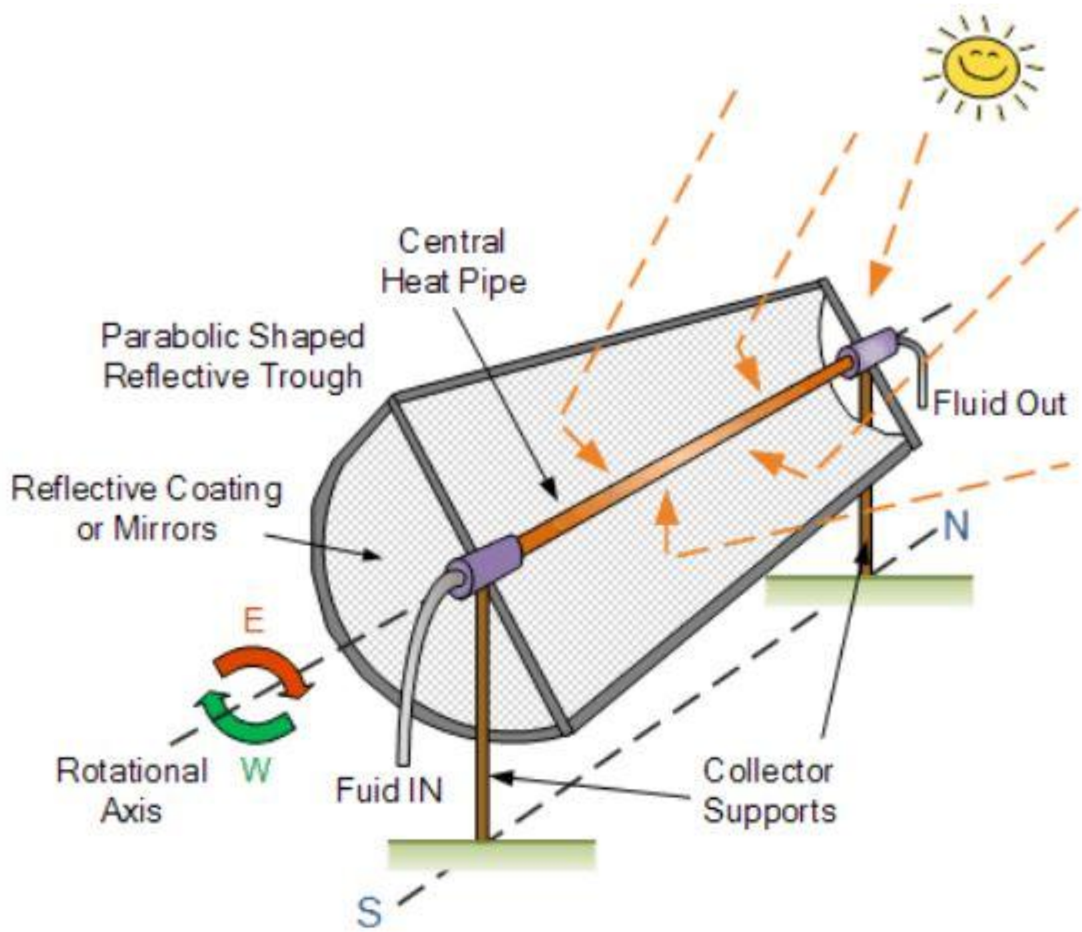

Fig. 20 – Solar parabolic trough [1]

3.2.3 Solar Power Tower (SPT)

In SPT system large no. of flat mirror are installed so that sunlight is concentrated on the receiver of the centrally located tower. These solar radiation are absorb by the receiver material usually ceramics and metals that are stable at high temperature. The average solar radiation receives at the top of tower varies from 200-1000 kW/m^2, providing an opportunity to achieve a high working temperature. The maximum temperature attain in SPTs are around 1000^oC.[1]

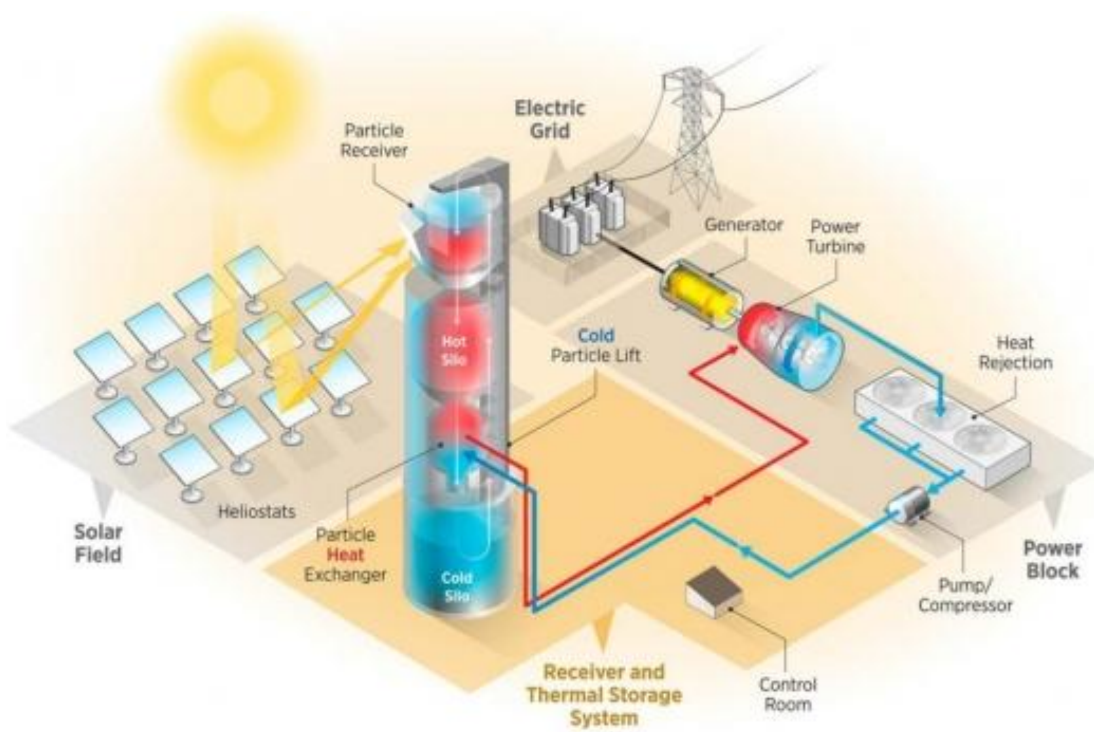

Fig 21 - Solar power tower [1]

3.2.4 Linear Fresnel reflectors (LFR)

LFR-CSP plants comprise of a variety of straight mirror strips as reflectors, with recipients, following framework, procedure and instrumentation framework, steam turbine & generator. The most significant segments in the framework are the reflector and the system of it is equivalent to that of the Fresnel focal point. The sun's beams are reflected by the Fresnel focal point and centered at a certain point, for the most part on to a lasting recipient on a straight pinnacle. In the daytime, the LFR are coordinated consequently toward the sun, and from that point the thought about sun powered illumination conveys to the straight pinnacle where a collector molded like a long chamber contains various cylinders loaded up with water. With high sunlight based radiation centered by the Fresnel focal point at the beneficiary warmth the water which vanishes and under high weight it is utilized to run the steam turbine that twists the generator that creates power.[1]

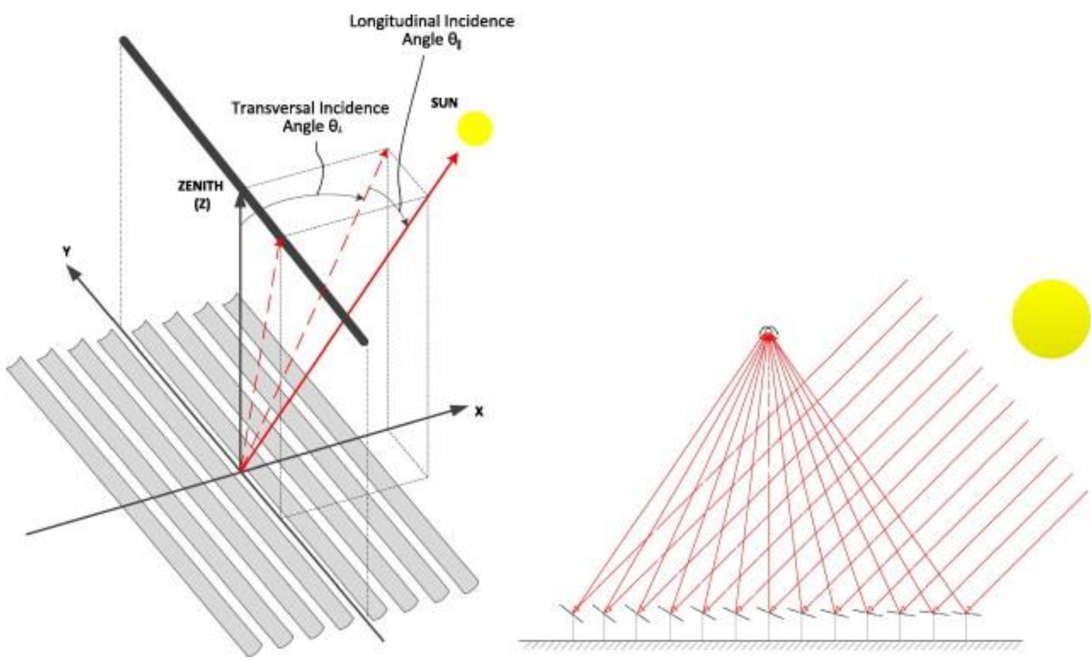

Fig 22 - Linear Fresnel reflectors [1]

3.3 Hybridization of Concentrating Solar powerplant

The solar radiation is not a dependable source of energy as it depends on weather, so for our future dependence we need to hybrid it with other source of energy. The solar radiation are available during the daytime only, so for its continuous operation we need a storage system or we have to hybrid it with some other powerplant. And the cost of CSP plant is very high ,so to make it affordable for the developing nation we have to hybrid it with some other plant to reduce the cost of standalone CSP and greenhouse gases from fossil fuel plant.The hybrid technologies are classified into three different categories high renewable ,medium renewable, low renewable. The high renewable hybrids are those which emit less CO_2(<100 kg/MW), medium emit CO_2(<200 kg/MW),and low emit CO_2(>200 kg/MW), The various hybrid system are –

a.) High renewable hybrids

- CSP- biomas hybrid
- CSP-geothermal Hybrid
- CSP- wind hybrids

b.) Medium renewable hybrids

c.) Low renewable hybrids

- Low-Brayton cycles
- Solar-aided coal powerplants
- Integrated solar combined cycles(ISCC)[27]

3.4 Solar power tower Technology

It is generally used for the power generation using solar energy. It is a method to concentrate the solar radiation at a point and convert it into heat energy which is used for electricity power generation.

