Review on advance tubular receivers for central solar tower system

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Abstract. This review focused on central tubular receiver modelling to obtain concentrated solar energy. Required specifications involved with efficient low cost receiver with suitable material which able to absorb concentrated solar radiations. This type of advance receivers shows excellent performance in the commercial and domestic applications. Review shows compiles literature engaged in mechanical and thermal modelling of receiver. Also highlighted on various geometries, tube sizes and various heat transfer fluids and their effect on overall performance of receiver. Recently authors concentrated on CFD simulations of different kind of receiver and put forth advanced design which offers superior flexibility and accuracy also explains stresses generated in the tube of receiver. The selection of stress theory is impacting on the mechanical life of the receiver with different approaches presented. Extensive technical analysis is investigated on different receivers for internal and external tubular geometry. Effect of heat transfer for different geometry is also observed. In this paper different aspects discussed thoroughly like receiver design, Numerical simulation, outdoor and indoor testing facilities, thermal efficiency and desired outlet temperature, benefits, future challenges, and research needs.

Keywords: Concentrating solar power, Tubular receiver, Cavity, HTF, Particle receiver

1. Introduction
The main challenge in the next generation is climate change due to CO₂ emissions main source is due to combustion of fossil fuels for transport and power generation. Recently European Union and UNFCC asserted on 70-80% decrease in the CO₂ emissions by 2030. The CO₂ discharges have adverse impact on the environment as rise of overall temperature of earth, melting of the ice bergs and worldwide extreme weather conditions. Furthermore, Price of crude oil, natural gas and all other conventional fuels has been increased for last decade also it is forecasted to increase in price from $120/barrel to over $200/barrel in 2025. Use of non-conventional energy source is the only solution. This policy will help nation to reduce fossil fuel import as well as to reduce carbon emissions.
Concentrated solar power (CSP) is next generation renewable technology which can reduce dependence on conventional fuels in areas where solar radiations are available in the range of 1500-2500 kWh/m²/year. It is forecasted to contribute to about 15-18% to worldwide energy production by 2030. Today there is near about 6 GWe of installed CSP capacity worldwide, and a further 5 GWe plants are in under installation phase till 2022 [3, 4, 5, 6, 7].

CSP systems are mainly classified as; parabolic trough, Fresnel lens concentrator, dish concentrator (Parabolic), and Solar tower. The main concentration of this review is on central tower system or CSP Technology (Fig. 1), which is predictable to grow faster than other renewable technology in the future. Concentrating solar thermal (CST) concentrates solar radiation and transfer this energy to heat transfer fluid for high-temperature thermal energy applications, like heating, power plant, process heat, energy storage, material processing, and pharmacy applications, etc. In the CST power plant, heliostats which are known as mirrors are arranged in a specific manner so that solar radiations reflected and concentrates at a one point on receiver which is installed at top of the tower. “This resulting into increment in the temperature of the working fluid. Then absorbed thermal energy by receiver is utilised in the cycle for power generation, generally use in high-temperature Brayton cycles is predominant” [3, 8, 9, 10]. As solar radiation concentrates at one point it facilitates to obtain High temperature of HTF in the receiver, also positive impact on the thermodynamic efficiency. Various HTFs are used in receiver as Water/steam molten salts, nitrate salts, liquid metals according to temperature range. Receivers are categorized by the

| Project                  | Developer     | Country     | Start | MWe | Receiver | Working fluid |
|--------------------------|---------------|-------------|-------|-----|----------|---------------|
| Luneng                   | SEPCOIII      | China       | 2018  | 50  | External | MS            |
| Ashalim (Plot B)         | MSPL          | Israel      | 2019  | 121 | External | Water         |
| Noor Ouazarze III        | SENER         | Morocco     | 2015  | 510 | External | MS            |
| Dunhuang Phase II        | Beijing Shouhang | China   | 2018  | 100 | External | MS            |
| Dunhuang Phase I         | Beijing Shouhang | China   | 2016  | 10  | External | MS            |
| Khi Solar One            | Abengoa Solar | S. Africa   | 2016  | 50  | Cavity   | Water         |
| Crescent Dunes           | Solar Reserve | USA         | 2015  | 110 | External | MS            |
| Ivanpah SEGS             | BrightSource  | USA         | 2014  | 377 | External | Water/steam   |
| ACME                     | E Solar power | India       | 2014  | 2.5 | External | Water/steam   |
| Gema solar               | Torresol Energy | Spain  | 2011  | 19.9| External | MS            |

