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Technological Advances to Maximize Solar Collector Energy Output: A Review

Since it is highly correlated with quality of life, the demand for energy continues to increase as the global population grows and modernizes. Although there has been significant impetus to move away from reliance on fossil fuels for decades (e.g., localized pollution and climate change), solar energy has only recently taken on a non-negligible role in the global production of energy. The photovoltaics (PV) industry has many of the same electronics packaging challenges as the semiconductor industry, because in both cases, high temperatures lead to lowering of the system performance. Also, there are several technologies, which can harvest solar energy solely as heat. Advances in these technologies (e.g., solar selective coatings, design optimizations, and improvement in materials) have also kept the solar thermal market growing in recent years (albeit not nearly as rapidly as PV). This paper presents a review on how heat is managed in solar thermal and PV systems, with a focus on the recent developments for technologies, which can harvest heat to meet global energy demands. It also briefs about possible ways to resolve the challenges or difficulties existing in solar collectors like solar selectivity, thermal stability, etc. As a key enabling technology for reducing radiation heat losses in these devices, the focus of this paper is to discuss the ongoing advances in solar selective coatings and working fluids, which could potentially be used in tandem to filter out or recover the heat that is wasted from PVs. Among the reviewed solar selective coatings, recent advances in selective coating categories like dielectric-metal-dielectric (DMD), multilayered, and cermet-based coatings are considered. In addition, the effects of characteristic changes in glazing, absorber geometry, and solar tracking systems on the performance of solar collectors are also reviewed. A discussion of how these fundamental technological advances could be incorporated with PVs is included as well. [DOI: 10.1115/1.4041219]

Keywords: solar thermal collector, solar energy, solar selective coating, glazing, absorber, heat transfer, nanofluid, concentrated photovoltaic, photovoltaic cooling

1 Introduction

The demand for a clean and sustainable environment is of top priority due to the impact fossil fuels have on the environment. To achieve a clean and sustainable environment, the usage of renewable energy resources should be increased because they have the potential to provide significant amounts of energy. There are a variety of renewable energy resources available like solar energy, wind energy, biomass, geothermal, ocean thermal, hydroelectricity, and nuclear energy on the earth's surface. Solar energy is a prime source of energy and is widely available. The sun's total power output is 3.8×10^{23} MW, out of which 1.7×10^{14} kW is incident on the surface of the earth. If this amount of power is incident on the surface of the earth for 30 min, it can fulfill the world's total energy demand for one year [1]. Solar energy is abundant, and widely available throughout the world, but it only represents a small slice of the "energy consumption pie" relative to oil, coal, and natural gas.

While delivery of solar energy is free, the collectors needed to convert it to useful energy have historically been expensive (relative to fossil fuels). However, with improvements in conversion efficiency and with mass production in China, the cost of solar collectors ($/W) has been falling rapidly. Photovoltaics (PVs) have enjoyed very rapid year-on-year growth rates (with a doubling of installed capacity every 2–3 years). In fact, $\sim$7–10% of the ~ 7–8×10^6 metric tons of silicon produced each year is now devoted to the production of silicon photovoltaics (even with continual trend toward using thinner wafers). In fact, compared to integrated circuits, photovoltaics now represent a $\sim$100× larger silicon wafer area than electronic packaging ($\sim 1100 \times 10^9$ m^2 of PV wafer versus $\sim 7 \times 10^6$ m^2 of semiconductor wafer shipments in 2017) [2,3]. Silicon PV modules convert only 12–18% of the incoming radiation into electricity, so more than 80% of solar

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irradiation either gets converted into heat or reflected back [4]. While this conversion rate does depend on the material of the cell and the working conditions, most of the incoming solar energy must be dissipated, either through passive or active mechanisms. In order to reduce the reflective losses of desired wavelengths (those above the bandgap of the cell), antireflective layers [5] can be added. To prefilter the incoming spectrum (e.g., ensure only short wavelengths reach the cells), decoupled photovoltaic/thermal hybrid solar collectors (PV/T) have been proposed. These use spectrally selective mirrors or absorption filters [6,7] to utilize the wasted infrared (IR) part of the spectrum and to avoid heating the PV cell.

