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Rankine Cycle Coupled with Heliostat Solar Receiver; A Review

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Abstract: *The present energy scenario needs a revolution by transforming from conventional energy sources to renewable energy sources. In this paper try to review on the past studies or researches which is based on renewable energy sources (mainly solar-based) such as solar thermal power plants, Solar plants coupled with heliostat field, solar receiver system etc. and try to concentrate disorganized energy at a single place in an organized form. After review, Concentrated Solar Power (CSP) technology and its application studied in detail. A detailed paper-based on CSP technology will try to publish followed by the paper in which its design and its application will discuss.*

Keywords*: Heliostat, Central receiver, Rankine cycle, solar thermal, receiver's tube simulation, Concentrated Solar Power (CSP).*

1. INTRODUCTION

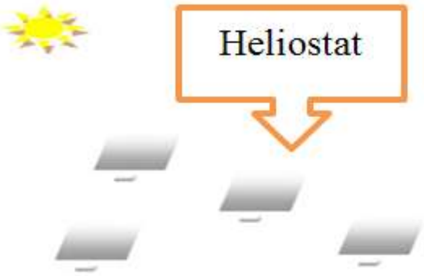
Why the Rankine system coupled with heliostat solar receiver?

In this epoch, there is a global energy crisis in India mostly as compared to other developed or some other developing country and this is increasing day by day because of the population, living style of citizen's increases consistently, and they mostly depend upon conventional energy sources. To overcome this serious issue, this is very necessary to initiate some alternative solution. Therefore, to fulfill this energy demand in future it is necessary to transform from conventional energy sources to renewable energy sources because conventional sources are limited and create too much pollution due to high carbon content. Another problem from conventional sources such as coal, it produces too much ash after burning, which is so difficult to handle. Therefore, in this paper, it is trying to minimize the consumption of conventional sources (i.e. coal) by coupling the Rankine cycle with solar energy sources.

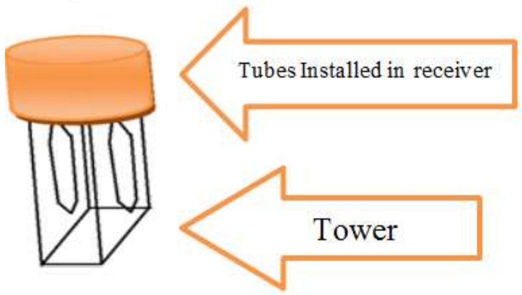
So, this method focused on the concentration of solar energy into a particular area to produce a large amount of heat, this heat will further utilized in the generation of electric power. This sun's energy concentrated at a particular area using so many highly reflective mirrors called "heliostat". Heliostats install in such a way that it concentrates a large area of sunlight (or solar energy) onto a small area (called receiver) at a nominal price compared to photovoltaic cells/plates. There is some other beneficial advantage of Concentrated Solar Power (CSP) system as we compare with other conventional sources such as nuclear, coal etc. The main advantages are it is cheap, reliable, flexible (depend upon design) and easy to install. If Concentrate Solar Power (CSP) system will couple with the traditional Rankine cycle in which most of the thermal power plants runs, the coal consumption will very low and it can easily operate at night without any obstacle. This can be achieved economically [1, 2] by implementing new technology, which enhances the efficiency of solar-to-electricity and also by proper optimization of operation and maintenance. There is another option to produce Rankine steam/gas cycle, in which steam can generate directly inside the tube with the help of parabolic trough solar collectors, on another hand; a good option uses high dense gas particles, containing some tiny particle that can easily fluidized at low speed of gas. The fraction of particles within the suspension is high i.e. around 40% by volume [3] resulting in a fluid with a high density (above 1000kg/m^3), due to the use of high density fluid the heat exchange between solar collector and convection heat fluid enhance (which is around or above 500 W/m^{2}K) [4]. The temperature inside the receiver cavity can be too high [8] for feeding a Rankine steam cycle of standard values. Use of ceramic particles in receiver/absorber tubes is highly beneficial to sustain the temperature around 1000^{0}C [5]. France has justified the feasibility of fluidized based solar receiver in which particles moving upward through cylindrical tubes with the help of air as entrance gas and the temperature of this type of solar receiver up to 650^{0}C have experimentally tested [6]. The kinetics of the flow in a combustion boiler inside the heated tubes well-known phenomenological correlation as the Lienhard expression for the film heat transfer coefficient [9]. Concentrated solar power generation mainly depends upon two factors, one is absorbing collector/receiver arrangements and other is working fluids, both are inside the collector and should in the thermodynamics cycle [10]. The central receiver should install at the peak of the tower to optimum absorption of the solar radiations, to overcome the problem of shadow formation caused by the tower height. There are different receiver configurations [11]. The 1st commercial plant of this technology found in Spain [12]. For a design point of view, it is mandatory to focus that the total area of the collector/receiver surface should must larger in width and height. Hence, this paper tried to present the new concept of concentrating solar power (CSP), heat exchanger.