It has Four main parts-

- Central Receiver
- Heliostat
- Power generation unit
- Thermal Storage

The Power tower consist of an absorber at the top of a tower encircled by field of a large no. of heliostat, concentrating the solar radiation onto the absorber(central receiver) .The receiver receive the working fluid from the pump, where it is heated and then returned down to generator or heat exchanger for electricity generation. Sometimes for continuous operation of solar plant thermal storage is also required.

The basic geometry is like paraboloid fragmented into segments & concentrating the parallel incident beam to a focal point.

3.4.1 Heliostat

The heliostat form an array of circular arc around the central tower. The purpose is to intercept, reflect, and concentrate the solar radiation onto the central receiver. The array is guided by tracking control system which ensures that each heliostat focuses solar radiation towards the receiver. A two-axis tracking mode is used to adjust two basic angle i.e., surface azimuth angle and slope of the heliostat. In addition to this when solar radiation are not available, the control system orient the heliostat in safe direction for prevention from any damage of the receiver.

The two major issues associated with the central receiver system is low availability of the heliostat and degradation of the mirrored surface of the heliostat. Thus increase in reflectivity and reliability of heliostat can helpful in increasing the efficiency of heliostat.[8,15]

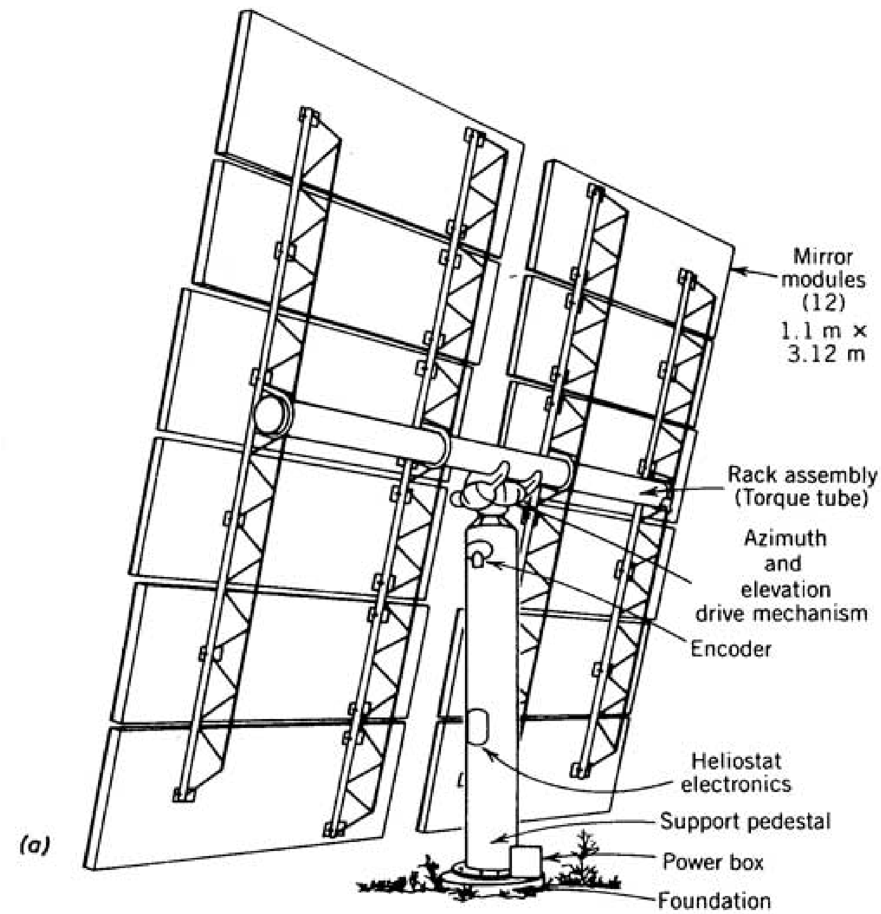

Fig 23 – Component of heliostat [13]

3.4.2 Receiver

The solar radiation from the heliostat are concentrated at the receiver, where solar energy is transferred to fluid as heat. The collector surface is exposed to non-uniform, one sided heat flux thus thermal stress happen .So beneficiary ought to be intended to withstand the weakness stress .And additionally recipient ought to be little in size ,surface zone, weight to limit the thermal losses. It ought to be enhanced as for operational condition & pressure loss.

There are 2 types of receiver – external or exposed and internal or cavity type .

- External receiver

  It is usually cylindrical in shape .The solar radiation is directed directly on the outer surface which consist of panel containing tube through which the heat transfer fluid flows

- Cavity receiver

  In cavity type receiver, the solar flux enters through one or more small apertures in a isolated enclosure. The geometry of cavity receiver is such that it maximize the radiation absorption & minimize the heat losses by convection & radiation.

The external type receiver had a very wide angle of acceptance, while the cavity type has a small acceptance angle. While cavity receiver traps more solar flux , therefore they have high efficiency.[15]

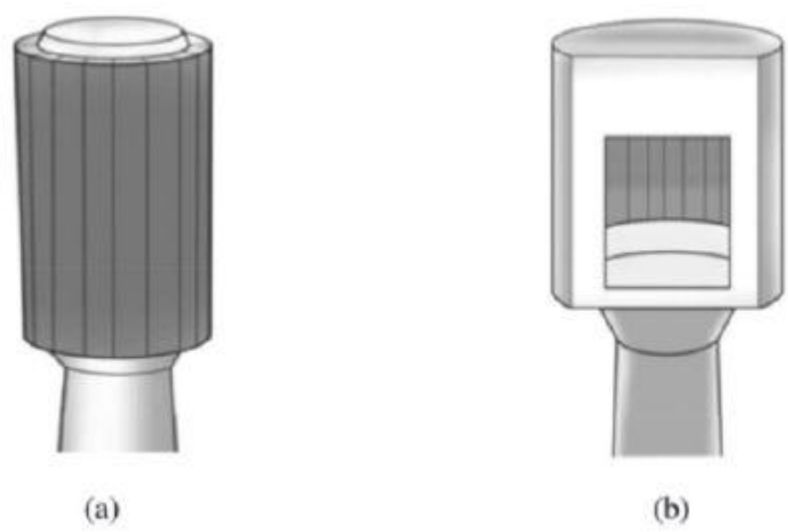

Fig 24 – Tubular receiver (a)External receiver, (b) Cavity receiver [13]

3.4.3 Materials for Solar Concentrators

The material used for solar concentrator system need to have spectral physical and thermal properties to achieve high overall efficiency and to ensure long life of the system.

3.4.4 Material for reflecting and refracting surface

For reflecting system such as mirror , good reflectance properties are required. Also various environmental effect has also be taken into consideration such as accumulation of dust, stability of reflective coating ,etc. A variety of mirrors used are-

- Glass reflector
- Metallized Plastic film
- Polished aluminum surface
- Other metallic surface such as stainless steel, etc.

Aluminum surface have reflectivity around 80-85%, while new and front surface glass reflectors can achieve 95% efficiency. The effect of environment vary with the type of material, length of exposure ,site Location, type of coating and cleaning techniques.

The selection of specific glass to be used in heliostat, depends on various optical and mechanical properties, durability, resistance to hail, rain, etc. By chemical composition, the primary types of glass are-

- Soda lime
- Lead alkali
- Borosilicate
- Aluminosilicate
- Fused silica

Among mention above glasses, Borosilicate and Aluminosilicate are found to be superior for solar concentrator. Silver coating is also done to increase the reflectivity. Refracting surface used in Fresnel solar collector are generally made up of plastics. Plymethyl methacrylate is generally used because of its extraordinarily resistant to oxidative UV radiation.

3.4.5 Material for the Absorber

The choice of absorber material is depend on-

- Physical properties such as yield strength, melting point, thermal inertia, modulus of elasticity
- Ease of fabrication
- Cost of material
- Corrosion resistance
- Resistance to stagnation temperature condition

In short, strong, durable, strong, and energy economic absorber material must be used.

3.4.6 Absorber Cover Material

The aspects which affect the absorber cover material are –

- Optical properties such as transmission of visible light and opacity to infrared radiation.
- Physical properties such as coefficient of expansion & melting or softening point.
- Durability including deprivation due to ultraviolet radiation.

3.4.7 Absorber Surface Coating material

The following properties of coating material required are-

- High absorptivity for solar radiation
- Sunlight and high stagnation temperature
- Durability when exposed to weathering
- Cost effectiveness
- Protection to base material
- Low emissivity for the reradiated infrared radiation.

Non selective black coating are of three types-

- Paint
- Fused vitreous porcelain enamels
- Certain metal conversion coating

3.4.8 Heat transfer Fluid

The heat transfer fluid should have the following characteristic-

- Stability at high temperature
- High operating temperature
- Low material maintenance
- Non corrosive
- Safe to use
- Low vapour pressure

3.4.9 Insulation on the Non-irradiated Portion of Absorber

The non-irradiated portion of absorber in solar concentration must be insulated to minimize heat losses. The other important factor beside these are chemical stability at high temperature, toxicity, cost effectiveness, persistent weathering, & flame spread properties. Some insulation material are fibre glass.[8]

3.5 Nanofluid

The thermal fluid like water, oil, ethylene, propylene glycol plays an important role in heating and cooling process, but these fluid have a poor thermal conductivity as compared to solids. Hence, new technologies to enhance thermo-physical properties of fluid has been an area of great research .The solid particle exhibit high thermal conductivity , so addition of these particle of micro or millimeter size in dispersed form can increase the thermal conductivity of the thermal fluid . But the problem with particle of micro or millimeter size is that they causes problem such as poor suspension quality, poor stability and leads to channel clogging. So nanoparticle served the best purpose for this. The extraordinary optical, mechanical, electrical and thermal properties of nanomaterial have made them most required after material of the present time. So mixing of some percentage of nanoparticle into base fluid is known as nanofluid.