Although there are a variety of semiconductor materials that work as photovoltaic materials—e.g., cadmium telluride (CdTe), copper-indium-gallium-selenide (CIGS), cadmium sulfide (CdS), amorphous silicon (a-Si), cuprous sulphide (Cu_2S) and gallium arsenide (GaAs) and others [8], mono- and multicrystalline silicon technology seems to have won the commercial battle [9], with 95.5% share of the global PV production in 2017 (the other 4.5% is thin-film technology, namely CdTe and CI(G)S, but also amorphous silicon) [10]. To highlight how far this technology has come in the last 6 decades, in 1958, the solar-to-electrical energy conversion efficiency of a silicon cell was ~11% and the cost was ~$1000/W [1]. Now, monocrystalline cells have achieved 26.7% efficiency in the lab and crystalline Si modules cost less than $1/W [10]. Due to the high initial cost of photovoltaics, the technology was originally limited to space applications (with very high efficiency cells *still* limited to space applications), where cost is not as much of a constraint as weight or reliability [11–13]. As costs came down, photovoltaics gained traction in terrestrial applications, such as remote monitoring [14–16], and off-grid lighting [12,13], water pumping [17,18], and battery charging [19–23]. In recent years, however, photovoltaics have achieved grid parity in many parts of the world and several $>100\,\mathrm{MW_e}$ solar farms have been constructed [10].

As the smallest commercially relevant technology, amorphous silicon cells (a-Si) utilize a thin, flexible layer of silicon deposited on the substrate. This "thin film" PV technology has relatively low efficiency (~ 6%), but the manufacturing cost is lower (in terms of $\$/m^2$) than crystalline cells. As noted above, the bigger players in thin-film technology are based on cadmium telluride (CdTe) and copper-indium-(gallium)-selenide, CI(G)S. Both of these technologies can also be made to be flexible, which enables them to follow contours useful for building integrated designs. CI(G)S (particularly gallium-free CIS) is thought to have the upper hand in the long run, due to materials availability [1,24].

Due to silicon's abundance and higher conversion efficiency, crystalline silicon has continued to increase its market share over thin-film technology [10]. For residential rooftops and large solar farms, where space in not usually a limitation, the efficiency of silicon (the dominant technology) is not usually a barrier. However, in some cases where spatial limitations cannot be ignored (e.g., multistory buildings or industrial sites), it may be desirable to avoid dumping >80% of the available solar resource. In these cases, it has been suggested that PV/T hybrid systems can provide an advantage [25]. This is because such systems require less area compared to separate PV and thermal collectors, which results in the lowering of the overall system cost. Another major challenge with silicon PV technology is that the cells become less efficient as they are heated by the >80% of the light that is not extracted as useful electricity [1]. In general, a temperature rise in a silicon PV cell reduces its efficiency by between 0.25 and 0.8% per °C, relative to standard test conditions of 25 °C, depending on its composition (*n*-type or *p*-type, mono-crystalline or multicrystalline, and the concentration of impurities and defects) [26–29]. Therefore, cooling of these panels is often considered so as to increase the efficiency of these panels.

1.1 Photovoltaic Cooling.

Photovoltaics—even the world-record, most efficient multi-junction PV cells like GaInP/GaAs and GaInAsP/GaInAs—use less than half of the solar spectrum and the rest of the incident solar energy (other than the band gap of semiconductor used) is dissipated as heat [28]. Thus, *most* of the incident solar energy ends up as heat. This heat can either be considered a waste product (dumped to the environment) or, potentially, as a useful source of energy for thermal applications (Heating, ventilation and air conditioning, process heat, and even further electricity generation), depending on its thermodynamic quality. Ultimately, the design of a PV cooling system is analogous to a typical electronics package, in that the goal is to keep a thin semiconductor from exceeding a set junction temperature. For example, to ensure a loss of less than 10% from its rated performance (at 25 °C), the cells would have to stay below 45 °C for a module with a degradation of 0.5% per °C. It should be noted, however, that this may not be possible with passive air cooling in hot climates where the ambient temperature can exceed 40 °C.

