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# Advances in Concentrated Solar Power: A Perspective of Heat Transfer

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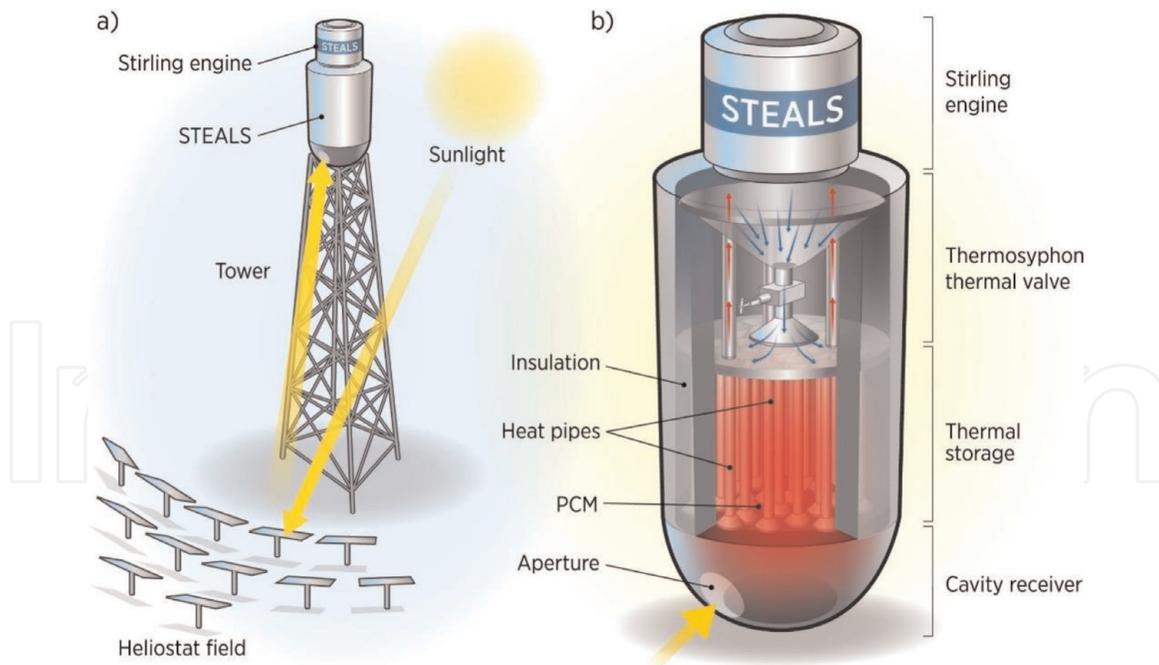
## Abstract

Solar energy has the potential to reduce the dependence on the dwindling supply of fossil fuels through concentrated solar power (CSP) technology. CSP plants utilize solar thermal energy to produce electrical energy based on different thermodynamic power cycles. Solar collectors, reflectors, receivers, thermal fluid, and turbines are the main components of each CSP plant and involve intensive heat transfer at all stages. This chapter illustrates the thermal characteristics of the main components used in CSP technology. In addition, the solar thermal fluid characteristics and its stable operational ranges are discussed in this chapter. Heat capacity, vapor pressure, volume expansion, density and viscosity of the thermal fluid should not differ significantly at different temperatures during various operation stages because these variations can cause failure in the system, which is designed at the fixed material properties. Currently, CSP technology is associated with a higher cost compared to the electricity generated through gas power plants. Many efforts are made to search for sustainable and inexpensive materials to minimize the cost of CSP. One critical issue faced by CSP technology is the intermittent nature of the sun. Modern CSP plants integrate thermal energy storage (TES) unit to smoothen the power production or to shift the production from peak sunshine hours to peak demand hours.

**Keywords:** concentrated solar power, thermal energy storage, sensible and latent heat storage materials, thermochemical materials

## 1. Introduction

Solar energy is the most abundantly available source of energy theoretically. It can be used to produce electricity by thermodynamic process and by photovoltaics conversion [1]. Initially, photovoltaic technology was incepted to convert solar energy into electricity. In this technology, solar cells produce electricity when exposed to irradiance. The amount of voltage produced per unit cell is very small; hence, hundreds of such cells are connected in series and parallel junctions to finally produce high voltage for daily use applications. Such systems are called PV arrays which are available from domestic scale to grid-connected commercial plants. In some cases, solar irradiance is concentrated at a small PV surface to generate more electricity from small PV surface; however, such systems have certain implications like accelerated thermal degradation [2]. Such systems are called concentrated



**Figure 1.** A novel compact design of heliostat field type CSP with integrated latent heat storage; a) overall schematic and b) close-up view of the heat storage unit and Stirling engine [5].

photovoltaics (CPV). In further advancements, PV cells are integrated onto the buildings to produce electricity by decentralized means [3].