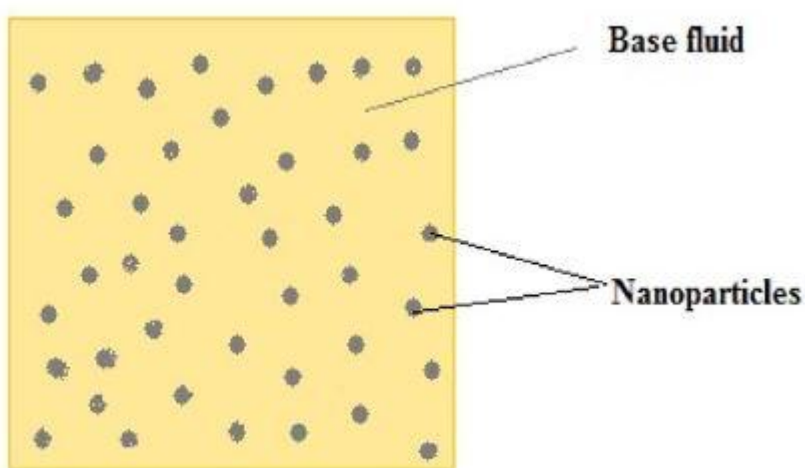

Fig 25 – Nanoparticle dispersed in base fluid

3.5.1 **Thermo-Physical Properties Of Nanofluid**

The nanofluid thermal properties like thermal conductivity, specific heat, density and viscosity depends on number of factors like-

- Particle size
- Particle shape
- Particle material and base fluid
- Temperature
- Concentration
- Purity level

The material with high thermal conductivity can be used as a nanomaterial in nanofluid to increase the thermal conductivity which is required in solar thermal application. However, the addition of nanoparticle in base fluid increases the thermal conductivity as solid particle has more thermal conductivity and with reduction in particle size & increase in temperature the thermal conductivity of nanofluid increases.

However the viscosity of nanofluid is higher than the conventional fluid dui to inclusion of solid particle.

The specific heat of nanofluid is higher than conventional which makes them more valuable for solar thermal application. As for same mass and same temperature rise large amount of heat can be stored.

There is not much difference in density as we mix very small amount of fraction in base fluid. So inclusion of nanoparticle doesn’t affect the density by large difference.[25]

CHAPTER 4

ENERGY AND EXERGY ANALYSIS

4.1 Introduction

The fig shows the schematic diagram of the solar power plant which use a molten salt nanofluid as the heat transfer fluid ,which is used by Chao Xu et al for energy & exergy analysis using molten salt as HTF. The entire system energy & exergy performance are discussed at a steady state, while thermal storage subsystem is not consider in this analysis. So the solar tower system consist of heliostat, central receiver, steam generation, and power cycle. And sun rays which fall on the heliostat field, concentrate them to the central receiver resulting in increase in temperature of the receiver which then used to heat the fluid flowing in the pipes implanted inside the receiver. Then the heated fluid passes through the heat exchanger in which water and heating fluid flow in counter flow mode.

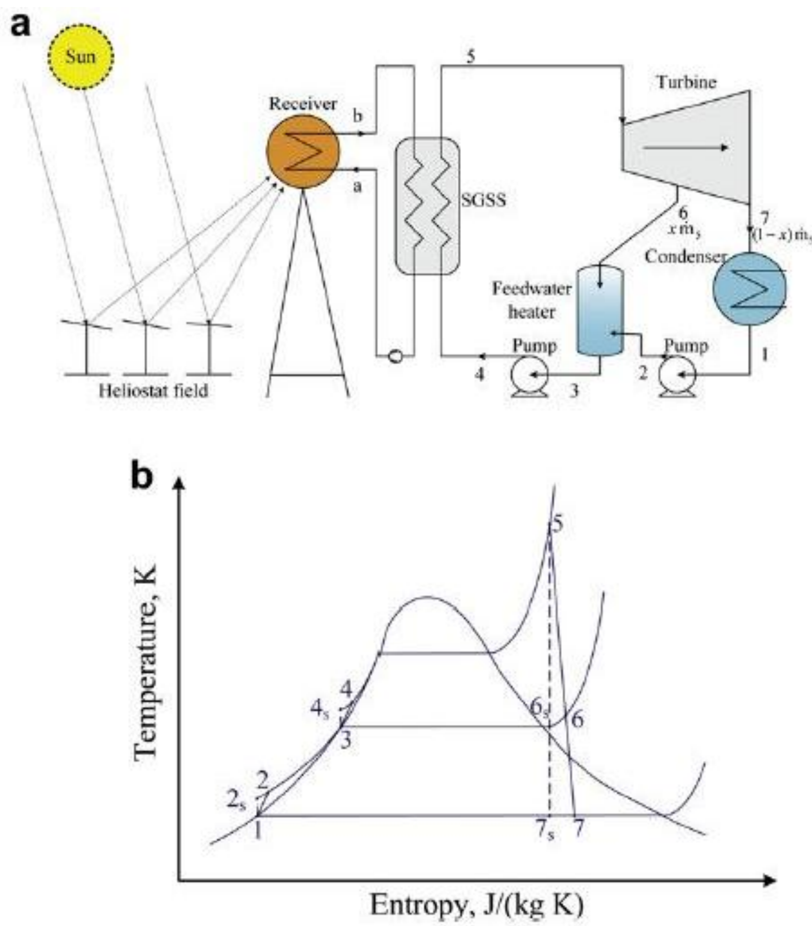

Fig 26 – Schematic diagram of solar power plant

The following assumption are made while analyzing energy & exergy analysis of the entire system-

- Constant solar isolation are ass
- All process are in steady state.
- Pressure drop are neglected.
- Heat loss in pipeline are neglected.
- Potential and kinetic energy & exergy are disregarded.
- Chemical exergy of material is neglected.
- The assumed parasitic efficiency of the entire system is 88%.
- Power cycle efficiency is independent of the power output of the turbine.[18]

For steady state the energy balance is given by

$$\dot{E}_{input} - \dot{E}_{output} = \Delta\dot{E}_{system} \quad (1)$$

$$\dot{E} = \dot{Q} + \dot{W} + \sum \dot{m}h \quad (2)$$

And for steady state the exergy balane is given by

$$\dot{X} = \dot{m}(x - x_o) = \dot{m}[(h - h_o) - To(s - s_o)] \quad (3)$$

4.2 Mathematical Model

4.2.1 Heliostat Field system

The total radiation is proportional to total area & given by-

$$\dot{Q} = A_h * \dot{q} \quad (4)$$

Where A_h is a total area of heliostat field and q is quantity of solar radiation received per unit area which is known as direct normal radiation (DNI).

The solar radiation which falls on heliostat is partially delivered to central receiver as Q_r, while the remaining heat fraction (Q_o) is lost to the environment by several mechanism. The mechanism include blocking, shading, cosine efficiency, tracking error, clean error, mirror reflectivity, etc.

The energy & exergy balance for heliostat field are

$$\dot{Q} = \dot{Q}_r + \dot{Q}_o \tag{5}$$

$$\dot{X} = \dot{X}_r + \dot{X}_o \tag{6}$$

$$\dot{X} = \dot{Q}\left(1 - \frac{T_o}{T}\right) \tag{7}$$

$$\dot{X}_r = \dot{Q}_r\left(1 - \frac{To}{T}\right) \tag{8}$$

$$\eta_{H,I} = \frac{\dot{Q}_r}{\dot{Q}} \tag{9}$$

$$\eta_{H,II} = \frac{\dot{X}_r}{\dot{X}} \tag{10}$$

4.2.2 Central Receiver System

This analysis consider the heat transfer process in the cavity receiver. The radiation which fall on central receiver are absorbed by the fluid flowing through it while some energy is lost to the environment by basically three method i.e. convective , emissive, reflective and conduction heat losses. So for the central receiver the energy & exergy balance are given by-

$$\dot{Q}_r = \dot{Q}_{r,abs} + \dot{Q}_{r,l} \tag{11}$$

$$\dot{Q}_{r,abs} = \dot{m}(h_b - h_a) \tag{12}$$

$$\dot{X}_r = \dot{X}_{r,abs} + \dot{X}_{r,l} + I\dot{R}_r \tag{13}$$

$$\dot{X}_{r,l} = \dot{Q}_{r,l}\left(1 - \frac{To}{T_{r,s}}\right) \tag{14}$$

$$\begin{aligned} \dot{X}_{r,abs} &= \dot{m}[(h_b - h_a) - T_O(S_b - S_a)] \\ &= \dot{m}c_p[(T_b - T_a) - T_O\left(\ln\frac{T_b}{T_a}\right)] \end{aligned} \tag{15}$$

$$\eta_{r,I} = \frac{\dot{Q}_{r,abs}}{\dot{Q}_r} \tag{16}$$

$$\eta_{R,II} = \frac{\dot{X}_{r,abs}}{\dot{X}_r} \tag{17}$$

Where $\dot{Q}_{r,l}$ is the total heat loss from the receiver which is calculated as

$$\dot{Q}_{r,l} = \dot{Q}_{r,conv} + \dot{Q}_{r,em} + \dot{Q}_{r,ref} + \dot{Q}_{r,con} \tag{18}$$

$$\dot{Q}_{r,conv} = \left[h_{air,ins,fc}(T_{r,s} - T_a) + h_{air,ins,nc}\frac{(T_{r,s} - T_a)}{F_r}\right] * A \tag{19}$$

$$\dot{Q}_{r,em} = e * \sigma * ({T_{r,s}}^4 - Ta^4) * A \tag{20}$$

$$\dot{Q}_{r,ref} = \dot{Q}_r * F_r * \rho \tag{21}$$

$$\dot{Q}_{r,con} = \left(T_{r,s} - T_a\right) * \frac{A}{\left(\frac{\delta}{k} + \frac{1}{h_{air}}\right).F_r} \tag{22}$$

Where the receiver surface temperature ($T_{r,s}$) is determined by

$$\dot{Q}_r = A * \frac{\left(T_{r,s} - T_{ms}\right)}{\left\{\frac{d_o}{d_i * h_{ms}} + \frac{d_o}{2 * k}\ln\frac{d_o}{d_i}\right\}F_r} \tag{23}$$