In conventional photovoltaic systems, this heat has almost exclusively been perceived as a harmful waste product, which must be removed as efficiently as possible (at low temperature). This perspective comes from focusing on minimizing the damage done by the loss coefficient. However, with the addition of a good thermal package, a significant portion of the >80% heat can be extracted (rather than dissipated) for use in air and water heating for buildings [30]. Further, with advanced photovoltaic materials and architectures, it may even be possible for this unused heat to be harvested at high temperature for industrial process heat or even as a means to generate additional electricity [31,32]. Regardless of its intended use, heat removal from PV cells can be done either actively or passively, depending on the heat fluxes and relative temperatures involved.

1.1.1 *Passive Photovoltaic Cooling.*

Whether they have been designed for it or not, all PV modules exhibit some amount of passive cooling via natural convection. This is because most of the solar radiation landing on them is converted to heat, which ensures that (during sunny hours) they operate at temperatures above the surrounding environment. Free natural convection can be intentionally enhanced through good design by simply optimizing their orientation [33] or through the addition of extra heat dissipation area (i.e., fins [34]). The thermal resistance of a PV module with free convection from its top surface can be estimated with straight-forward natural convection correlations that depend on the Rayleigh number, Ra, such as the following [35]:

$$R_{Natural\,Convection} = \frac{1}{h} = \frac{L}{k}\frac{1}{Nu} = \frac{L}{k}\frac{1}{C * Ra^b} \tag{1}$$

where C is either 0.1 or 0.6 and b is either 0.25 or 0.33, depending on the range of the Rayleigh number. If we recall that the Rayleigh number is directly proportional to the temperature difference (between the PV cells and the ambient), it is clear that relying on natural convection for cooling has only limited room for responding to an increase in module temperature. That is, the thermal resistance reduces only slowly as temperature increases.

Another common passive cooling method utilizes the thermosiphon effect, wherein heat is carried by a fluid (via a closed circulation loop). Even though this method still relies on the same buoyancy-driven flow as natural convection, it opens the door to better heat transfer fluids (HTF) (discussed later) and more controlled means of heat extraction to a thermal reservoir or for direct use. Closed-loop passive systems are also characterized by the fact that the heat dissipation rate is beneficially proportional to the cell temperature, but it is a stronger, proportional link. Much like other electronics cooling designs, air is the most common heat transfer fluid [36,37], but water [26,38] and even oils [39–41] have been proposed and used. Unlike the electronics cooling industry, heat pipes, which utilize liquid–vapor phase change, have yet to become widespread in PV cooling. This is likely due to the fact that air has so far proven to be "good enough" for cooling nonconcentrated PV modules (where the heat flux rarely exceeds 0.1 W cm^{-2}). The cost of large-area heat pipes is also a barrier in the solar industry. Heat pipes may eventually be employed in concentrated photovoltaics (CPVs) cooling designs as they are more applicable to higher heat fluxes. Portable electronics often use heat pipes because they have relatively high heat flux over a small area (chip) and the heat needs only to be passively (and safely) spread to a surrounding chassis. If the thermal resistance (R) and heat flows of the heat pipe (q) are known, it is possible to estimate the amount of temperature drop (dT) between the semiconductor and the heat sink with the following equation [35]:

$$dT_{\mathrm{HeatPipe}} = q_{\mathrm{evap}}\mathrm{R}_{\mathrm{evap}} + q_{\mathrm{axial}}R_{\mathrm{axial}} + q_{\mathrm{cond}}R_{\mathrm{cond}} \tag{2}$$

For a typical heat pipe operating in a CPV system, the following characteristic values can be inserted: $dT_{\mathrm{heat\ pipe}} = (3.8\ \mathrm{W\ cm^{-2}})\ (0.2\,^\circ\mathrm{C\ cm^2\ W^{-1}}) + (95.5\ \mathrm{W\ cm^{-2}})\ (0.02\,^\circ\mathrm{C\ cm^2\ W^{-1}}+) + (3.8\ \mathrm{W\ cm^{-2}})(0.2\,^\circ\mathrm{C\ cm^2\ W^{-1}}) \approx 3.4\,^\circ\mathrm{C}$.

Thus, for an application where the heat from a CPV system is to be gainfully employed, only 3–4 °C are lost by employing a passive heat pipe.