Concentrated solar power (CSP) is next generation renewable technology which can reduce dependence on conventional fuels in areas where solar radiations are available in the range of 1500-2500 kWh/m²/year. It is forecasted to contribute to about 15-18% to worldwide energy production by 2030. Today there is near about 6 GWe of installed CSP capacity worldwide, and a further 5 GWe plants are in under installation phase till 2022 [3, 4, 5, 6, 7].

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Figure 1. Schematic diagram of Concentrated Solar Tower
state of HTF as gas, solid or liquid. This review focused on all types of recent receiver designs on the basis of geometry and working fluid. Recently main focus of researcher is on liquid receiver. There has been constant development in tubular receiver design over the decade. Due to latest advances in receiver technology various researcher concentrate on the Mathematical models and simulate these models for thermal and mechanical design of receiver for dissimilar boundary conditions.

2. **Commercial CST Project**

![Figure 2. A) LunengHaixi, B) Ashalim Plot B, C) NOOR III, D) Dunhuang Phase II, E) Khi Solar One, F) ACME India [3]](image)

There have been many notable updates of installations of central solar tower projects around the world till 2019. We have tried to mention these notable projects with their technical details and data. For deeper understanding an overview about these projects have also been mentioned. Fig 2.A) LunengHaixi 50MWe Molten Salt Tower Concentrated Solar Power with an area of 600000m² which covers solar radiation field along with use of more than 4500 heliostats (138m²) The solar tower height is approx. 180m out of which 150m height is constructed with concrete blocks. Solar radiations concentrate along the periphery of cylindrical tubular receiver with solar salt (MS) is used as a working fluid in receiver. Fig.2B. The Ashalim Thermal Power Station, situated in Negev desert, which is a desert area located in Israel. is one of the biggest projects of its type in the world. It is also the foremost concentrating solar power plant erected in Israel by the partner businesses- GE Renewable Energy, Bright Source and the Noy Fund. Capacity of CSP is 121MW installed with external tubular receiver and water as a heat transfer fluid. Fig.2C. Noor III CST plant situated in Morocco having 134 MW running capacity with molten salt external receiver. This plant has started in 2018 with thermal storage capacity of 7hrs per day. [11, 12, 13, 14]

Fig.2D. Dunhuang Phase II, 100MW MS external tubular receiver CST Project developed at Jiuquan Shi, China. This one of the important CSP project in China. Thermal storage capacity of this plant is 12hrs is now under development by Beijing shouhang group. Fig.2E. Khi Solar (KSO) is the first solar thermal power plant of South Africa having 50MW installed capacity, with 2 hrs thermal storage. Plant area is near about 340 acres out of which 4000 mirrors are located in 4000-acre area. Cavity receiver with steam as a working fluid is incorporated in the plant. Fig.2F. This plant has a capability of generating 2.5MW
which was put up in 2011 in Bikaner, Rajasthan, India. This plant has an entirety of 14280 heliostats individually with an area of 1.136 m². E Solar has manufactured the heliostats of this plant. This plant is based on Rankine steam cycle with use of external tubular receiver.

3. Tubular receiver

3.1 External receivers

Liquid based tubular receivers are broadly categorized as external and cavity receivers further classified on the basis of geometry tube material, flow rate and velocity, inlet temperature and outlet temperature of working fluid (HTF). Tube diameter as well as thickness are designed in such way to get maximum heat transfer enhancement with compromising pumping losses. Small tube diameters are always beneficial for convection. At the same time need to give attention on material costs and pumping losses. Optimize tube geometry should be finalized for maximum efficiency at a given pressure. [15, 16, 17]

Exterior tubular receivers are strategically constructed in tube array type aligned in systematic manner via incident focused solar radiations. For further understanding consider Fig 1 in which the figure defines simple billboard design for ensuing generation of high temperature applications.