4.2.3 Steam generator System

It usually consist of a series of heat exchanger, so from receiver HTF flows to the heat exchanger and gives heat to the water and water gets heated from sub-cooled liquid into superheated steam. And assuming heat that exchanger are well insulated & heat loss to the environment can be ignored. The energy & exergy balance are

$$\dot{Q}_{r,abs} = \dot{m}(h_b - h_a) = \dot{Q}_{s,abs} = \dot{m}_s(h_5 - h_4) \tag{24}$$

$$\dot{X}_{r,abs} = \dot{X}_{s,abs} + \dot{IR}_{sg} \tag{25}$$

$$\dot{X}_{s,abs} = \dot{m}_s[(h_5 - h_4) - T_O(S_5 - S_4)] \tag{26}$$

$$\eta_{sg,I} = \frac{\dot{Q}_{s,abs}}{\dot{Q}_{r,abs}} = 100\% \tag{27}$$

$$\eta_{sg,II} = \frac{\dot{X}_{s,abs}}{\dot{X}_{r,abs}} \qquad (28)$$

4.2.3 Power generation System

In solar power plant we consider rankine cycle as given in fig in the power generation unit. The rankine cycle consist of high & low pressure turbine stages, feed water heater, turbine, and condenser. And in this analysis we consider one stage regenerative rankine cycle, which uses feed water heater to avoid low temperature at the inlet of steam generator system to prevent freezing of molten salt. The corresponding T-s diagram and the temperature and pressure condition at each point is given in appendix. The energy & exergy balance of power cycle is given by

$$\dot{Q}_{s,abs} = \dot{W}_{net} + \dot{Q}_{p,l} \qquad (29)$$

$$\dot{X}_{s,abs} = \dot{W}_{net} + I\dot{R}_{p,l} \qquad (30)$$

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_{p1} - \dot{W}_{p2} \qquad (31)$$

$$\eta_{ps,I} = \frac{\dot{W}_{net}}{\dot{Q}_{s,abs}} \qquad (32)$$

$$\eta_{ps,II} = \frac{\dot{W}_{net}}{\dot{X}_{s,abs}} \qquad (33)$$

The overall energy and exergy is given by –

$$\eta_{o,I} = \frac{\dot{W}_{net}}{\dot{Q}} * \eta_{para} \tag{34}$$

$$\eta_{o,II} = \frac{\dot{W}_{net}}{\dot{X}} * \eta_{para} \tag{35}$$

4.3 Model Validation

The present analysis is based on energy & exergy analysis using molten salt nanofluid as HTF in central receiver of solar tower powerplant .To validate model, the present model was used to calculate the efficiency using molten salt as a HTF. And then this result is compare with the Chao Xu et al result[18], we find that it is almost similar. Therefore mathematical model is correct.

	Chao Xu model result	Present model result
Energy Efficiency		

Heliostat	75	75
Receiver	90.02	89.76
Steam generator	100	100
Power cycle	37.85	38.4
Overall	22.89	22.75
Exergy efficiency		
Heliostat	75	75
Receiver	55.48	55.32
Steam generator	89.77	91.24
Power cycle	74.48	73.05
Overall	24.48	24.33

Table 1 – Comparison of existing model and present model

4.4 Heat transfer fluid

This analysis consider the molten salt nanofluid. The base solution is molten salt and SiO_2 of diameter 20mm was added as nanoparticle with a mass fraction of 0.5 %. Xia Chen et al. specify the value of several thermal properties of molten nanofluid, as per given data specific heat is almost constant with value of 1950J/Kg.K, while thermal conductivity, viscosity, density is given by[23]

Density (Kg/m^3) –

$\rho = 2066 - 0.54 \times t(^{o}\mathrm{C})$

Thermal Conductivity (W/mK) –

$k_{ms} = 0.396 + 4.087 \times 10^{-4}\, t(^{o}\mathrm{C})$

Viscosity (mPa.s)–

$\mu = 2.19 + 2.25 \times 10^{-3}\, t - 1.19 \times 10^{-5}\, t^{2}(^{o}\mathrm{C})$

CHAPTER 5
RESULT AND DISCUSSION

5.1 Introduction

The solar powerplant model including all the system, heliostat ,central receiver ,steam generation unit and power cycle is consider from chao Xu et al ,and the heat loss analysis on cavity central receiver is consider from X. Li et al . The thermal-physical property of heat transfer fluid i.e. molten salt nanofluid using SiO_2 (spherical shape of 20nm diameter), mass fraction of 0.5% is consider from Xia chen et al.