Concentrated solar power (CSP) is another technology to generate electricity from solar energy; however, it works on the principles of thermal energy. Solar radiations are concentrated at a point from where thermal fluid is passed. This fluid at high temperature and high pressure is passed through the power-generating unit (turbine or engine) to produce electricity [4]. The process of CSP plant is illustrated in **Figure 1** [5]. The components of a CSP plant are shown including reflectors, receiver, thermal fluid, and turbine/engines. Below is the comparison of photovoltaics with concentrated solar power. **Figure 1** shows a recent design of heliostat type CSP plant with a latent heat storage system coupled with the power generation unit. In this design, solar radiations are concentrated using heliostat mirrors on a point at the bottom of thermal energy storage tank containing phase change material (PCM), namely, aperture [5]. The tank is equipped with vertically arranged sodium pipes so that heat can be supplied passively to the entire part of the tank from receiving point. Above the tank is a thermal valve at the interface of sodium pipes. Sodium in vapor phase (at very high temperature) rises through the thermal valve (red arrows) and strikes at the head of Stirling engine where it passes its thermal energy to the energy, get condensed, and flow downward through the funnel (blue arrows). Opening and closing the thermal valve controls the flow of sodium vapors, and hence thermal energy flows to the power block and in a way regulates the power generation of the plant. The concept is proposed and tested for a plant in the capacity range of 0.1–1 MWelectric (MWe) [5]. In the case where multiple Stirling engines are needed, all will be integrated at the top of the tower in a parallel arrangement.

## 2. Comparison of photovoltaics with concentrated solar power

The subsequent section covers the comparison of photovoltaics technology with the concentrated solar power in terms of system energy efficiency and systems sustainability.

## 2.1 System efficiency

Annual electricity production in CSP plants is higher than the PV plants. The main reason behind this difference in electricity production is that PV plants work only during sunshine hours. In the case of cloudy days or during night time, outputs of such plants are zero. CSP plants can function for prolonged hours because such plants may have additional storage for thermal energy which is exploited when sun is not available like night time [6]. Other than this feature, efficiency of PV plants decreases with time due to thermal degradation and cracks in the cell. However, in terms of land use, PV plants are better in producing more electricity from the same area as compared to CSP. It is because PV modules occupy less space comparatively with reference to the solar collectors and reflectors in CSP. It is estimated that contemporary PV plants are functioning at the solar conversion efficiency of 14–22% [7].

## 2.2 System sustainability

Sustainability of a system is a vital measure to decide the future of any technology. Generally, cost of the systems, environmental impacts, and social acceptance define the sustainability of the system. Cost is the primary indicator to choose the most economical technology among all available options. It includes all types of costs including start-up, installation, operation, and maintenance cost. Environmental impact is another important parameter which considers the effects of any technology on the environment from its initiation to disposal. Severity of this parameter in decision-making is increasing continuously because of greenhouse gas emissions and consequent global warming [7].

### 2.2.1 Cost

As described earlier, the cost of any system is the most important factor for the sustainability of the system. It is quite logical that any renewable energy technology will be able to penetrate market if the cost associated with its unit production is less than the unit cost of electricity through grid station operated on fossil fuels. It is defined as grid parity, and it is based on the levelized electricity cost (LEC) which can be estimated using Eq. (1):

$$LEC = \frac{f_{cr}IC + C_{O\&M}}{E_{el}} \quad (1)$$

where  $f_{cr}$  is the annuity factor,  $IC$  is the investment cost,  $C_{O\&M}$  is the annual operation and maintenance cost, and  $E_{el}$  is the annual net electricity output, and annuity factor can be calculated using Eq. (2):

$$f_{cr} = \frac{k_d(1 + k_d)^n}{(1 + k_d)^n - 1} + k_{ins} \quad (2)$$

where  $k_d$  is the real debt interest rate,  $k_{ins}$  is the annual insurance rate, and  $n$  is the depreciation period in years [7].

In both cases, the primary cost component is the initial cost of the system. According to the International Energy Agency (IEA), estimated initial cost for PV plant ranges from 2000 to 5200 US\$/kW, while it lies in the range of 4200–8400 US \$/kW for CSP plants. Further, the maintenance cost for PV is 1% of the initial cost. This value is approximately 2% of the initial cost in CSP. The difference in such

costs is due to the complexity of the CSP system. Interestingly, even after the initial and maintenance cost difference, economic returns and incentives of CSP plant are higher as compared to PV plants. PV technology works only during daytime and totally unavailable during peak consumption hours of electricity. CSP technology has the capability to shift its production to peak consumption hours and also takes advantage of higher tariff rates during peak consumption hours [7].

### *2.2.2 Environmental impact*

Impacts of any technology on the environment throughout the life cycle of the technology are an important measure to define sustainability of the system. The approach usually considered from cradle to grave is called life-cycle assessment (LCA). In terms of PV and CSP plants, most of the carbon footprints are during the manufacturing/installation and decomposing. During operational stage, there is almost no impact on the environment [7, 8].

In the case of PV plants, primary reason is the manufacturing of PV cells and modules, and the measure of greenhouse gas emissions is almost 50 g CO<sub>2</sub> eq/kWh for PV plants throughout the life of the plant according to NREL. It involves such ways and materials that pose severe threat to the environment [7, 8]. Particularly, the cell materials in second generation are more hazardous, and breathing in silicon dust is dangerous for workers according to NREL claims. In CPV, the issue is mainly due to mirrors and collector tube. The institute also reported that greenhouse gas emissions for CSP plants range from 22 to 23 g CO<sub>2</sub> eq/kWh during the life cycle of such plants. Overall, environmental impact of CPV is higher throughout life as compared to CSP [7, 8].