1.1.2 Active Photovoltaic Cooling. Active PV cooling systems are generally only employed in concentrated PV systems. The advantages of using an active system are twofold: (i) It enables control over the flow rate (for better temperature control), and (ii) Forced convection heat transfer can achieve much higher heat flux than natural convection. For linear concentrators, forced convection can be as simple as the flow of a heat transfer fluid along a receiver pipe which removes heat from the solid-state device (e.g., see Ref. [42]). For dish and tower (spot focus) concentrators, a well-designed cold plate or a two-phase cooling apparatus is required. Passive cooling methods are not capable of removing the higher heat flux (typically in excess of 10–100 W/cm^2). While this is nowhere near pushing the boundary of some of the thermal management solutions that have been developed for high heat flux electronics (i.e., which can remove heat flux in excess of 1000 W/cm^2 [43]), scale can be an issue since the area of the CPV focal spot is on the order of 10–100 cm^2, which is well over the 1–10 cm^2 area of computer chips. Another major difference is that CPV systems run in a continuous mode at capacity during sunny hours, whereas electronics cycle and are only infrequently operated at their highest heat flux. Portable electronics are an example of how a relatively high heat flux (over only a small area chip run at a relatively low capacity factor) can simply (and safely) spread heat to the surrounding chassis. In a CPV system, however, 1–100 kW$_{\mathrm{th}}$ of heat must somehow be cost-effectively dumped (or extracted) from the cells. Since the scale is so much larger, the solar industry solution has relied upon water-cooled cells, which move heat to fan coils, which dump heat to the surrounding air [44]. However, with advances in solar technologies, much of this currently wasted heat *could* be extracted (before or after the cells) in a solar thermal collector (STC).

Traditional methods for PV cooling (both active and passive) typically look at strategies to increase convective heat transfer either to the environment or to a cooling fluid. While these strategies are highly effective, they neglect that radiation can act as a significant mode of heat transfer from a PV cell [45–47]. Because of advances in nanoscale optics, it is possible to design structured and/or layered coatings capable of having high emissivity to the sky window. Zhu et al. demonstrated the potential cooling that could be achieved with a micropatterned pyramidal structure that could reduce the temperature of bare crystalline silicon by 18 K under 1-sun conditions [45,48]. Safi and Munday completed a detailed balance demonstrating the potential for 0.87% improvement in terrestrial cells while up to a 2.6% improvement for extraterrestrial cells [49]. While this form of cooling has received increased interest as a means to improve performance a recent analysis calls into question the value of this improvement when all of the side and base losses are considered for a module covered with glass (as is almost exclusively done in the commercial market) [50]. This concept has been further refined for devices that are both highly thermally emissive and highly reflecting in the sub-band-gap and ultraviolet wavelengths, using one-dimensional photonic crystals [51,52]. In addition to the structured and layered surfaces, such techniques may also be possible with nanoparticle-embedded films, although this has not been demonstrated yet for PV [53].

1.2 Solar Thermal Collectors. A solar thermal collector is a special kind of heat exchanger that absorbs the incident radiation, converts it into heat and then transfers the heat to the working fluid (water, oil, gas [54], etc.) by conduction and convection [55]. Solar thermal collectors are of two types: (a) nonconcentrating or stationary type and (b) concentrating or sun-tracking type [24,56]. For stationary collectors, such as a flat-plate collector, the intercepting area, and the absorbing areas are the same. These collectors are sufficient for low-temperature applications like water/air heating (up to around 90 °C). But in order to run a primary solar thermal cycle (which involves the absorption of solar energy and its conversion to thermal energy in the working fluid), this cycle should be coupled with a secondary power cycle (power generation cycle) [1,57]. Therefore, in order to operate the secondary cycle, the heat transfer fluid should be at high temperature, which motivates the design of concentrating solar collectors (e.g., line-focused and point-focused) and the working mechanism of a solar thermal power plant is as shown in Fig. 1. It shows that solar irradiation is focused on the receiver with the help of heliostats, due to which the working fluid in the receiver gets heated (primary cycle), which eventually helps run the turbine (secondary cycle) [58].

Concentrating collectors (both solar PV and solar thermal) require a sun-tracking mechanism because they concentrate only the direct component of the solar irradiation [59,60]. On the other hand, a sun-tracking mechanism is not required in nonconcentrating collectors, because they absorb both the direct and the diffuse components of the solar irradiation. A large variety of solar thermal collectors are available in the market and a comprehensive list is presented in Table 1.