5.2 Result-

5.2.1 Effect of Solar radiation (DNI)

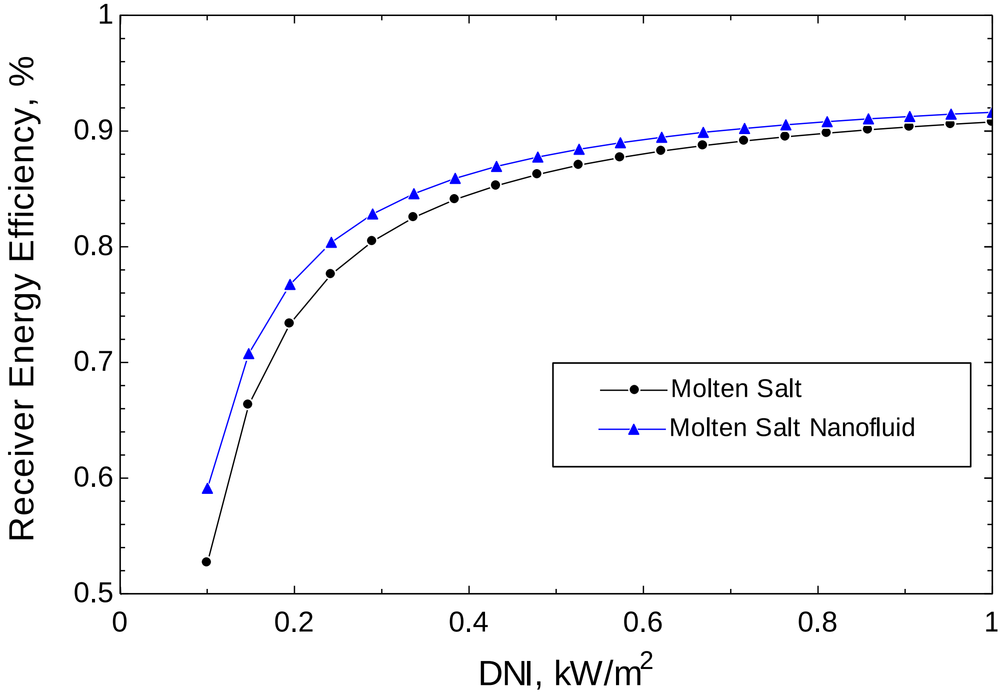

Fig. 27- Effect of solar radiation on receiver efficiency

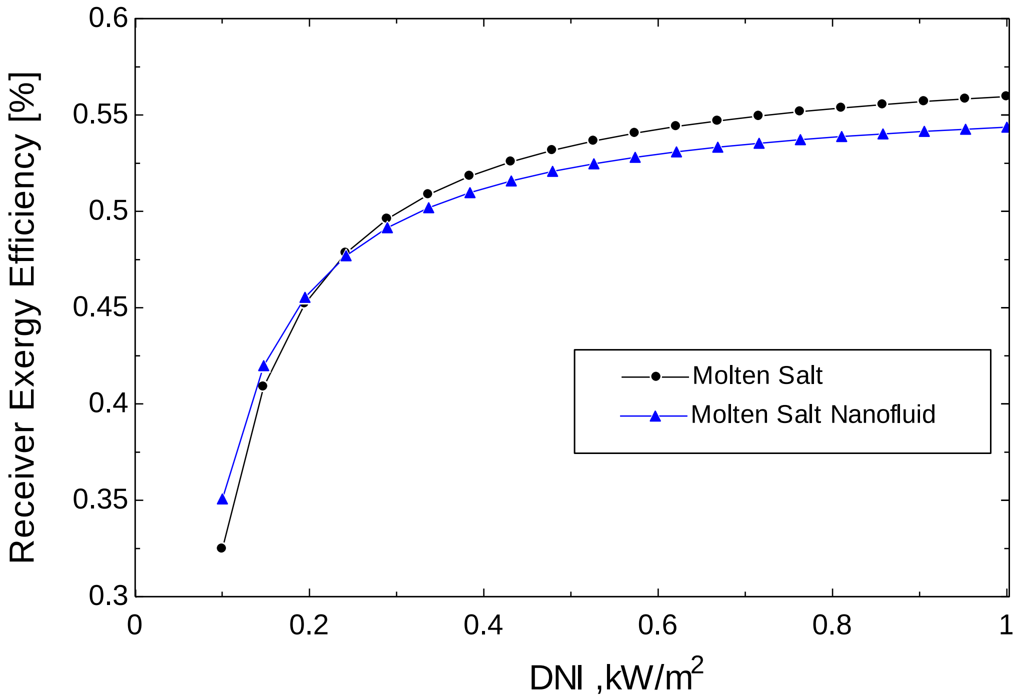

Fig. 28 - Effect of solar radiation on receiver second law efficiency

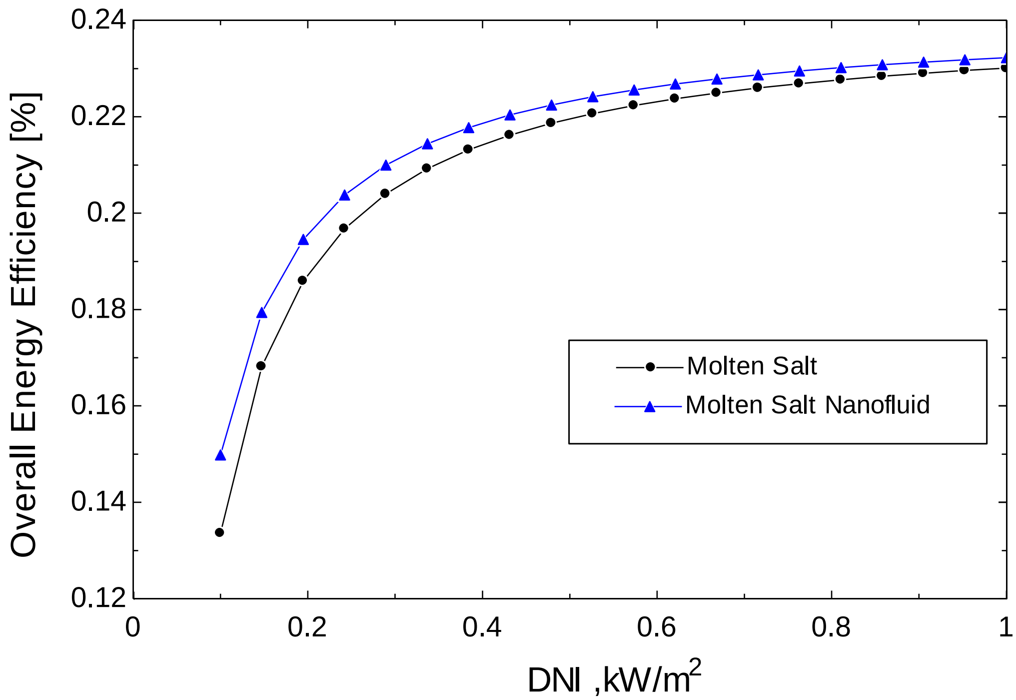

Fig. 29 - Effect of solar radiation on overall energy

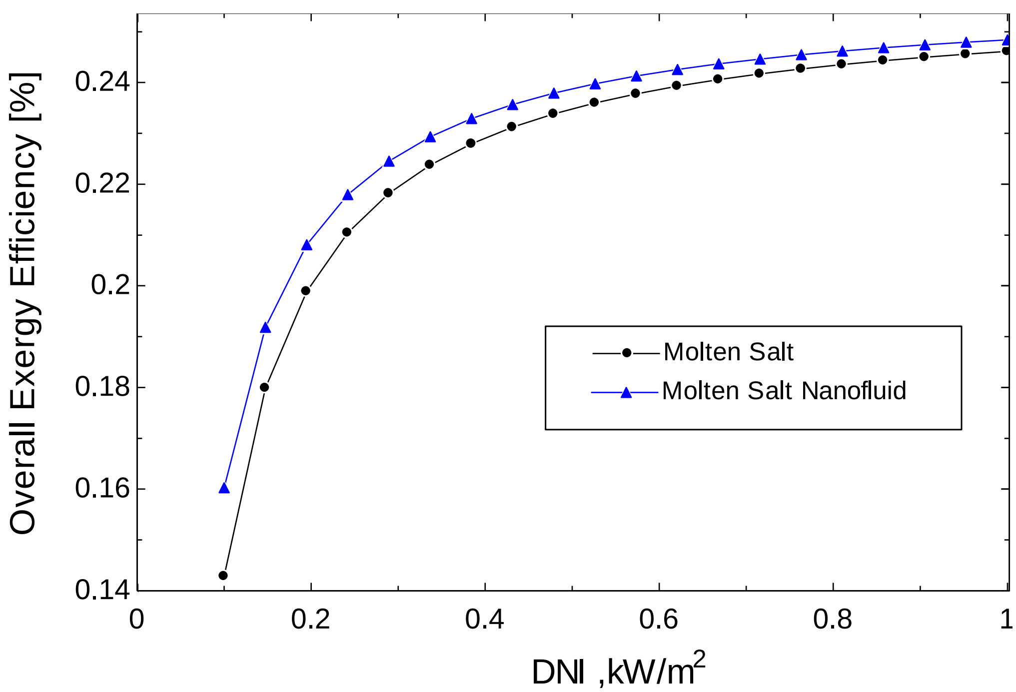

Fig. 30 - Effect of solar radiation on overall second law efficiency

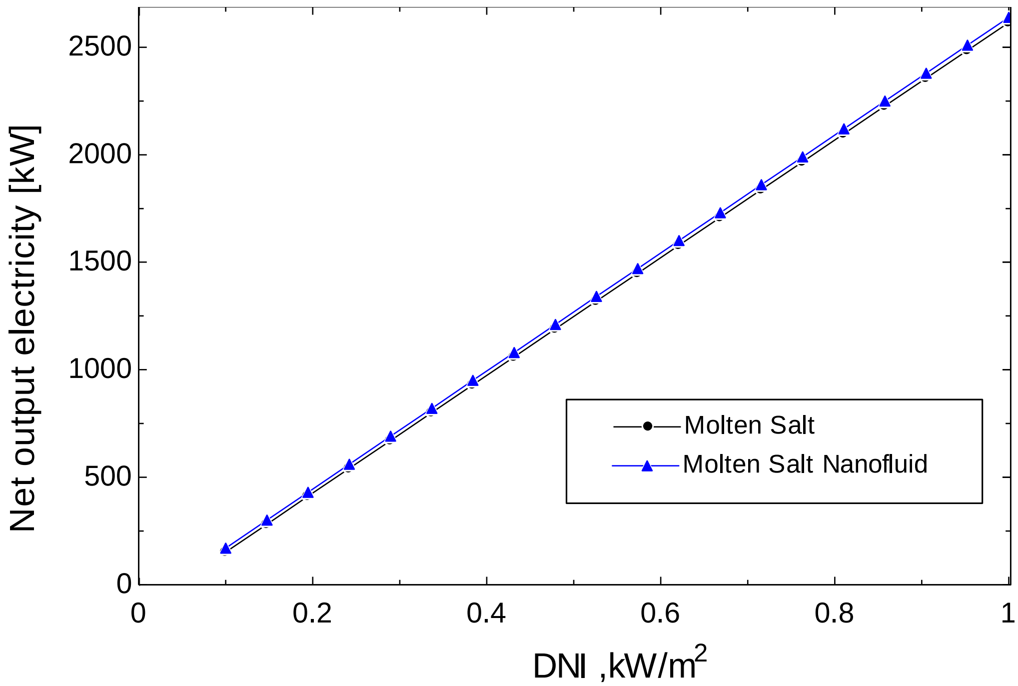

Fig. 31 - Effect of solar radiation on net work

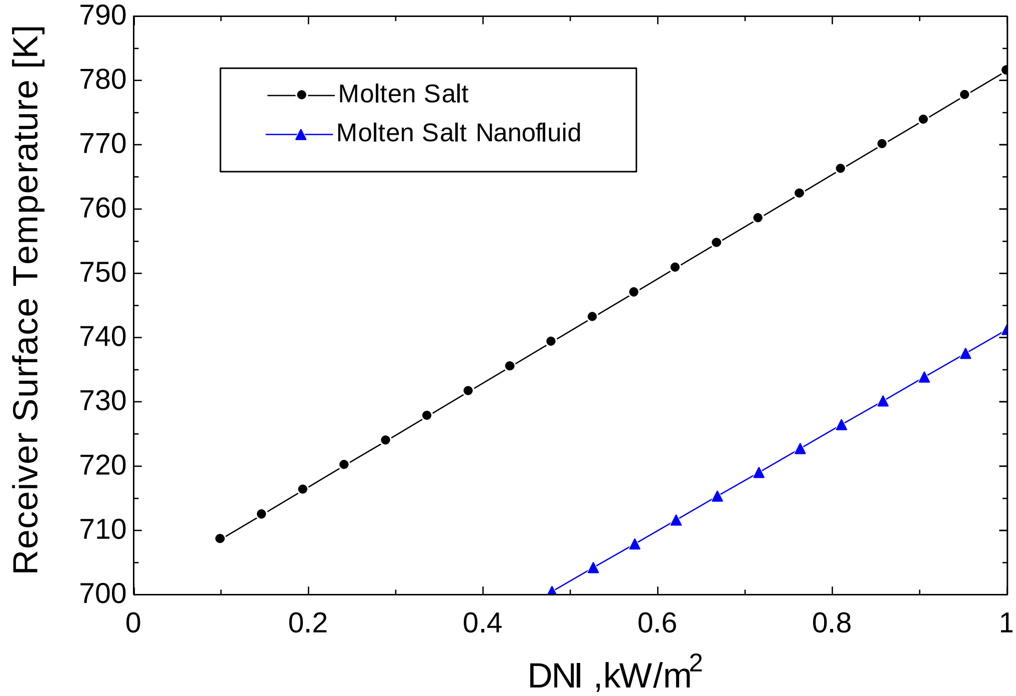

Fig. 32 - Effect of solar radiation on receiver surface temperature

The CSP plant performance mainly depends on solar radiation which depends on geographical area, time of day, etc. To study the effect of DNI on energy & exergy efficiency we vary the solar radiation from 0.2-1 (kW/m^2). Fig.(27-30) show the variation of energy & exergy efficiency with DNI. And it is seen that exergy and energy efficiency increases with solar radiation and the pattern is same for receiver and whole system, which indicate that effect of DNI on system overall energy & exergy efficiency mainly depends on receiver.

The energy & exergy efficiency increase can be stated by heat loss from the receiver. The heat loss is mostly due to convection and radiation .From equation (19) and (20) we see that these losses depends on receiver surface temperature rather than DNI. The change in receiver surface temperature with DNI is shown by Fig.- 32, which shows that with increase in solar radiation from 0.2 – 1 (kW/m^2) there is very little increase in receiver surface temperature ,i.e. from 660 to 710 K, but the energy input increases proportionally. So the energy & exergy efficiency increases.

It is also seen the for small value of DNI the energy efficiency increases linearly, while afterwards it increase slowly, i.e energy efficiency increase from 44 to 86 % when DNI increases from 0.2-0.4 (kW/m^2), while when DNI increases from 0.4 -1 (kW/m^2) the efficiency increases from 86 to 91 %. The net work variation with DNI is shown in fig. 31 ,state the linear relationship.