### *2.2.3 Social acceptance*

Adoption of a new technology by the customers and end user is extremely important for the success of the technology. In the case of PV and CSP, the technology is warmly welcomed by all societies around the globe. Mainly, such plants are developed in Spain, the United States, and India. Solar energy is used in street lights, for pumping water and solar cooking, domestic level applications, and grid level mega power plants. The growth in both sectors is continuously increasing as the cost of the technology is getting lower than the fossil fuel-based electricity. Further, the public is aware of the clean and noise-free generation of electricity. Mainly, CSP is used for large-scale applications; however, the scale of PV is extremely large spanning from domestic use to the grid-integrated mega power plants [7].

Next sections deal with the concentrated solar power (CSP) technology from different design, thermal fluid and heat transfer characteristics.

## **3. Heat transfer in concentrated solar power plants**

Basic principle of CSP lies on thermal energy capturing, transportation, and harnessing it. In all stages, heat transfer is involved. All modes of heat transfer in CSP are detailed in the subsequent section.

### **3.1 Heat transfer by radiation**

Radiation is energy emitted by a solid object, liquid, or gas that is at a finite temperature. This matter can also dissipate radiant energy impinging on it by

reflection and can be capable of absorption. It is classified into two, short wavelength of high energy originating from the sun and long wavelength of low energy originating from lower-energy sources [9]. The radiation energy can be balanced in CSP plants as [10]

$$(1 - r)S + L = L + H + \lambda E + G \quad (3)$$

where  $(1 - r)S$  represents short radiations,  $L$  represents long radiations,  $H$  is sensible heat,  $\lambda E$  is latent heat, and  $G$  is heat exchange by conduction.

Therefore, the net radiations are

$$R_n = (1 - r)S + L - L = H + \lambda E + G \quad (4)$$

The total energy absorbed into the system is converted into sensible heat, latent heat, and heat conduction [10].

Sunlight includes different spectra of wavelength starting from very short (extreme energy) to very long (low energy). The relation of wavelength and frequency is given as

$$\lambda = \frac{c}{\nu} \quad (5)$$

where  $\lambda$  is the wavelength,  $\nu$  is the frequency, and  $c$  is the speed of light.

For a radiative-emitting surface of an arbitrary element of area  $dA_1$ , a differential solid angle  $d\omega$  may subtend a point onto a differential area  $dA_2$ ; the differential solid angle can be defined as

$$d\omega = \frac{dA_2}{r^2} \quad (6)$$

where  $dA_2$  is the differential area.

Spectral radiation ( $G$ ) can be calculated as

$$G_\lambda(\lambda) = \int_0^{2\pi} \int_0^{2\pi} I_\lambda(\lambda, \theta, \phi) \cos\theta d\omega \quad (7)$$

where

$$d\omega = \sin\theta d\theta d\phi \quad (8)$$

Considering total radiations as the rate of radiation from all sides per unit area from all directions and at all wavelengths

$$G = \int_0^\infty G_\lambda(\lambda) d\lambda \quad (9)$$

For the case of diffuse radiations,  $I_\lambda(\lambda)$  is free of  $\theta$  and  $\phi$  as

$$G_\lambda(\lambda) = \pi I_\lambda(\lambda) \quad (10)$$

The amount of reflected radiation radiations is the rate at which radiation of wavelength  $\lambda$  leaves a unit area of the surface per unit wavelength interval  $d\lambda$ . It can be calculated as

$$J_\lambda(\lambda) = \int_0^{2\pi} \int_0^{2\pi} I_{\lambda, e+r}(\lambda, \theta, \phi) \cos\theta \sin\theta d\theta d\phi \quad (11)$$

Finally, in general, most engineering heat transfer applications are employed to characterize the radiative heat transfer interaction between an object and its environment with respect to wavelength:

$$\dot{Q}_{rad} = \sigma \varepsilon_{\lambda} A (T^4 - T_{\infty}^4) \quad (12)$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ ,  $A$  is the object surface area, and  $T_{\infty}$  is the ambient temperature.

### 3.2 Heat transfer by conduction

Heat transfer by conduction is occurred due to lattice vibration in solids and particle collision in stationery fluids. In a solid with temperature gradient onto surfaces, the one with higher temperature experiences higher level of collision among particles, so it transfers its energy to the neighboring particles which transfer it further [11]. In the same way, heat is transferred from hot to cold surface until steady state is achieved. The rate of heat transfer by conduction is given by Fourier's law as

$$\dot{Q}_{cond} = kA \frac{dT}{dx} \quad (13)$$

where  $A$  is the surface area,  $k$  is the thermal conductivity,  $dT$  is the temperature gradient across surfaces, and  $dx$  is the length between the surfaces between heat transfers that are measured.

In CSP plants, heat transfer due to conduction is always changing with time; that's why it is necessary to understand the transient nature of conduction heat transfer. In certain scenarios, lumped systems are assumed while calculating heat transfer at the interface of solid and liquid. The reason is that heat conduction within the solid is comparatively negligible as compared to the heat transfer from solid to the fluid at its interface. It is further necessary to confirm that there are no spatial temperature changes within the solid to assure its lumped natured. After a specific time, the system will reach a steady state when high thermal energy of solid is transferred to the low-temperature fluid to eventually reaching the same level of temperatures [12]. The time can be calculated as