Borema et al defined “the tubular billboard receiver solitary one side flow inlet through one direction and multiple pass billboard design illustrated in IEA projects.” This advance design that was developed employs variable geometry tubes with variable velocity and mass flow rate. This innovative designed have been conceived to collect equal outlet temperature in non-uniform heat flux over parallel tubes. [18, 19]

Marco Cantone et al “studied 3 absorber tubes for central receiver. Fabricated tubes in Inconel 718 material were smooth and with internal helical ribs tested at solar furnace. It is observed that use of turbulence promoters reduces surface temperature and also it is useful in reducing thermal stresses of the tube wall. As compared to smooth tube use turbulence promoter increases lifespan of component.” [20]

Satyavan et al conducted many experiments on the spiral receiver for small CST system. For the experimentation he has used 5 and 9 heliostats. During experimentation considerable change in average outlet temperature was observed like for 5 heliostats-72.4°C, for 7 heliostats-82°C and for 9 heliostats 92.4°C. Results simulated with the help of CFD and both results were validated with minute error. It is concluded that for small scale CST system arrangement of 7 to 9 heliostats are preferable and it shows positive result The temperature parameter of the water/steam was changed with the number of heliostat and the mass flow rate. After the experimentation the experimental results and observation was noted and it was in compact space. It is found that the highest temperature of 102°C for 9 heliostats for the flow rate of 0.0017 Kg/sec at the time 11.00am to 02.00pm and average temperature of 80.4°C for the whole day. [21]

Conroy et al the multiple pass designs indicates very good results for high temperature uses. It enhances HTF (Heat Transfer Fluid) tube velocity with even distribution flux over entire panel. This design shows considerable increment in the fluid flow path resulting in to increment in overall efficiency due to enhancement in velocity and flow rate of fluid. Which enables reduction in tube diameter with higher power output with considerable pressure drop. [22]

Wen-Qi Wang et al studied the performance of fin like molten salt receiver and compared the data with simple cylindrical structure. In that experiment tubular panels were arranged as a fin construction along cylindrical circumference. As illustrated in fig. After experimentation the experimental data/observation were noted and after careful examination it was observed that for the same diameter as the number of tubes of simple cylindrical receiver rises with increase of overall efficiency. “Fin type
receiver’s maximum efficiency is around 87.3% which is 3.7% higher than cylindrical receiver with an added benefit of considerable reduction in thermal stresses but on the other hand a disadvantage is that the cost of the fin like receivers is two times more than conventional receivers.” [23]

MR et al “created external tubular cylindrical receiver (TETR) at Gemasolar power plant assembled with various valves that allows subdivision of segments for each panel into the 2 different panel. This design is built on principle of VVR (variable velocity receiver) with benefits of reduction in solar field size by 12.5% due to enhanced aiming strategy. This design uses alloy 800H tube material with 60%NaNO3 and 40%KNO3. It shows increment in overall efficiency and reduction in tube wall temperature so that it solves problem of overheating of the tube.” [24]

Maria Lopez-Herraizet al conducted experiment on external MS receiver in non-homogeneous heat source condition. Initially tube is heated by electric heater coil which is wounded on the tube surface. It is noted that total temperature difference is290 °C approx. with 0.8 m/s velocity. During trial thermal stresses and deformation were developed. So that high flow velocity is recommended to reduce thermal stresses.[25]

Zhirong Liao et al successfully developed a scientific model by using governing equations and heat transfer correlations. This model is used to determine maximum heat flux density on two solar receivers. It is published in the data as in order to attain high heat transfer flux on the receiver’s different parameter needs to change like, Material of receiver tube with high strain, Increment in velocity of the fluid, Reducing overall resistance, Diameter and Thickness of the tube. Finally, it is concluded that highest density of heat flux is achieved by using molten salts as a working fluid. It shows better results than use of water as a working fluid. [26]