Furthermore, the temperature of CPVs becomes very high because they operate at very high concentration ratios. This results in the reduction of the system efficiency (because semiconductor performance reduces with an increase in temperature). For improving the efficiency, a special arrangement can be made with PV devices in order to make a hybrid photovoltaic/thermal device (PV/T), which can produce thermal as well as electrical energy [61–63]. There are two types of arrangements for PV/T, (a) thermally coupled, and (b) thermally decoupled. For the thermally coupled arrangement, the heat from the PV panel is removed by the working fluid, which is in direct contact with it. Whereas, thermally decoupled systems are those in which spectral splitting mirrors (beam splitting mirrors) are used to filter a specific energy band utilized by the PV. The remaining spectrum, which lies in other than the specified band range, is diverted to a thermal collector or vice versa in some cases. This serves both purposes, preventing the PV from getting heated, and at the same time the fluid is heated. Some examples of beam-splitting mirrors are $\mathrm{SiN_x/SiO_2}$ and $\mathrm{Nb_2O_3/SiO_2}$ [7,64,65]. Thermally decoupled systems are proven to be a more efficient configuration (compared to thermally coupled systems) because the PV panel does not get affected by thermal fluctuations and high temperatures [31].

The heat transfer enhancement in solar thermal collectors is of paramount importance for increasing the overall efficiency of the solar collector. The heat transfer phenomenon depends on multiple parameters like radiative and convective losses from the absorber surface, conduction resistance of the absorber material, flow condition of the working fluid, the surface area of the absorber in contact with the working fluid, etc. [1,66]. For solar thermal collectors, four components play an important role in order to enhance their thermal performance and these components

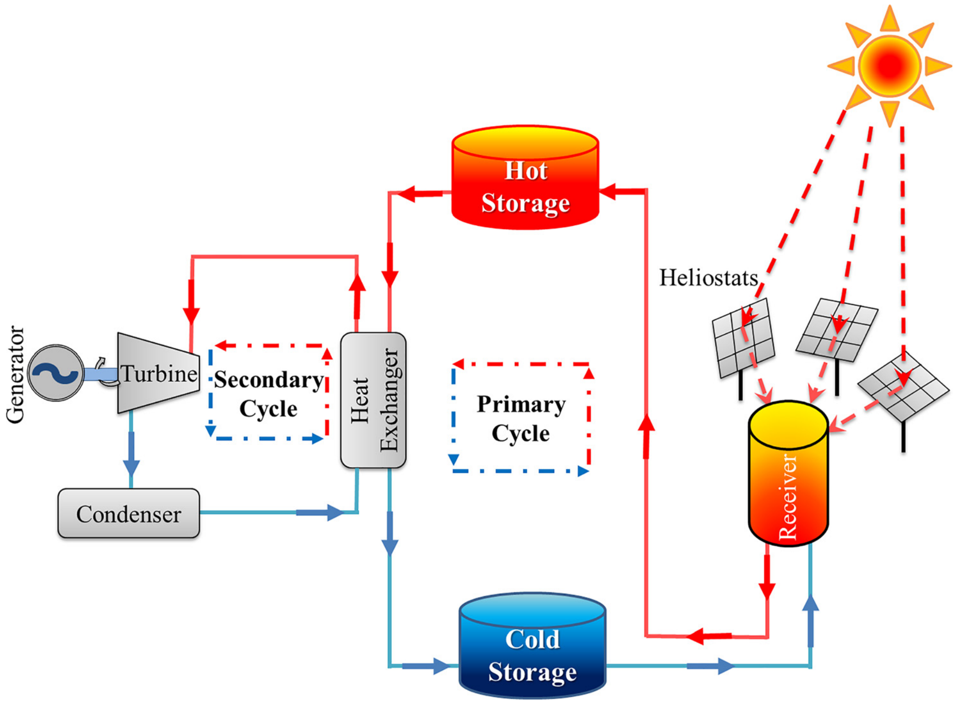

Fig. 1 Working mechanism of a solar thermal power plant

Table 1 Various types of solar thermal collectors and their temperature ranges [55,57–60]