5.2.2 Effect of outlet temperature

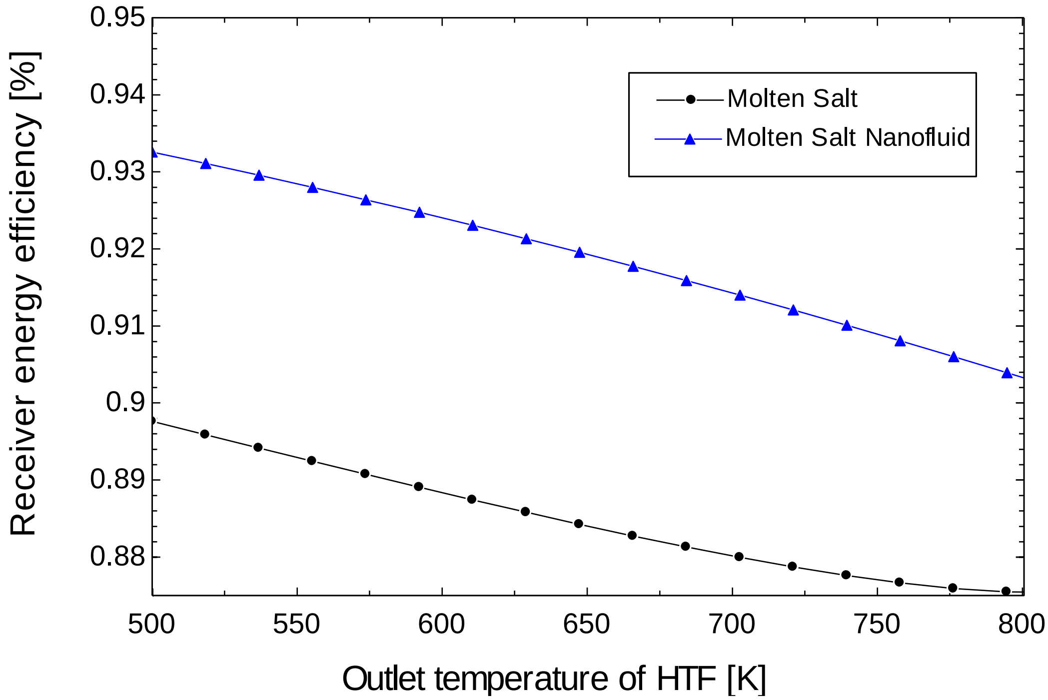

Fig. 33 - Effect of HTF outlet temperature on receiver efficiency

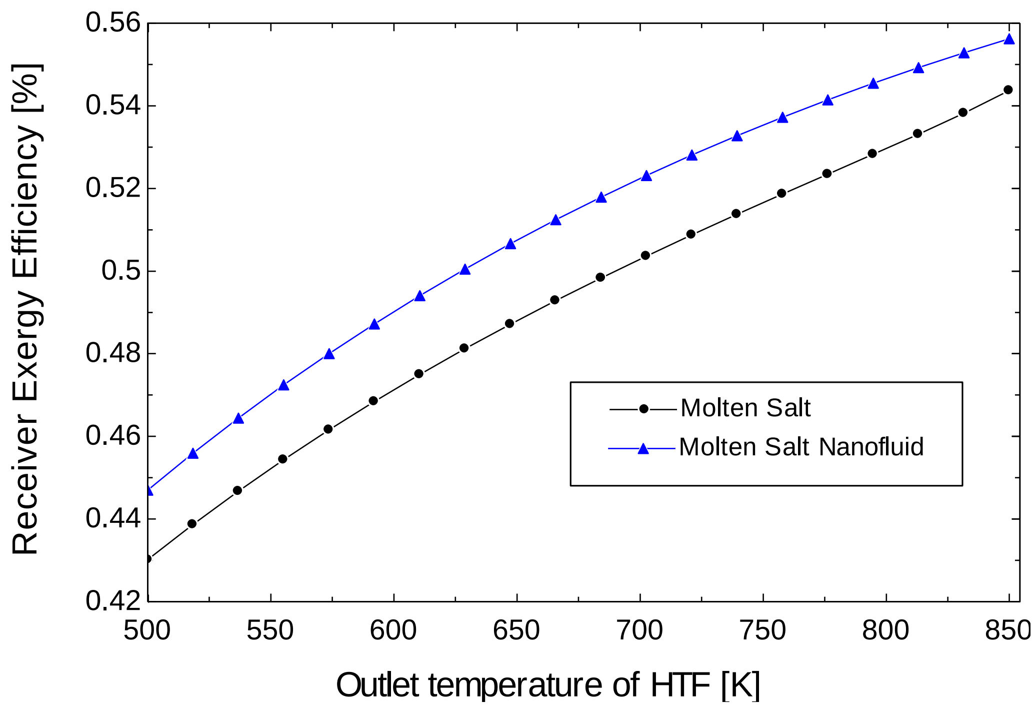

Fig. 34 - Effect of HTF outlet temperature on receiver second law efficiency

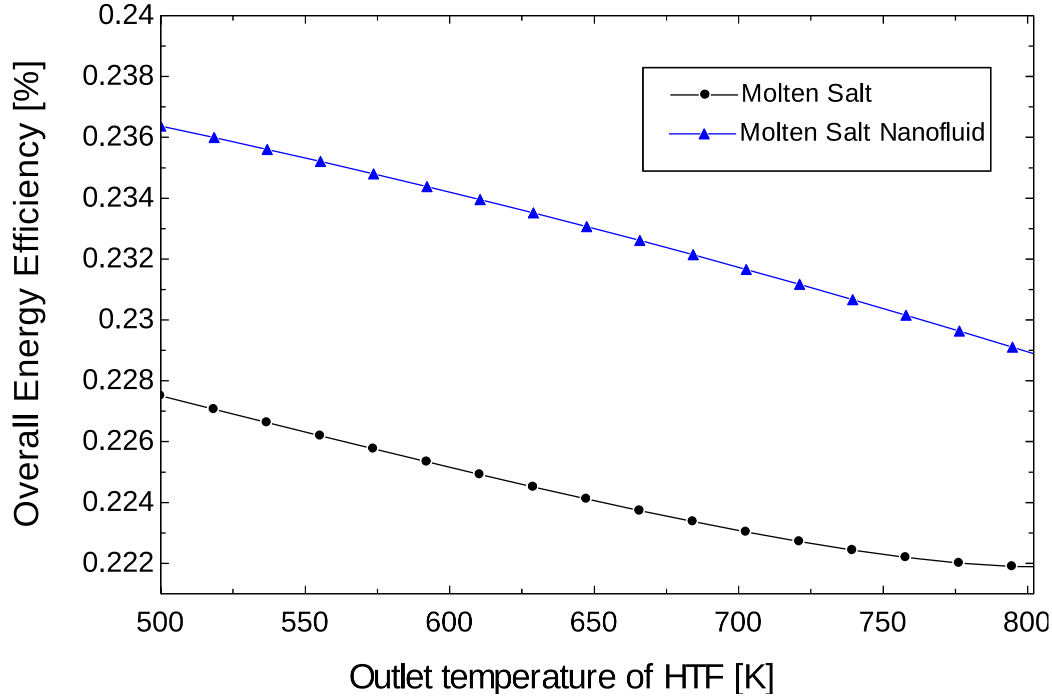

Fig. 35 - Effect of HTF outlet temperature on overall efficiency

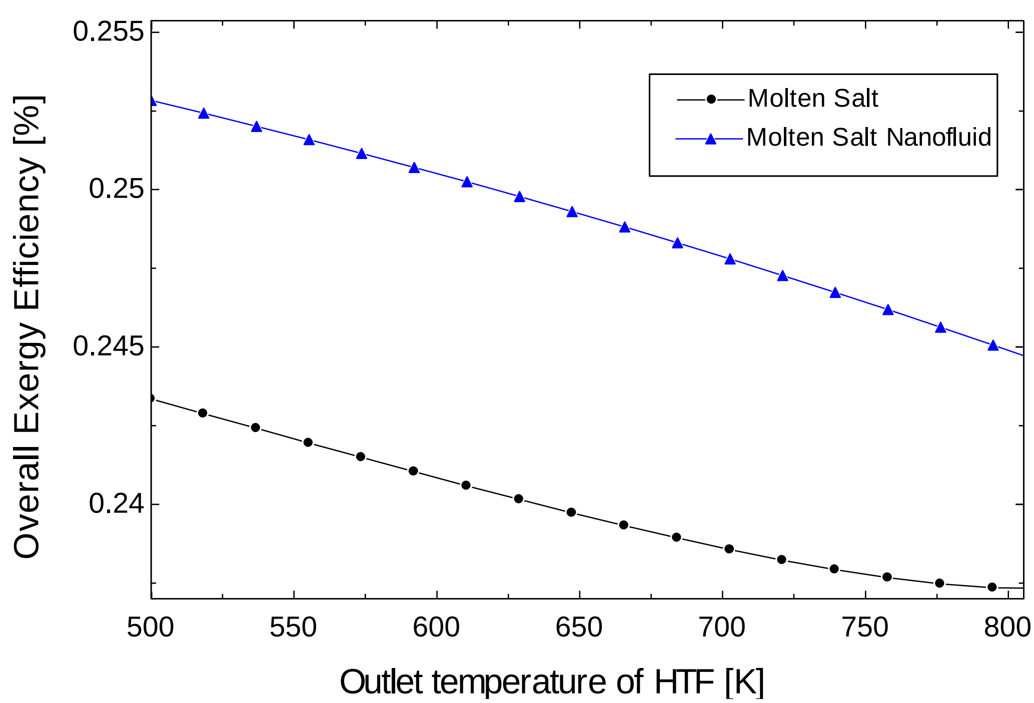

Fig. 36 - Effect of HTF outlet temperature on overall second law efficiency

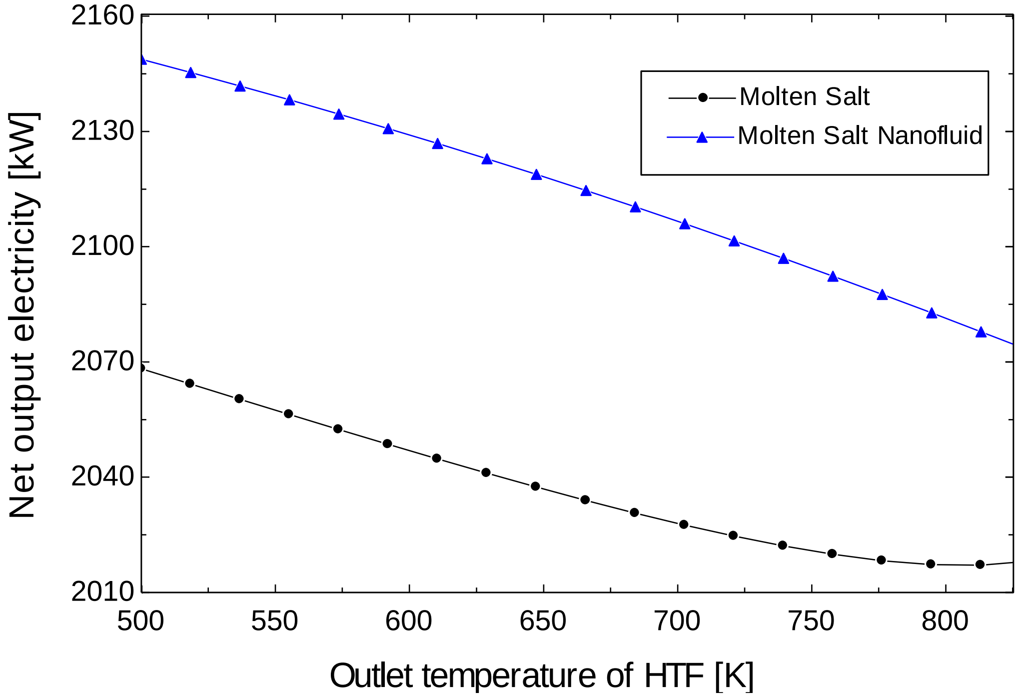

Fig. 37 - Effect of HTF outlet temperature on net work

5.2.3 Effect of concentration ratio

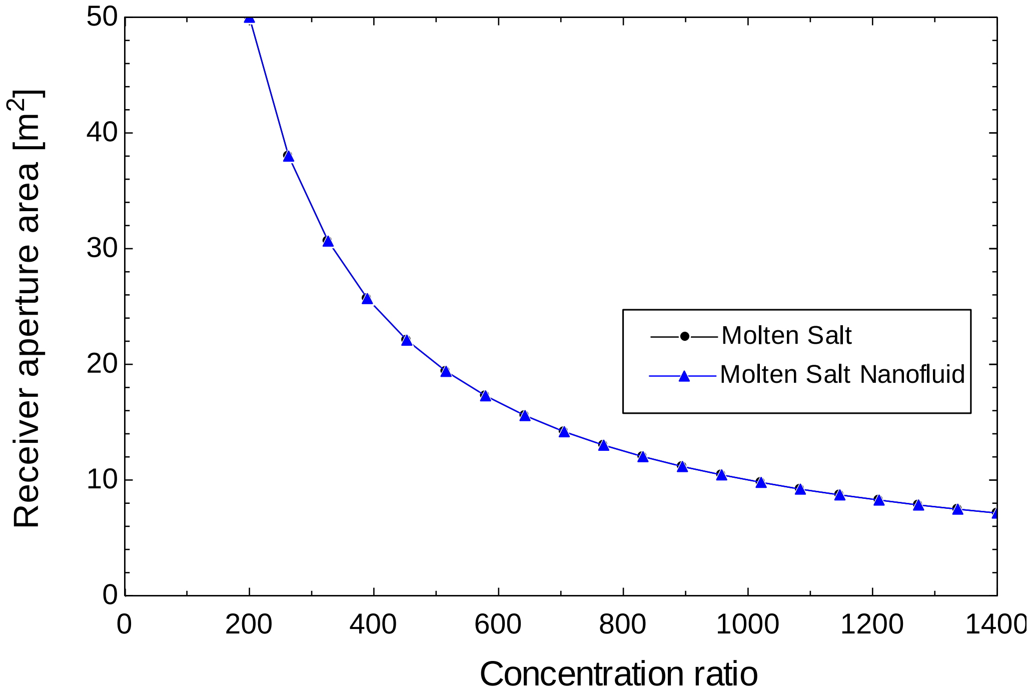

Fig. 38 - Influence of concentration ratio on aperture area

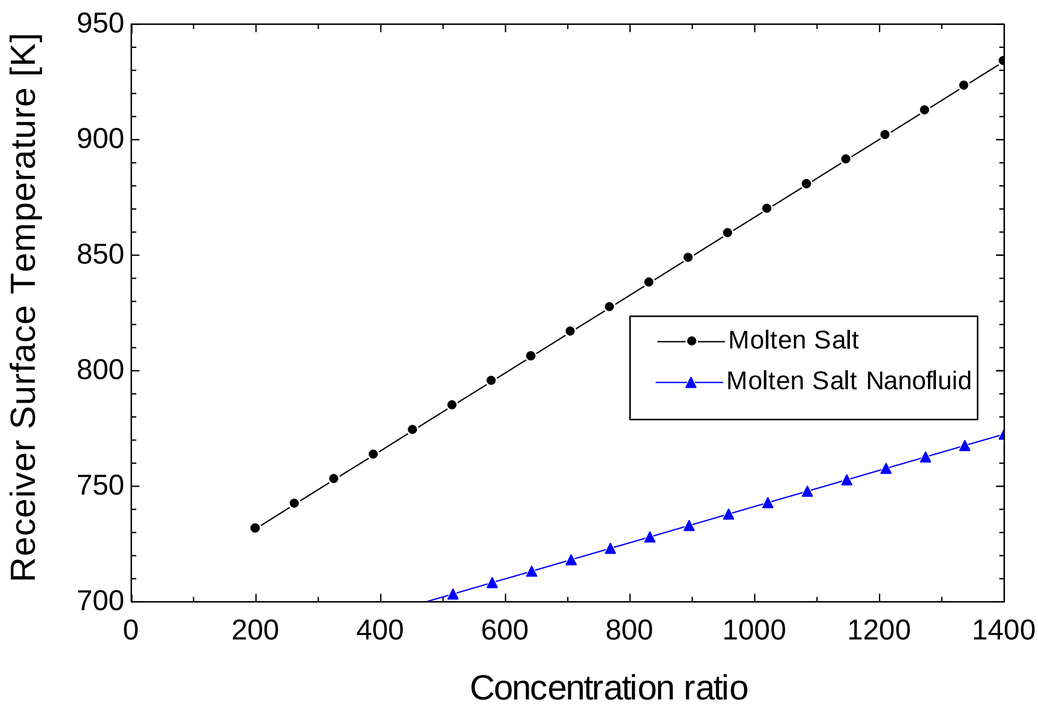

Fig. 39 – variation of receiver surface temperature with concentration ratio

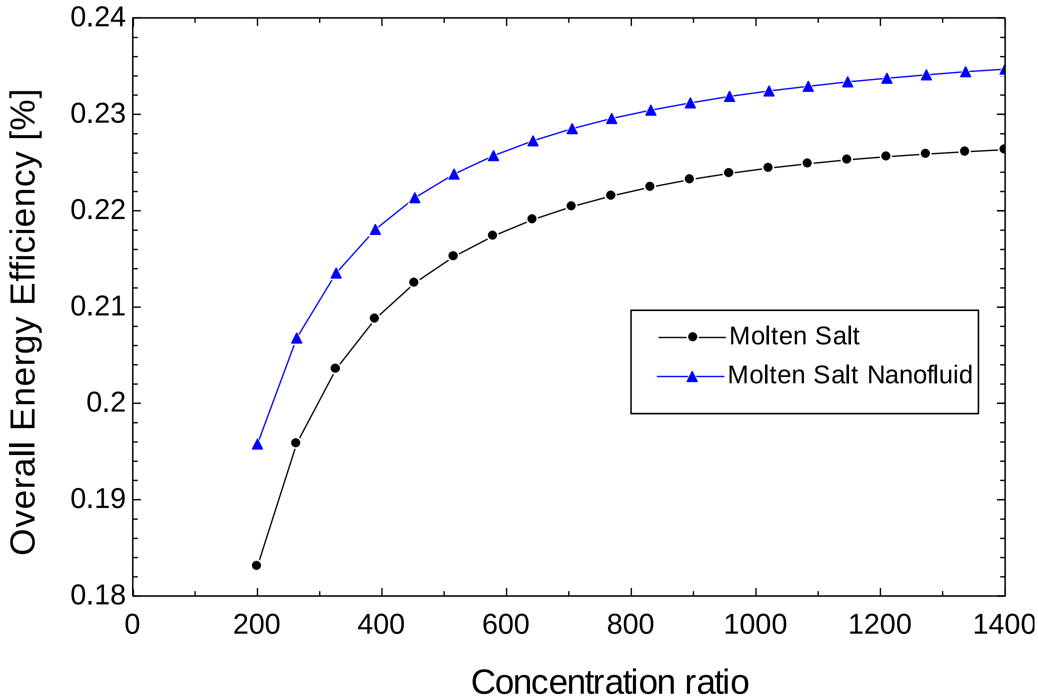

Fig. 40 - Influence of concentration ratio on overall efficiency

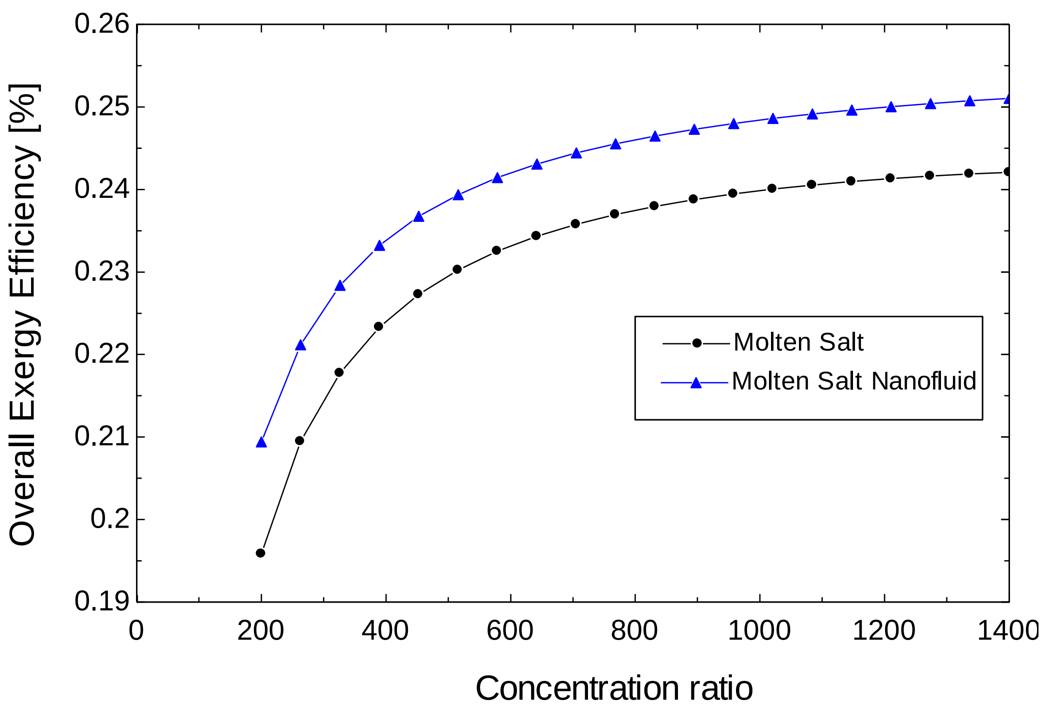

Fig. 41- Influence of concentration ratio on second law overall efficiency

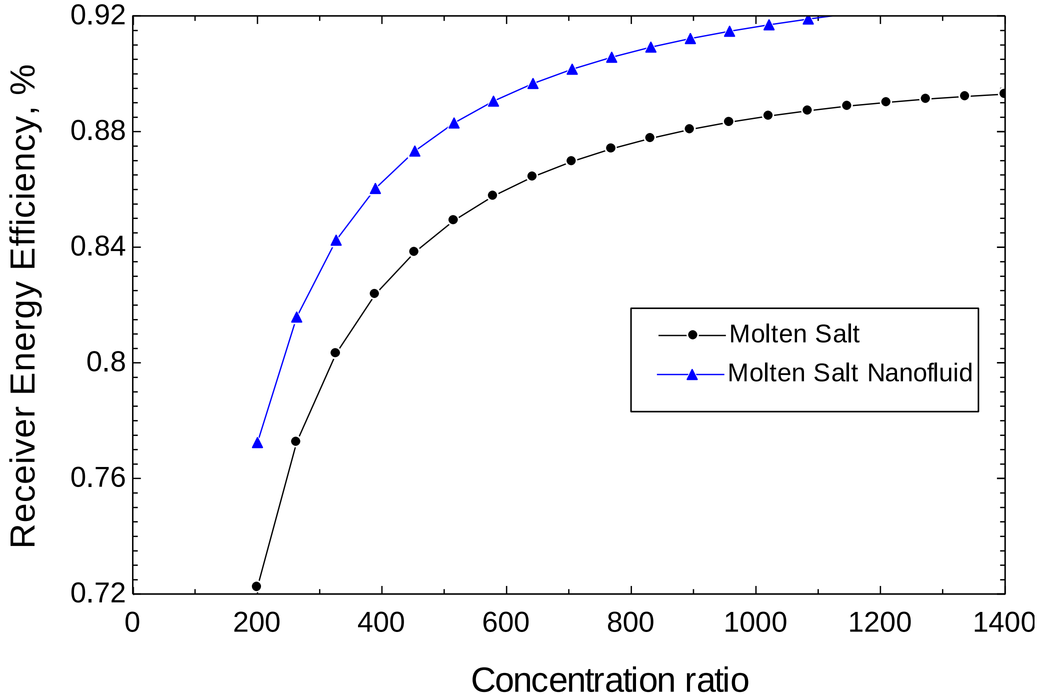

Fig. 42 - Influence of concentration ratio on receiver efficiency

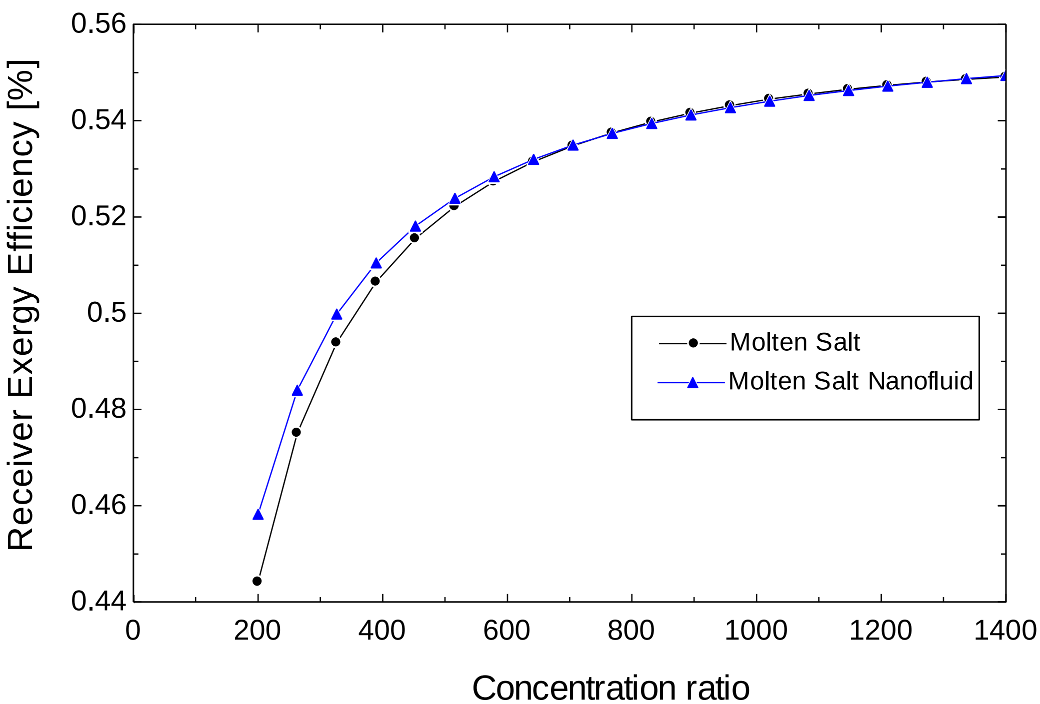

Fig. 43 - Influence of concentration ratio on second law receiver efficiency

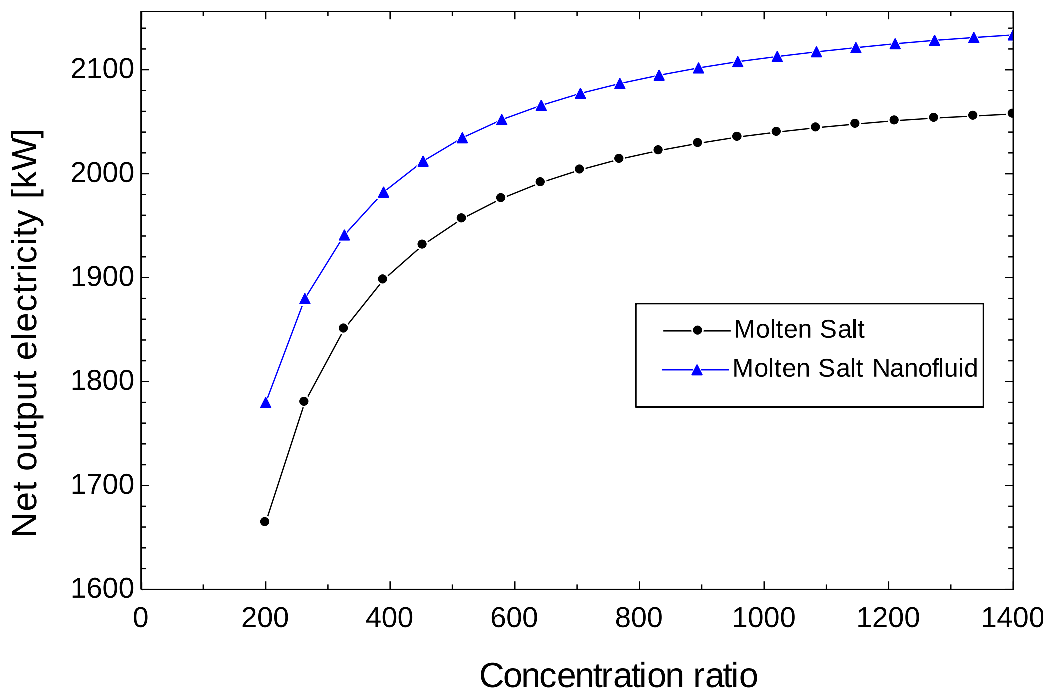

Fig. 44 – Variation of net work output with concentration ratio