3.2 Cavity receivers

Cavity receivers are now popular in commercial CSP power plant. Currently three cavity receivers installed successfully for power generation. PS10-10 to 15 MW and PS20-25 to 30MW located in Spain, Khi Solar -130MW located in South Africa. All these plants installed by advance MCRT optimized heliostat field. [6]. Cavity receivers are always preferred over external tubular receivers due to less radiative and reflective losses resulting in to higher thermal efficiency. However, these receivers have some limitations as spillage loss, restrictions to heliostat layout, complexity in cavity design, low temperature range, working fluid. To adjust these restrictions cavity receivers are generally installed on a higher height than external receivers leading to increase in overall installation cost. [20, 27, 28]

Kuldip et al did many research and experimentation on inverted conical and conical cavity receivers. The experimental data observed by them in inverted conical and conical cavity receivers were compared and contrasted with experimental data of conventional cylinder receivers. They thoroughly analysed each aspect. Like geometry of receivers, radiation absorbed, overall thermal
After thorough analysis of the aspects they observed that thermal performance of conical and inverted conical is considerably better than cylindrical cavity. After further research and observation, it was concluded that inverted conical displayed better performance than conical cavity as 27.6% increase in Nusselt number with almost same pressure drop. [29, 30]

Zhou Si Quan et al established a 3D model by using MCRT method and CFD of the spherical cavity receiver to analyse thermal and optical functioning of the receiver. Results revealed that more uniform distribution of flux with 88.9% optical efficiency which is more than other cavity shapes. Convectiive loss and overall efficiency is directly related to D/d ratio. It shows best results in range of D/d 1.0 to 2.5 with inclination up to 90°. It is concluded that the differences between inlet and outlet temperature of the tube decreases inversely with increasing D/d ratio. [31, 32]

Santosh B. Bopche et. al. “have conducted experiment on a cavity type solar receiver with steam as a working fluid. Overall performance of receiver is analysed in extreme windy condition atmosphere. Heat transfer correlation for boiling condition is developed to calculate flow rate of atmospheric air is and to determine energy absorb by receiver. MCRT method is utilized for this calculations. They found that heat loss from cavity receiver is maximum when atmospheric air reached to its highest value.” [31, 33]

Qiang Yu et al built a 3D Model of the DAHAN power plant receiver. This is cavity type structure and cover with aerosol carbon insulation entrapped. This model is optimized for ray tracing with FVM and MCRT method. Further model is investigated on the basis of temperature distribution and overall thermal efficiency. Cavity receiver analysed in steady state condition of mass flow rate of steam, velocity, Reynold number of steam flowing in receiver tube is calculated. [34, 35]

Gurcan Tiryakii et al successfully developed a model for a cavity receiver. In the model different parameters are analysed as view factor, CR (concentration ratio), temperature rise, overall heat loss, etc.
After trial it was observed that efficiency of receiver value stands between 86 to 97% as changes in view factor. It was also observed that efficiency of receiver value stands between 83 to 90% as variation in concentration ratio. After through research and experimentation it was finally concluded that around 1000 concentration ratio and smallest possible view factor shows highest efficiency with minimum heat loss. [36]

Mostafa Abuseadaa et al conducted extensive experimentation and studied novel variable aperture mechanism. These mechanisms were for a cavity-type receiver. For his research he conducted experimentation in which they used a solar simulator on receiver with and without their new aperture mechanism. The 15 KW solar simulator is developed and use for experiment trials. This HFSS simulator is rated for 3 different power levels, 8 different aperture sizes. By experimental observation and validated model, they concluded that nearly 50-65% of the receiver’s energy at entry point is lost is lost by reflection and irradiance, further this loss may have recovered by fixing optimum aperture size of the receiver. [37, 38, 39, 40]

C. Ophoffa & M. Abuseada et al fabricated a 3kW cavity receiver and conducted experiments on it. The 15 kWe HFSS simulator used for indoor experimentation as a source of intake energy. After that 1100-1250 temperature contours were observed inside cavity. It is found that distribution of temperature along axial plane is neither steady nor uniform. Due to this at the back side of cavity red hot spot was developed. The solar simulator was used as a radiation source for indoor trial. It is discussed in the in the results as red hotspots on the back plate reduced is possible by change in angle of entry level port. Parametric study was conducted in the study and following outcomes were discussed as for maintaining uniformity of temperature distribution there must be rise in flow rate and velocity of working fluid. Experimental testing was conducted and it was observed that the receiver temperature up to 1200K was measured with solar input at the entrance of the cavity of around 3kW radiative power. [41, 42]

4. Heat transfer fluid

4.1. Water

Water has been frequently used as a working fluid (HTF) in CSP thermal power plant since long time due to good chemical and physical properties. In plant, from storage tank water is supplied to solar receiver where it absorbs sensible as well as latent heat and get converted in to superheated steam then feeds to the turbine. Water has phase transition from liquid to vapour and properties like Thermal conductivity, specific heat, density varies according to phase. Though water is chemically stable but difficult to use at high pressure and high temperature.