Type of solar collector	Absorber shape	Tracking system	Concentration ratio	Temperature range (°C)
Flat plate collector (FPC)	Flat	Stationary	1	30–80
ETC	Flat	Stationary	1	50–200
Compound parabolic collector (CPC)	Cylindrical	Stationary	1–5	60–240
PTC	Cylindrical	Single-axis tracking system	15–45	60–300
Linear Fresnel reflector (LFR)	Cylindrical	Single-axis tracking system	10–40	60–250
Parabolic dish reflector (PDR)	Point	Two-axis tracking system	100–1000	100–500
Heliostat field collector (HFC)	Point	Two-axis tracking system	100–1500	150–2000

Note: Concentration ratio is defined as the ratio of aperture area to the receiver area.

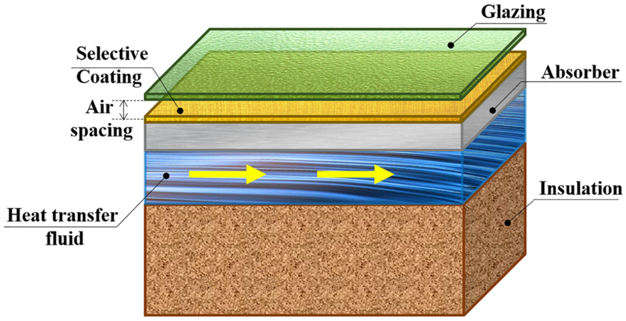

Fig. 2 Cross section of a flat-plate solar thermal collector

are: (a) solar selective coating, (b) absorber geometry, (c) glazing, and (d) insulation, as depicted in Fig. 2. Suppressing the heat loss from a solar thermal collector will be the first and very important step toward heat transfer enhancement. The solar selective coating along with an antireflection layer on the absorber surface can be used to efficiently absorb the solar radiation as well as to cut down the radiative losses from the absorber surface [59,67]. On the other hand, the glazing is used to reduce convective losses by eliminating the direct contact of surrounding air with the absorber surface. It is also used to suppress the emission losses from the receiver by implementing a solar selective coating on glazing, which reflects most of the infrared radiation emitted from the receiver [56]. The insulation prevents conductive losses from the receiver base. The heat transfer enhancement can also be achieved by altering the flow conditions of the working fluid [60]. Turbulence promoters like ribs, grooves, and various absorber shapes can be introduced to increase the turbulence and thereby enhance the convective heat transfer coefficient due to an increase in the Nusselt number. Incorporation of extended surfaces on the absorber can also enhance the heat transfer due to greater absorber surface area [68].

The solar selective coating plays an important role in the collector (as well as in CPV). For CPV (high temperature PV), the solar selective coatings (selective transmitters) are placed in front of the PV and in solar thermal collectors the selective coating is used to absorb the solar irradiation. Ideally, the selective coating should have 100% absorptivity below the cutoff wavelength ($\lambda_c \sim 2$–$3\ \mu$m), and 0% absorptivity above the cutoff wavelength. However, a real solar selective coating does not exhibit a sharp cutoff wavelength, due to which they do not have 100% absorptivity.

Fundamentally, the cutoff wavelength is a tradeoff between the solar radiation absorption capability and the radiative losses from the selective coating, and the absorptivity and emissivity are not mutually independent of each other. In order to optimize the performance of a solar selective surface, a compromise needs to be made between the absorption and emission from the surfaces. The solar-weighted absorptivity (A_{sa}) of an ideal solar selective

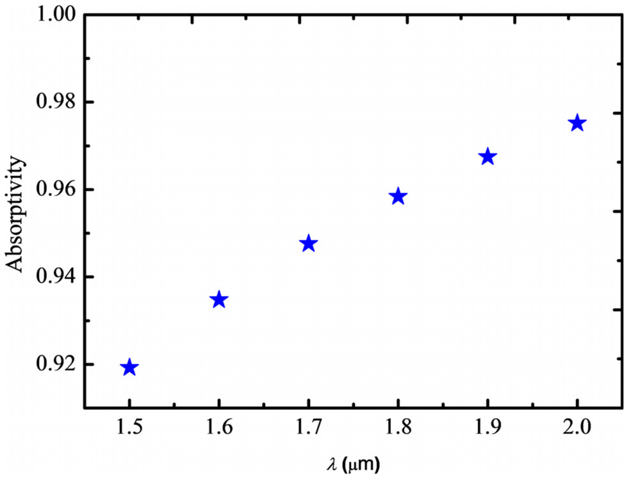

Fig. 3 Absorptivity of an ideal solar selective surface at different cutoff wavelengths (Adapted from Ref. [69])