Concentration ratio of solar field is a vital factor while designing to increase the efficiency of the central receiver. So to study the energy & exergy efficiency variation with concentration ratio of receiver and entire system, the concentration ratio is varied from 200 to 1400, while fixing area of heliostat field. So we see that, when we increase the concentration ratio the aperture area decreases sharply first & then decreases slowly, shown in Fig. 38. As concentration ratio affect the solar radiation which fall on the receiver which is shown by fig 39, which shows the increase in receiver surface temperature with increase in concentration ratio and receiver surface temperature is depended on solar flux as given by equation (23).

So with increase in concentration ratio receiver surface temperature increases, so the losses due to convection and radiation are also increases but aperture area is decreasing, so losses are reduced.

The energy & exergy efficiency is also depended on the concentration ratio as shown in fig (39-43). The energy & exergy efficiency increases with concentration ratio.

5.3 Energy and Exergy Result

Subsystem	Energy analysis			
	Received (KW)	delivered(KW)	Loss (KW)	Efficiency %
Heliostat field	8000	6000	2000	75
Central receiver	6000	5446	554	90.77
Steam generation unit	5446	5446	0	100
Power cycle	5446	2091	3355	38.4
Overall	8000	1840.6	6159.4	23.01
Subsystem	Energy analysis			
	Received (KW)	delivered(KW)	Loss (KW)	Efficiency %
Heliostat field	7479	5609	1870	75
Central receiver	5609	3037	2571.5	54.15
Steam generation unit	3037	2863	174	94.26
Power cycle	2863	2091	772	73.05
Overall	7479	1840.6	5638.4	24.61

Table 2 – Result calculated using nanofluid

5.4 Future Scope