As concern to CSP steam superheating separated from water heating/steam production because both have different thermodynamic characteristics as capacity factor and thermal conductivity of water is lower than other HTF. For superheated dry steam heat transfer coefficient inside tube is decreases which leads to inducing excessive pressure thermal stresses resulting in increment in the tube thickness. Ultimately 350°C and 220 bar and 500kW/m² flux density is higher limit to use water as a HTF. Also sensible heat storage for high temperature system become very difficult ex. PS10, PS20 worked for 2 hrs sensible heat storage. Despite of some limitations water is used in high temperature steam generation is implemented in the different commercial power projects; Ivanpah SEGS –USA (No storage), Khi Solar Plant - S. Africa (2Hrs storage), PS10 & PS20 – Spain (1Hr steam accumulation). [43, 44, 45]
4.2. Thermal oils

Thermal oils used initially for small scale solar applications as TherminolVP-1, Downtherm-A, Paratherm, HYTHERM 600 are popular HTF. Thermal oils are compared as per chemical properties a) Synthetic, b) Minerals c) Silicon. Synthetic oils produced by artificial chemical compound process. Ethylene is the very raw synthetic material from which oil is extracted. Base oil is produced by chemical compound i.e. Poly Alpha Olefin or alpha olefin. This is called synthetic technology. Some synthetic oils further classified as semi-synthetic oils, which is mix combination of minerals and synthetic. There are several advantages of synthetic oil use as a HTF like, High operating temperature range from -20 to 400°C, Better viscosity index, Chemical stability, Less oxidation, Nontoxic, Reduced clogging and improvement in overall performance.

Mineral oils have many benefits over the synthetic oil for heat transfer fluid (HTF) applications. As compared to synthetic oil mineral oils are very cheap and easily available so that cost of replacement drastically reduces. Synthetic oils require pressurise at high temperature but mineral oil can operate at atmospheric temperature up to 300°C. Mineral oil is colour less, odour less, no toxic, High heat capacity and can be reused with any fuel for any furnace. Silicone is known as liquid polymerized siloxane with organic side chain. Silicone oil used for special applications due its good heat transfer characteristics and different unique properties i.e. low viscosity, Chemical inertness, low surface tension, Dielectric properties, etc. In spite of this silicone oils are not preferred over synthetic and mineral oils due its higher cost as compared to performance. [44, 46, 47]

4.3. Molten salt

Molten salt has been used since 1992 in central tower power plant and parabolic trough, as a working medium and storage medium. Molten salt is the next generation replacement to thermal oil because of several Advantages. First one is the suitability to operate in between 400°C to 700°C temperature range in the solar thermal power plant which leads to increase thermodynamic efficiency of CSP. Molten salts have many technical feature as compared to other fluids to use it as a HTF like; better density, heat capacity, good thermal stability, low viscosity, better heat absorption, less vapour pressure. MS is very cheap and more economical than other HTF. As the investment price of the energy storage of molten salt is considerably lower than thermal oil and metal fluids. This is because there is dissimilitude in the temperature of hot and cold storage so that stock of storage fluid is reducing by 50%. One of the drawback of solar salt is the high melting and freezing point.[48, 49, 50, 51]

The salt used in mercantile CST plants are secondary and ternary HTF and if other side fluid enters in the heat exchanger with low temperature or in between 100°C to 250°C t then it leads freezing of molten salt. This high melting and freezing point leads to a major threat to the receiver. Main reason behind it is when power plant is not in working condition there is formation of solid state salt block takes place in the receiver tube resulting into breakdown of the plant. However Molten salt receivers have been used from past two decades in high temperature power plants on commercial scale as; Redstone, Crescent (Nevada), YARA, SUPCON, Aurora, MBR solar shown very good results in sensible heat storage up to 12 hrs. [32, 52, 53, 54]
4.4. Metal fluids