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = \exp\left(-\frac{hA_s}{\rho V c_p} \tau\right) \quad (14)$$

where  $T$  is the temperature of hot-surfaced solid,  $T_{\infty}$  is the ambient temperature,  $T_i$  is the initial temperature,  $h$  is the convective heat transfer coefficient,  $A_s$  is the surface area at the solid-fluid interface,  $\rho$  is the density of the fluid,  $c_p$  is specific heat capacity, and  $\tau$  is the thermal time constant. The constant can be calculated as

$$\tau = \frac{\rho V c_p}{hA_s} = RC \quad (15)$$

where  $R$  is the convective resistance and  $C$  is the lumped capacitance of the solid. To confirm the validity of lumped capacitance, Biot number (Bi) can be calculated as

$$Bi = \frac{hL_c}{k} = \frac{R_{cond}}{R_{conv}} = \frac{L_c/kA}{1/hA} = \frac{T_{s,1} - T_{s,2}}{T_{s,2} - T_{\infty}} \quad (16)$$

For the value of Biot number less than 0.1, it is assumed that temperature within the solid is nearly the same, and the maximum temperature difference is at the interface of solid-fluid. Rearrangement of equations provides us

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = \exp(-Bi.F_0) \quad (17)$$

where  $F_0$  is a dimensionless number which characterizes transient problems and can be calculated as

$$F_0 = \frac{\left(\frac{k}{\rho c_p}\right)t}{L_c^2} \quad (18)$$

where  $L_c$  is the characteristic length which is different for rectangular, cylindrical, and spherical coordinate systems [12].

For rectangular coordinates,  $L_c = L$

For cylindrical coordinates,  $L_c = \frac{r}{2}$

For spherical coordinates,  $L_c = \frac{r}{3}$

### 3.3 Heat transfer by convection

Heat transfer through convection occurs between fluid in motion and its bounding surface. The heat transfer can happen naturally due to buoyancy effect in which medium moves due to the density difference caused by the variation in temperature. It is called natural convection. On contrary, a fluid can be forcefully pushed or pumped through mechanical means like fans or pumps. The heat transfer through this way is called forced convection. Heat transfer through convection can be measured as

$$\dot{Q}_{conv} = hA_s(T_s - T_{\infty}) \quad (19)$$

where  $h$  is the convective heat transfer coefficient,  $A_s$  is the surface area,  $T_s$  is the temperature of hot surface, and  $T_{\infty}$  is the ambient temperature. The range of convective heat transfer coefficient for gases is 2–5 and 25–250 W/m<sup>2</sup> K for natural and forced convections, respectively [12]. The ranges 50–1000 and 100–20,000 W/m<sup>2</sup> K are for liquids in natural and forced convection cases, respectively [12]. For materials that involves phase change (boiling and condensation), the range is 2500–100,000 W/m<sup>2</sup> K [12]. This extraordinary difference in the coefficient value is exploited in CSP plants using heat pipes involving boiling and condensations. In CSP applications, Newton's law of cooling ( $dt = T_s - T_{\infty}$ ) can overpredict the heat transfer rate. More accuracy to calculate heat transfer rate per unit length can be obtained using [12]

$$\Delta T_{lm} = \frac{(T_s - T_{\infty}) - (T_s - T_0)}{\ln\left(\frac{T_s - T_i}{T_s - T_{\infty}}\right)} \quad (20)$$

and the outlet temperature of the fluid passing through the pipe can be calculated using

$$\frac{T_s - T_i}{T_s - T_{\infty}} = \exp\left(-\frac{\pi DN \bar{h}}{\rho V N_T S_T c_p}\right) \quad (21)$$

where  $S_T$  is the transverse pitch,  $D$  is the tube diameter,  $N$  is the number of tubes, and  $(\bar{h})$  is the average value of heat transfer coefficient. Finally, heat transfer can be obtained with the following

$$\dot{Q}' = N(\bar{h}\pi D\Delta T_{lm}) \quad (22)$$

#### 4. Thermal energy storage in concentrated solar power

The prime difference between PV and CSP plant is an optional storage of solar energy in CSP and to harness it during the most demanding hours to produce electricity. This feature makes the CSP capable of electric power production during evening, the time after closing of offices, when the demand of electricity is at its peak [13]. At that time, output of CPV plant is zero, and it creates a big mismatch between supply and demand. Although a solution for such mismatch is to store electricity in large-scale batteries during sunshine hours so as to supply during evening and night, the option of batteries is very costly and environmentally unacceptable. Solar energy in the form of thermal energy storage (TES) is comparatively much better option as compared to the electrical energy storage in batteries because it is inexpensive and has minimal environmental impacts [14]. Few of the CSP plants are equipped with TES systems, while others do not have this feature.

Performance of a CSP plants with TES systems is dependent on the design of integration of TES into the power generation cycle (thermodynamic process) of the plants [15]. Generally, TES is classified into two main categories based on the motion state during charging and discharging, i.e., active systems and passive systems. Charging is the process in which heat is fed to the medium to raise its energy, while discharging is the process in which heat is extracted from the medium to bring it back to the original state. In active systems [16], thermal energy is stored into a medium which also acts as energy carrier. The medium with high thermal energy is pumped, and it transfers its energy to the thermodynamic cycle through forced convection. In passive system [17], thermal energy is stored into a stationery and motionless medium through which thermal fluid is circulated to extract heat, and the thermal fluid is circulated through the thermodynamic cycle to deliver thermal energy there. The following sections contain the further classifications of such systems with visual illustrations for clear understandings.