As mixing of 0.5% of SiO_2 nanoparticle increases the efficiency of receiver by 1% . So there is improvement in the receiver and overall energy efficiency and exergy efficiency. So by using nanofluid the outlet temperature is also reduces for the same mass flow rate which also reduces the losses . So nanofluid can also be used for the thermal storage system due to high specific heat. So using molten nanofluid as a HTF in receiver efficiency can be increase by 1% and cost of molten salt nanofluid is less than pure molten salt .So in less cost we are getting more efficiency and material cost is also reduce in thermal storage system.

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APPENDIX

Table A-1

Properties of the base case solar tower power plant [2]

Subsystem	Properties	Values	Unit
Heliostat field	solar radiation (DNI)	800	W/m^2
	overall field efficiency	75%	
	Total heliostat aperture area	10000	m^2
Central Receiver	Aperture area	12.5	m^2
	Inlet temperature of HTF	290	^oC
	outlet temperature of HTF	560	^oC
	View factor	0.8	
	Tube diameter	0.019	m
	tube thickness	0.00165	m
	Emissivity	0.8	
	Reflectivity	0.04	
	Wind velocity	5	m/s
	Passes	20	
Steam generator	Inlet temperature of water	239	^oC
	outlet temperature of water	552	^oC
	Ambient Temperature	20	^oC

Table A-2

Properties of state point in steam power cycle [2]

State point	Temperature(^{o}C)	Pressure(KPa)
1	45.8	10
2s	45.9	3150
2	46	3150
3	236.6	3150
4s	238.7	12600
4	239	12600
5	552	12600
6s	327.4	3150
6	353.5	3150
7s	45.8	10
7	45.8	10

Table A-3

Comparison of properties of pure molten salt and molten salt nanofluid [7]

Properties	Pure molten salt	Molten salt nanofluid
Melting point (^{o}C)	96.8	106.8
Decomposition temperature (^{o}C)	612	610
Average Cp(J/g.K)	157	1.95
PC $/Kg	1.6	1.6
Heat storage(KW.h)/kg	0.19	0.217
TC $/KW-h	8.2	7.2