1.1 These are the following main components of CSP System:

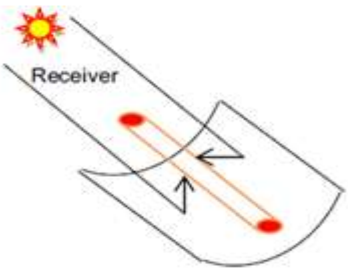
A) Heliostat



B) Central Receiver and Tower



C) Concentrator



2. HISTORY OF CONCENTRATING SOLAR POWER USING HELIOSTATS

Actually Concentrating Solar Power (CSP) technology is not a recent innovated technology, It had discovered so many decades ago i.e. approximately 212 BC. In 212 BC, Archimedes has first used the mirrors to concentrate the solar rays [22]. During 1615 Salomon De Caux had developed a motor which is driven by solar energy, this motor is consists of glass lenses [22]. At Paris World's Fair exhibition an engine had exhibited which driven by the tiny solar power plant, which consists of parabolic dish collector. At the 1970s, the oil crisis was very high which results in an energy crisis at a high level [23]. To overcome with this kind of crisis in future, during 1984-1991 the first commercial plant had operated in California (USA). After this, so many countries had promoted the advancement of CSP technology because the price of gas and oil fluctuate consistently at that time.

3. CURRENT ENERGY SCENARIO OF INDIA

In India, most of the energy-producing thermal power plants and manufacturing plants are dependent upon the conventional sources mainly coal but in upcoming decades, they will not able to fulfill the demand of upcoming decades due to the limitation of energy sources. The scenario of the previous six years cocking coal imported by the manufacturing units such as SAIL (Steel Authority of India Limited) to fulfill the indigenous availability and requirement is as follows:-

	2013-14	2014-15	2015-16
Total coal import (Million Tons)	166.86	217.78	203.95
	2016-17	2017-18 (Prov.)	2018-19* (Prov.)
Total coal import (Million Tons)	190.95	208.27	235.24

Source: https://coal.nic.in/content/production-and-supplies (*import up to April-March 2018-19).

3.1 Main advantages of CSP technology

These are the main advantages of CSP technology:

- This system is mainly depending upon the non-conventional energy source i.e. Sun.
- This system helps to reduce the dependency of fossil fuel.
- CSP system is also eco-friendly.
- It does not produce any kind of noise.
- No, any harmful exhaust produces by this system.

4. LITERATURE REVIEW

Literature review plays a very important role in the plot of research work. To achieve a successful result previous research helps like a footprint of success. To innovate something new, a researcher needs some tools such as some relevant thesis, previous research papers, dissertation and some other sources of information like the internet.

Some important terminologies are:

- Heliostat: Reflective mirrors have mounted in such a way that sunlight reflects in a constraint direction in a particular area.
- Central tower: It is a tower-like structure, which is located in such a way that the solar radiations can focus or concentrate at a particular height.

- CSP: The abbreviation of CSP is Concentrated Solar Power (CSP).
- Receiver: A container generally mounted at the peak of the central tower in which fluids flow inside the tubes, which collect the solar radiation and collected heat is transfer to the flowing fluid.

In a central tower receiver/collector power station, arrays of sunlight reflected from Heliostat are collect at the peak of the tower [13]. At the top of the tower, the receiver collects all the radiations coming from sunlight and utilizes the heat energy into the conversion of outlet water/steam into high temperature and high pressure. This heated water/steam can be further proceeding in the Rankine cycle for the generation of electricity. Heliostats install on the ground in a particular manner so that the sunlight collects the rays at small area due to which it produces a large amount of heat energy. The technology of producing solar power based on Fresnel concept. According to Fresnel concept, the hollow hemispherical curved mirror split into small pieces and then further arranged on a common Centre (as shown in the figure: 1-d). This advancement helps in the enhancement in efficiency and in the reduction of cost. The simple option is the use of a parabolic dish, which is mounted directly facing the sun. To reduce the height of the tower (focus point), concentric parabolic dish arrangement has introduced (fig: 1-c). After this, the design has further optimized to avoid the negative shadow of the dish by increasing the distance between the mirrors, as shown in fig: 1-d and the final arrangement called as standard Heliostat.

Fig: 1-a

Fig: 1-b

Fig: 1-c

Fig: 1-d

Fig: Evolution of design from a simple concept to advance technology.