##### 4.1 Active direct concept for TES

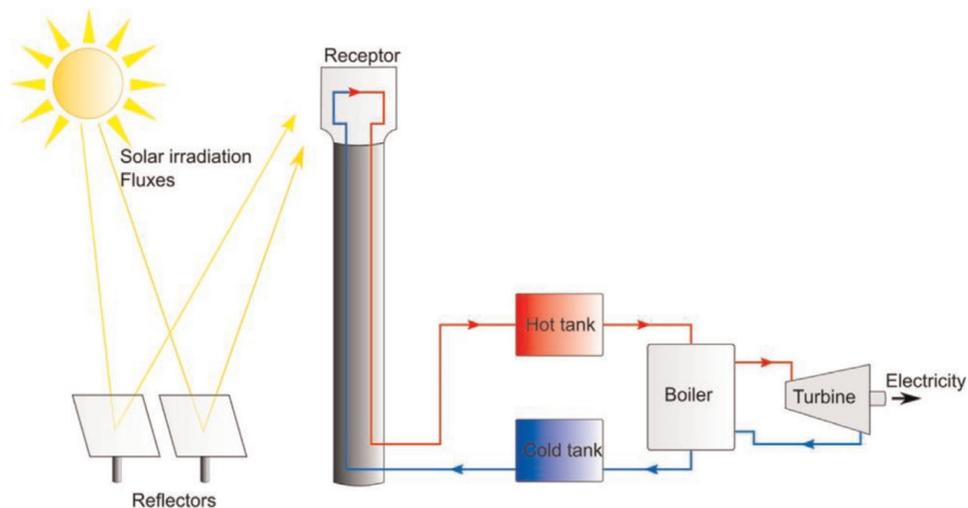
Active systems are further categorized into direct and indirect systems. In direct active systems, energy materials serve the dual functions of energy storage and transportation. In such systems, TES materials absorb heat from solar absorber during charging and stored in a hot tank as shown in **Figure 2** [13]. During discharging, the TES material is pumped from the hot tank to the thermodynamic cycle where it transfers its energy to the system and return back to cold storage. For the next charging cycle, the TES material is again pumped to solar absorber to gain energy for the next cycle. In this design, heat exchanger is not required; however, the TES material should have properties of heat storage capacity and good flowability [15].

## 4.2 Active indirect concept for TES with two tanks

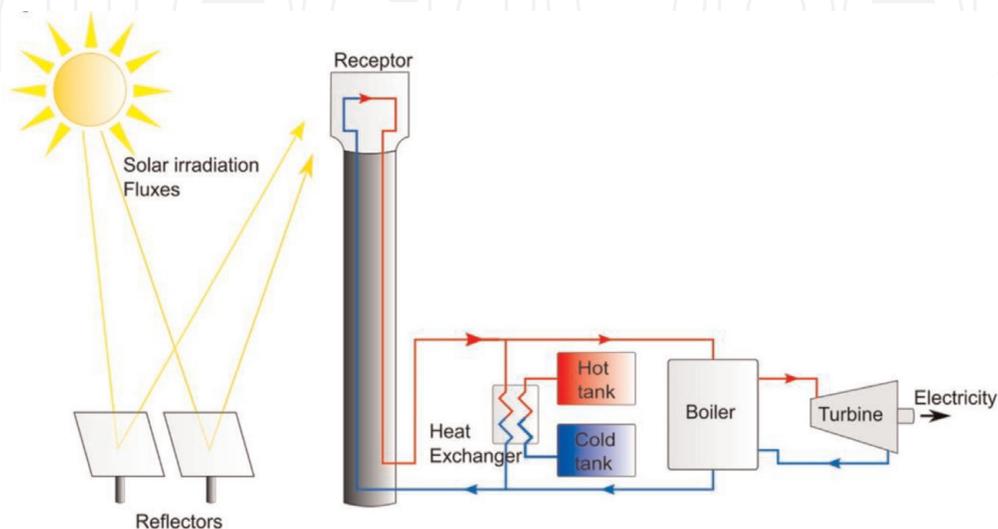
Active indirect systems have further two designs for TES integration into CSP plants with the options of two tanks and single tank for storage. In such systems, materials to store thermal energy are different than the heat transfer fluid (HTF). An example of active indirect system with two-tank storage is shown in **Figure 3** [13]. At the start of the charging/discharging cycle, TES material is stored in a cold tank, while HTF is moving in the flow path of solar collector, thermodynamics cycle, and heat exchanger. During charging, TES material is pumped from the cold tank to a hot tank through the heat exchanger where it absorbs heat from HTF and stored into the hot tank. The TES is pumped back to the cold tank during discharging in which the materials return heat to the HTF through heat exchanger. Hence, TES material and HTF are totally different and are not mixed with each other during the process.

## 4.3 Active indirect concept for TES with single tank

Active indirect design with a single storage tank is also possible which is quite efficient than the two-tank storage system. In this design, TES material in cold and hot