Metal fluids have shown magnificent results as a working fluid in the CST tubular receivers. Metal fluids possess many advantages as operation running in high temperature range up to 900°C, high heat transfer coefficient in liquid phase. Generally, metal fluids receivers have combine with the Rankine cycle with subcritical and supercritical steam with upper temperature range 640 °C (Na, Na-k, Pb-Bi). Similarly, for Brayton cycle heat exchange with gas as a secondary HTF in gas power plant operates at higher temperature limit up to 900°C (Pb, Pb-Bi, Sn). Metal fluids are cheaper than other sources as well better energy storage capacity than other fluids. Metal fluids show highest thermal efficiency up to 80% due to these fluids preferred in next generation CST combine power cycle plants. Metal fluids like Sodium (Na), Lead-bismuth (Pb-Bi) and Na-K sodium potassium are popularly used in power cycles for -10 to 800°C. [55, 56]

As compared to the solar salts and other thermal fluids, metal fluids have better thermal conductivity, higher boiling point, moreover for same heat flux metal fluids has higher heat transfer coefficient which reduces temperature gradient in the convection mode on internal surface periphery. This will reduce local hot spot on the tube wall thus it produces lesser thermal stresses. Uniform and lower wall temperature will further reduce overall thermal losses in radiation/convection and material cost of the tube which tends to achieve highest thermal efficiency of the receiver. Ultimately in comparison with solar salts for the same heat flux input receiver size reduces, so overall cost of power plant is also reducing. But this is possible with accommodating some limitations as high melting point leads to increase maintenance cost and running costs. Lead-bismuth eutectic (Pb-Bi) is recently come up with a good alternative to sodium. [57]

It offers a better working temperature range. However, its high heat flux density decreases the heat capacity in energy storage systems, again main disadvantage of large corrosion rate. In future we need extensive research to solve these problems associated with metal fluids. Recently many research groups and laboratories conducting experiments on the liquid metal use in CSP. Ex Vast Solar. Research groups, Australian National University. The 10 kW thermal range domestic sodium receiver for concentrating solar thermal powerplant system is developed in Thermax ltd, Pune, India, [58, 59, 60, 61, 62]

Table 2. Solar salts configurations [55]

| Salts         | Constituent                  | Configuration              | Flash point (°C) | Highest temp(°C) |
|---------------|------------------------------|-----------------------------|-----------------|-----------------|
| Hitec XL      | Chile saltpetre              | 42 wt. % KNO3 +41 wt. % Ca(NO3)2 +16 wt. % NaNO3. | 140             | 500             |
|               | Nitrate of potash Calcium nitrate |                              |                 |                 |
| Hitec         | Chile saltpetre              | 56 wt. % KNO3 +39 wt. % NaNO2 +6 wt. % NaNO3. | 142             | 538             |
|               | Nitrate of potash Sodium nitrate |                              |                 |                 |
| Solar salt    | Sodium nitrate               | 55-60 wt. % NaNO3 + 35-40 wt. % KNO3. | 240             | 600             |
|               | Potassium nitrate            |                              |                 |                 |

Table 2. Solar salts configurations [55]
5. Conclusion
A lot of research work has been conducted on solar receivers for central solar power plant. In this review paper performance of External tubular receiver, Cavity receiver, Volumetric Receivers and Particle receivers is investigated. It is found that external tubular receivers (i.e. Billboard receiver and cylindrical receiver) shows better overall performance than other type of receivers. Due to simplicity in construction and maintenance with addition to better heat transfer characteristics.

For low temperature domestic application Billboard, tubular receivers are more compatible than cylindrical receivers. In this review performance and technical challenges associated with all type of receivers are discussed thoroughly. However, more research focus on tubular billboard receivers is needed in future because like other types of receivers have limitation of space and construction cost. Future scope in existing tubular receivers is like higher operating temperature range, improvement in receiver’s efficiency, selection of appropriate heat transfer fluid with capability

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