(Fig. source: Nils Björkman thesis, Sweden 2014)

In large power plants, where the number of heliostats is 100 or more than 100, needs an advanced sun tracking system because the earth rotates around the sun that means between sun and earth there is a relative motion between them. So to collect the optimum amount of sunrays from sunshine to sunset at the receiver it is mandatory that the reflect angle of heliostat should be set as per the rotation of the sun.

(Picture source: Google)

Principle of Heliostat sun-tracking:

The instantaneous position of the sun can be defined with the help of two angles i.e. azimuth angle and altitude angle in the horizontal coordinate system. The algorithm of solar position gives the exact location of the sun from the current longitude, the latitude of the site and the time of observation at any instant [16]. The energy source of the CSP plant is sun or solar radiations. The calculation for the trajectory path of the sun can calculate with the help of heliostat formula i.e.

If “j” is an even number then,

$X_{ij} = i * 2 * L_x$ (j=±1, ±2, ±3, ±4…)

Else,

$X_{ij} = 2 * (i + 0.5) * L_x$ (j=±1, ±2, ±3, ±4…)

$Y_{ij} = \pm R_{min} + j L_{y/2}$ (j =±1, ±2, ±3,±4…)

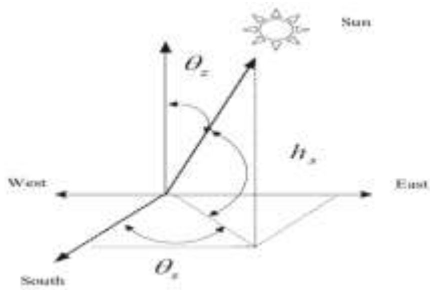


Fig: Schematic of the sun’s position

Where, h_s= Altitude angle

The little change takes place in azimuth angle of the sun in a year; on the other hand, the significant changes take place over the period in latitude angle. In summer solstice angle of latitude is largest where in winter solstice the latitude angle is least [15].

In a design point of view, heliostat mirror orientation plays a very important role to collect the optimum amount of solar radiation. According to (Spellning, 2012), these are the following factors on which the Concentration of optimum solar power depends.

- The reflectivity of the mirror should high.
- Optical precision should also high.
- Efficient sun tracking system.
- Resistant structure.

According to Nussbaumer, 2011 [17], the cost of the heliostat increases due to the high-speed flow of wind. Since this, high-speed flowing winds produce a mechanical force on heliostats. These forces affect the heliostat mainly in two ways; primarily, it produces rigidity problem i.e. due to wind load the mirror support structure can be elastically deformed. This circumstance minimizes the quality of reflected light. In a secondary way, it produces a strength problem; in this case, the structure may fail after several load cycles because wind force is overloaded.

Sandia National Laboratory (SNL), which is the most experienced laboratory in the CSP field, located in the U.S.A., they performed a cost reduction study and claimed that the picture shown below is the most feasible.

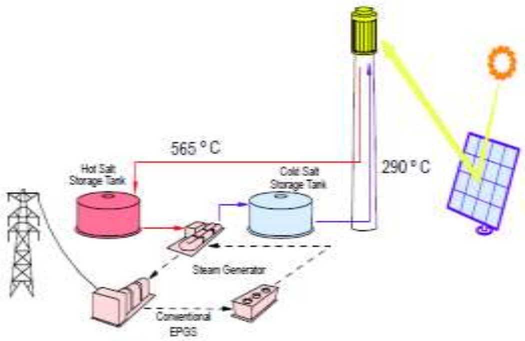


Fig: - Proposed picture by SNL.

(Image Source: Kolb, 2007)

The main points to note from this study are:

- Rankine-Cycle appears feasible (Kolb, 2007) on power-plant size of 100 MW.
- Thousands of heliostats, each of area 50-150 m^2 reflect the sunrays to the central receiver, which mount at the peak of the tower.

Mirror Geometry: An ATS-heliostat of size 147 m^2, the simulation done by Sandia in 2007, they found that the fully flat mirror panel would have given the best economy from a system perspective's view.

5. THE BASIC FEATURES, CONCEPT AND WORKING PRINCIPLE

The working principle of the CSP system and the concept behind this technology can be understood with the help of a flow diagram, this flow diagram shown in fig (A) below.