**Figure 2.**  
*Active direct concept for TES [13].*



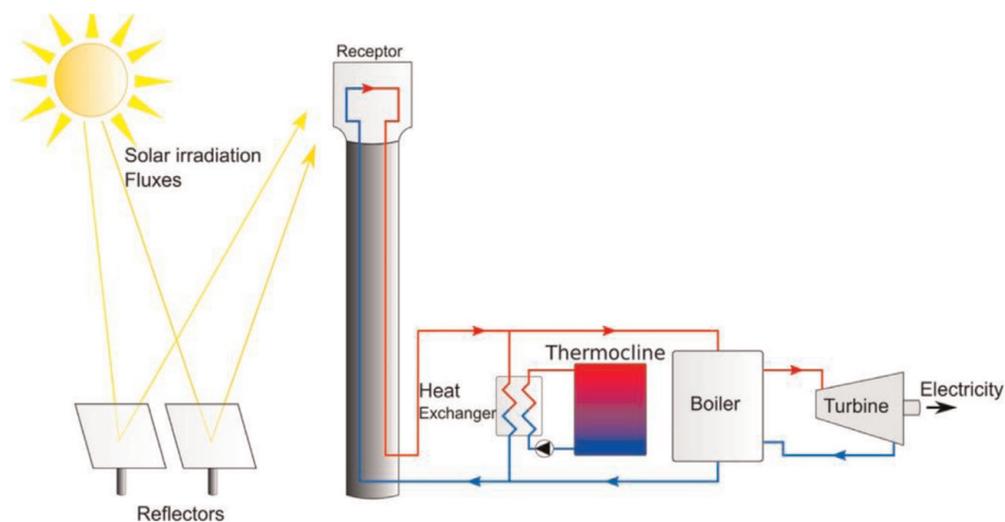
**Figure 3.**  
*Active indirect concept for TES using two tanks [13].*

state is stored in the same tank as illustrated in **Figure 4**. The materials get separated by itself due to different material properties at different temperature. Thermal stratification causes the hot material to be stored in the upper part of the tank, while cold material is stored in the bottom. This system is also known as thermocline system, which is approximately 35% cheaper than the two-tank storage system.

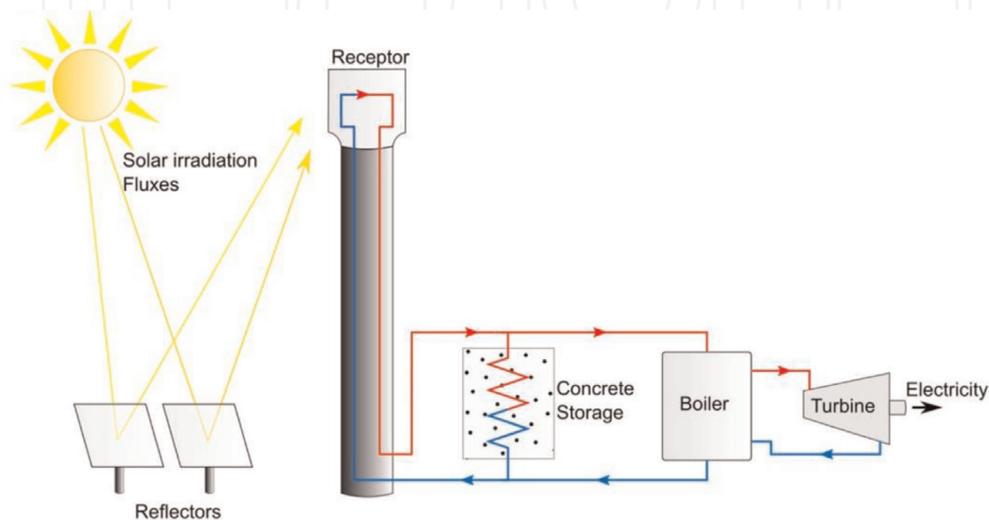
In thermocline storage systems, a filler material like rocks, concrete, or sand is used so that less quantity of TES materials is required to enhance the thermocline effect. In this system, handling accuracy during charging and discharging of the TES is required using controlled methods and devices to avoid mixing of materials. Among differently investigated structures during discharging of thermocline, packed-bed configuration is reported to be the best performing [13].

#### 4.4 Passive concept for TES

This is another concept of thermal energy storage in which TES materials are fixed and do not move during entire processes. The concept is demonstrated in **Figure 5**. The TES material is kept in a tank through which HTF is circulated. During charging phase, hot HTF is passed through TES and it transfers its heat to the TES. During discharging, cold HTF is passed from TES which is already at very



**Figure 4.**  
Active indirect concept for TES integration, single tank [13].



**Figure 5.**  
Passive concept for TES [13].

high temperature. In such systems, thermal conductivity of the storage material and surface contact area defines the rate of heat transfer from and to the HTF during charging and discharging, respectively. In this type of design, rocks and concrete are used as TES materials.

## 5. Materials for thermal energy storage

Thermal energy storage materials are very specific in terms of physical and thermal properties for the best performance of the CSP plants. These materials are generally categorized into three, namely, sensible storage, latent storage, and thermochemical storage. Explanation of these categories is given in the subsequent sections. There are few properties of TES materials which are common for all materials. Energy storage density is very basic thing that defines the size of the TES tanks as well as associated cost with it. The higher is the energy storage density of a material, the less of its quantity is required to store a specific amount of thermal energy [14]. Similar is the case of mass density of the material. In the case of latent heat and thermochemical storage, equivalent terms are heat of fusion of the material and heat of reaction of the materials, respectively [14]. Thermal conductivity and operating temperatures are very important parameters in defining the overall efficiency and performance of the system. If a material is a good thermal conductor, it takes less time during charging and discharging. In case thermal conductivity is low, conductivity enhancers, nanofillers, and enhanced contact surface geometries are utilized for better results. In general, the materials should be inexpensive, readily and widely available, less corrosive, and less hazardous to the environment and to human health [14].

### 5.1 Sensible TES storage materials

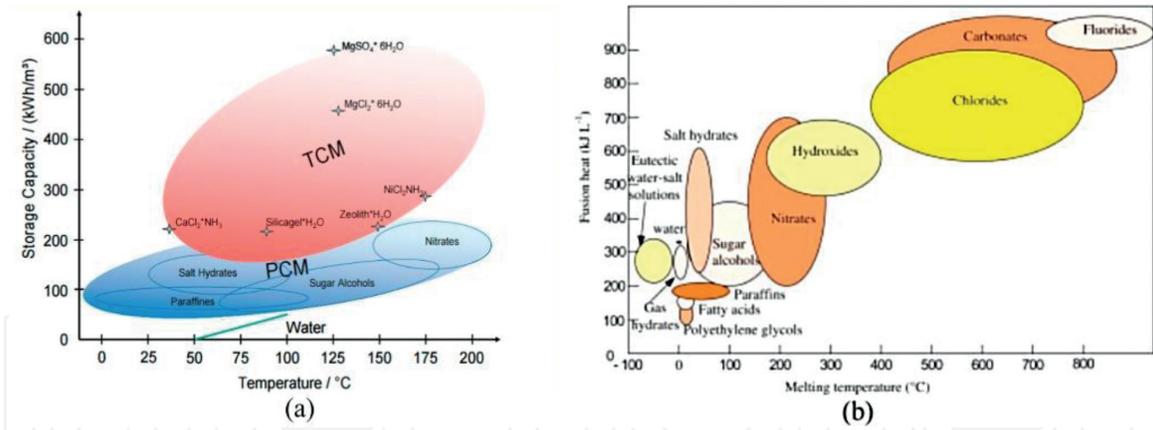
These materials store heat in the form of rise in temperature. The property of the material that is associated with this phenomenon is the heat capacity. A material with higher heat capacity is good for energy storage. Examples of such materials are sand, rocks, concrete, etc. [18]. The amount of thermal energy stored in TES materials as sensible storage can be calculated using Eq. (23):

$$Q_T = V \times \rho \times C \times \Delta T \quad (23)$$

where  $V$  is the volume,  $\rho$  is the average density,  $C$  is the specific heat capacity of the sensible energy storage material, and  $\Delta T$  is the difference of temperature from initial to final stage.

### 5.2 Latent heat storage

In these types of materials, energy is stored in the form of change of phase. This phase change may be in solid-liquid, liquid-gas, solid-gas, and solid-solid [19]. Commonly known materials lie in the categories of liquid-gas and solid-liquid phase change materials for CSP applications. Water-steam is an example of the former type, and binary salt is an example of the latter type. For latent heat storage materials, parameter of interest is the phase transition temperatures and latent heat of fusion during this phase transitions. It is highly desirable that materials are stable within a long temperature range, and its solidification temperature is as low as possible. The reason behind the low preferred solidification temperature is that it should not be deposited as a solid in the circulation pipes in active systems. The



**Figure 6.** (a) PCM with respect to storage capacity and (b) PCM with respect to heat of fusion [21].

amount of energy in this type of material is the sum of sensible energy storage from initial temperature to the final temperature and the energy storage during phase transition as a latent heat [18, 19]. Energy stored as a latent heat of fusion can be calculated using Eq. (24):

$$Q_{\text{latent}} = V \times \rho \times L \quad (24)$$

where  $L$  is the latent heat of fusion of the material.

### 5.3 Thermochemical energy storage

This type of energy storage is based on the chemistry of endothermic-exothermic reversible reactions. Surplus heat energy is used to initiate a reaction which is highly endothermic. During charging, the heat is taken by the reactants, and due to reactions occurrence, the reactants are converted into products. These products are stored for days, weeks, and seasons. Interestingly, the storage is at ambient conditions, and energy losses in this storage are minimal. During discharging, these products are converted back to the reactants with the release of huge amounts of heat. That heat is transported to the thermodynamic cycle [20]. The reversible  $\text{CaO}/\text{CaCO}_3$  carbonation reaction (CaL) is one of the most promising since CaO natural precursors are affordable and earth-abundant. However, CaO particles progressively deactivate due to sintering-induced morphological changes during repeated carbonation and calcinations cycles.

**Figure 6(a)** is the representation of different types of materials based on the heat storage capacity [21]. As it is evident from the figure, thermochemical materials (TCM) possess the most storage density in the range of 170–600 kWh/m<sup>2</sup>. Energy storage density of latent heat storage called PCM comes lower than TCM ranging from 70 to 250 kWh/m<sup>2</sup>. Sensible storage materials are the lowest in terms of energy storage density. The only advantage in sensible storage is the absence of degradation and corrosion and very low cost. **Figure 6(b)** is the classification of TES materials based on the melting points [21]. This analysis gives an indication about the selection of materials for specific ranges of melting points.