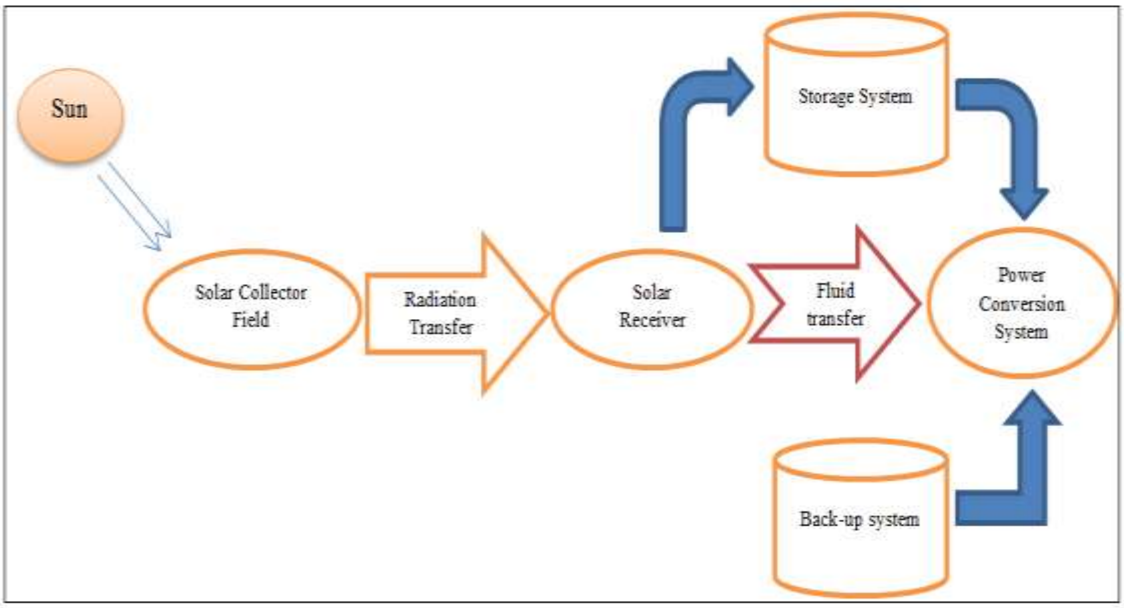


Fig (A): The picture shows the flow diagram of a CSP system.

The basic concept can understand with the help of the above flow diagram. The first solar collector receives the solar radiations with the help of some collector field (i.e. sometimes Heliostats are used) after this collected radiation transfer to the central receiver, which is mounted at the top of the tower to overcome with the effect of shadow. In this, central receiver tubes install in which fluid flow. These flowing fluids absorb the heat and perform two types of functions i.e. sensible heating, which raise the temperature of flowing fluid and other is latent heating which changes the phase of same flowing fluid (i.e. if the water is flowing then it will change into the form of vapours). In doing so, the temperature and pressure of flowing fluid raise and this heated fluid transferred to the Power Conversion system for further process. Here the power conversion system may be different, this depends upon the condition (i.e. it may be Rankine cycle or some other cycle). Now days mostly in India Rankine cycle are mostly preferred in thermal power stations as a power conversion system but instead of this Brayton cycle, combined cycle or Stirling cycle for parabolic disc technology [24] can use. Nowadays there is an important issue is advanced Brayton cycle with pressurized air [25]. To enhance solar power technology $C0_2$ and steam cycle, air Brayton cycles are well-positioned [26,27,28].

These are the following features of CRS:

- It offers a very high range of temperature (up to 1000 ^{0}C) due to which higher efficiency can be obtained [29,30]
- There are so many varieties of option to use it with the hybrid operation and used with fossil plants.
- It can be able to generate electricity with high capacity factor such as 0.40 to 0.80 [29] with the help of thermal storage [31].
- Can also help in cost reduction and improve efficiency (up to 40-65%) [29, 30, 31].

Solar thermal power station mainly consists of three sub-systems (shown in fig (B)), which are mention below-

1) Heliostat field, it consists of a large number of the heliostat in which reflecting mirrors are mounted.
2) The second system called solar receiver, solar receiver installed at top of the central tower. It placed in such a way that all the solar radiation can be collected at a particular region and convert the all heat energy into raising the temperature of the flowing fluid. The upper working temperature can range from 250 ˚C to 1000 ˚C [29, 30].
3) Moreover, the third sub-system is the main component of power plant i.e. Power conversion system which may be based on the Rankine cycle, gas turbine cycle etc.

These are the following advanced research projects, which based on the CSP system,

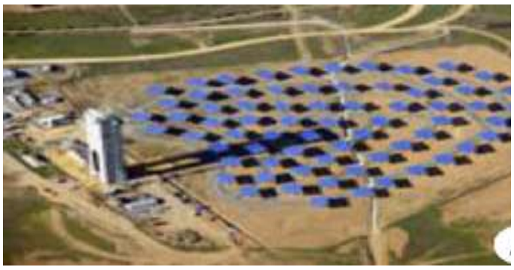


Fig: SOLUGAS project at the Solucar Platform, it has installed in Seville, Spain [32].