## 6. Characteristics of thermal fluids

According to the 2050 vision of the International Energy Agency (IEA), energy production share by CSP is 630Gwe. Keeping in view the high future targets,

scientists and researchers are working on different designs of CSP. Among all parameters, thermal fluid is a key component because overall performance of the CSP is dependent on the thermal energy. Thermal fluid is the transport material that carries thermal energy from solar receiver/hot storage and delivers it to the thermodynamic cycle [22]. In the context of thermal fluids, required characteristics are:

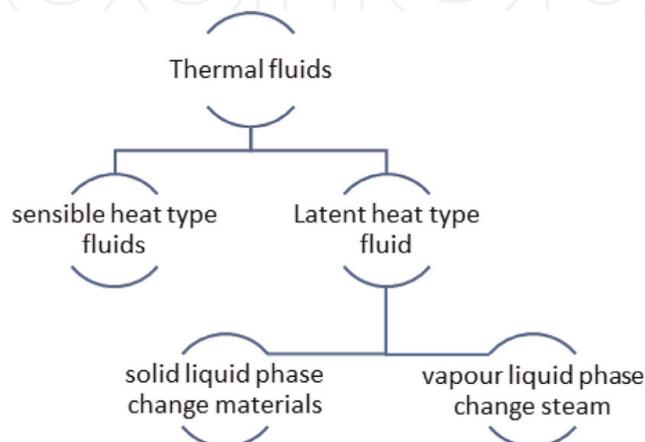
1. High heat capacity
2. Low viscosity
3. Uniform thermophysical properties in the operational temperature range
4. Enhanced heat transfer at heat exchanger

Thermal fluids are categorized into two classes based on the behavior of the materials. The classification of the thermal fluids is represented in **Figure 7**.

In certain cases, thermal property enhancer nanoparticles agglomerate and form clusters after a limited operational life. This agglomeration of nanoparticle declines the performance of thermal fluids. A quaternary salt is developed recently with low melting point (85.4°C), wide operating range (600°C), reduced risk of blockage, and less corrosive effect with the system [23]. Correlation of heat transfer with nanofluid is described in the subsequent section.

### 6.1 Heat transfer with nanofluids

Thermal characteristics of nanofluids are different than solid-liquid mixtures as these fluids contain suspended particles (metallic or nonmetallic) in the liquid base. Heat transport properties are altered because of the suspended ultra-fine particles [24]. Generally, the volume content of these particles is below 10% in the fluid. Addition of nanoparticles increases thermal conductivity and heat transport properties of the fluid as compare to the pure fluid. For instance, Xuan and Li reported an increase in the thermal conductivity ratio from 1.24 to 1.78 with the increase in particles from 2.5 to 7.5% [25]. The change in properties of the fluid is dependent on the particle shape, dimensions, quantity, and characteristics. However, micrometer- and millimeter-sized particles are reported to settle down quickly producing clogs in the channels, eroding pipelines, and causing huge pressure drop [26]. Heat



**Figure 7.**  
*Classification of thermal fluids.*

transfer correlations, fundamentals, and theory can be read through the literature presented in [24, 27, 28].

## **7. Current issues in CSP**

One critical issue in TES for high-temperature applications is corrosion of the TES materials with its containment. Most of the molten salts used for TES are highly corrosive. The reactions of salts and formation of corrosion is not completely understood, and the problem still needs attention especially in the context of stress corrosion cracking in molten salts [29]. The corrosion is either in the form of oxide layer formation on the container or degradation of the container material. Standard structural materials (stainless steel or carbon) degrade after coming into interaction with salt chlorides by the chloridation. Protective coatings are under investigations to mitigate the effects of corrosion [29].

Currently, energy production from CSP technology is costly [30]. To circumvent the issue of high cost, the US Department of Energy launched the SunShot Initiative in 2011 and has put forth an aggressive research and development (R&D) plan to make CSP technologies cost competitive with other energy generation sources on the grid by the end of the decade [31]. The goal of the SunShot Initiative includes the levelized electricity cost (LEC) from solar power plants less than 6 ¢/kWh without subsidies, a round-trip annualized exergetic efficiency greater than 95%, storage cost less than \$15/kWh, by 2020, which would pave way for rapid, and large-scale adoption of solar electricity [31].

## **8. Conclusion**

Among different available options of solar energy, concentrated solar power is considered the most efficient technology available contemporarily and trending in future developments. Its conversion efficiency from solar thermal energy to electricity is very high because it can achieve as high temperature as 800°C. The higher-achieved temperature leads to higher efficiency because it enhances the exergy level of the system. For future developments, molten salts and liquid metals are considered better options for energy storage as well as for thermal fluids. Although many combinations of salts in different mixing ratio are available in literature and rapid research is undergoing on the developments of further mixtures, the problem of corrosion is still existing. It is anticipated that liquid metals can solve the problem of corrosion and their stability and energy storage density is even higher than salt hydrates. Research in the similar lines for HTF is also undergoing at a high pace. Most of the developed molten salt HTFs are based on nitrates/nitrites. However, the annual nitrate/nitrite salts production is limited due to their reserves. Therefore, carbonate or chloride-based salts are proposed and evaluated in the most recent studies. One of the major issues of the molten salts is their relatively high corrosive nature to metal alloys. The corrosion issues must be resolved completely before commercial application of the molten salts as the HTF in the CSP Technology.

## **Acknowledgements**

The authors would like to express their appreciation to the United Arab Emirates University (UAEU) for funding the research through grants (31N265 and 31R153).

## Conflict of interest

The authors declare no conflict of interest.

## Nomenclature

$C_{O\&M}$	annual operational and maintenance cost
CPV	concentrated photovoltaics
CSP	concentrated solar power
$E_{el}$	annual electricity output
$f_{cr}$	annuity factor
HTF	heat transfer fluid
IC	investment cost
IEA	International Energy Agency
$K_{id}$	real debt interest rate
$K_{ins}$	annual insurance rate
LOC	levelized electricity cost
MWe	megawatt electricity
$n$	depreciation period
PV	photovoltaics
PCM	phase change material
TES	thermal energy storage

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