Fig: Central receiver with variable Geometry at CTAER [32].

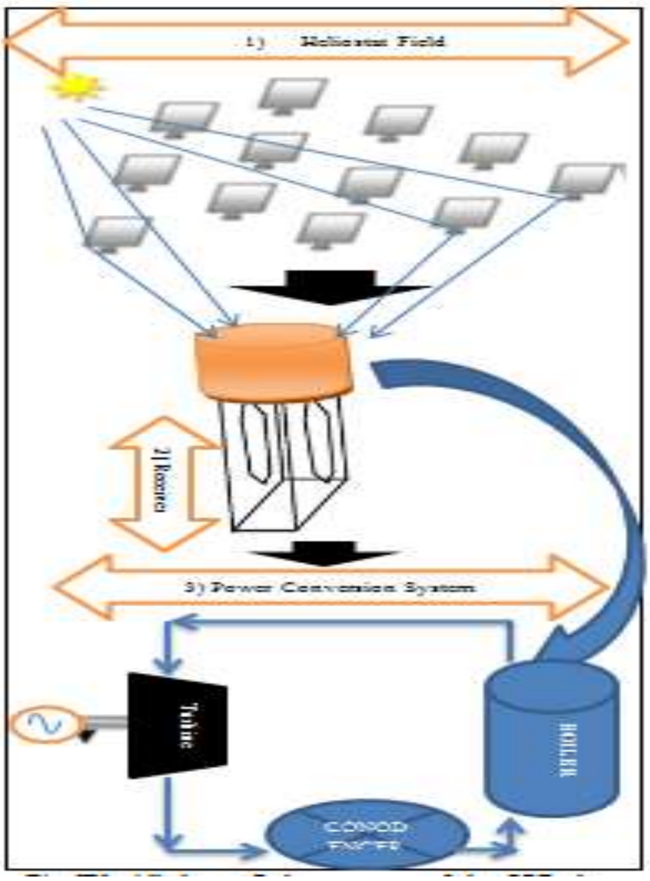


Fig (B): All three Sub-systems of the CSP plant

6. OBJECTIVE:

These are the following objectives are expecting from the present work:-

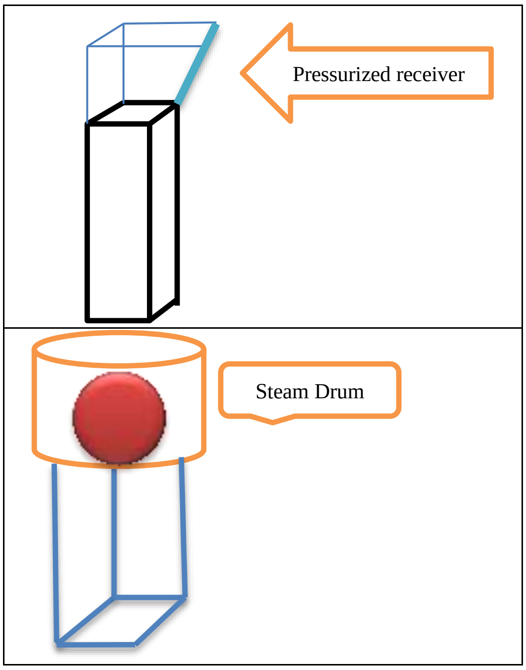
The main objective of this work is to concentrate all the disorganized solar energy into a particular zone or area in an organized form. The second objective is to analyze central receiver at different parameters such as Temperature-pressure variation, stress variation etc. and the third objective is to compare the variations at different parameter such as stress concentration, temperature distribution etc. in the circular cross-sectional tube versus elliptical cross-sectional tube.

7. OUTLOOK

In this review, it has observed that the central receiver technology is propagating rapidly. Mostly in four countries which are Spain, China, Germany and the USA. These countries have started broad R&D projects on this technology.

8. CONCLUSION

To overcome the upcoming energy crisis, solar energy is one of the best substitutions of the conventional energy source (mostly in India) because India blessed with solar radiation [33]. For the advancement in thermal applications, CSP technology can contribute and can play an important role in power generation in upcoming decades. This also concluded that the design of the solar receiver can vary in geometry and can base on a different concept. These are the following two types of the proposed model of central receiver.



In order to enhancement in the collection of the optimum energy with the help of the sun-tracking system, there are mainly two methods are preferred: which are Azimuth-Elevation (AE) and Spinning-Elevation (SE). This helps to collect more energy collection at receiver.

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