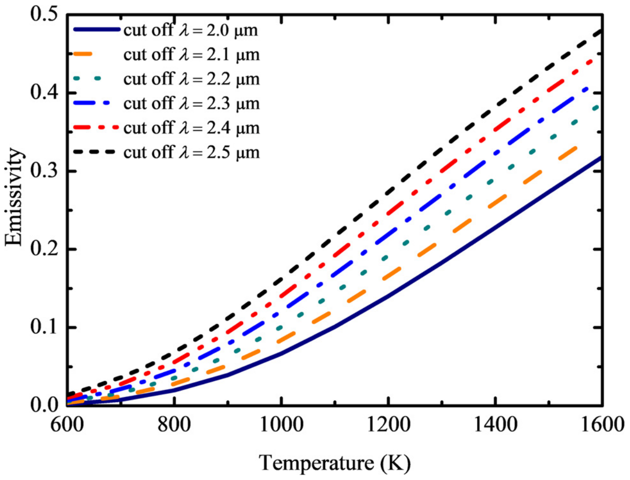

Fig. 4 Emissivity of an ideal solar selective surface as a function of surface temperature at different cutoff wavelengths (Adapted from Ref. [69])

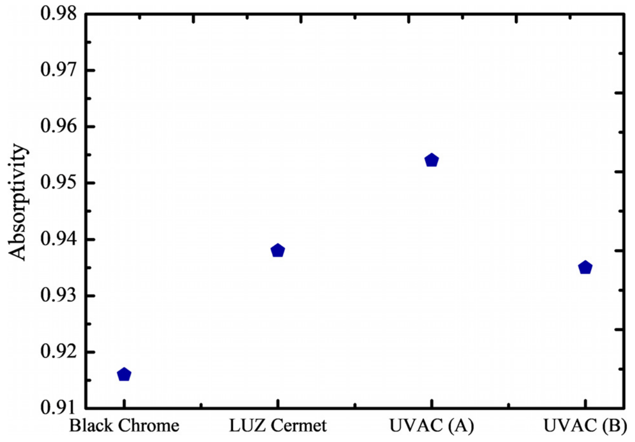

Fig. 5 Absorptivity of commonly available selective coatings (Adapted from Ref. [70])

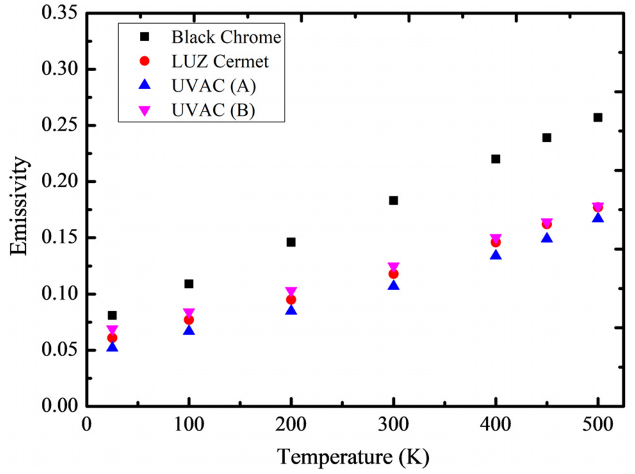

Fig. 6 Emissivity of commonly available selective coatings at different surface temperatures (Adapted from Ref. [70])

coating for various cutoff wavelengths is calculated by using Eq. (3) below and is shown in Fig. 3.

Furthermore, the effective emissivity as a function of surface temperature for different cutoff wavelengths is evaluated by Eq. (4) and the calculated emissivity is shown in Fig. 4

$$A_{\mathrm{sa}} = \frac{\displaystyle\int_0^{\lambda_{\mathrm{cutoff}}} \alpha_\lambda Q_\lambda d\lambda}{\displaystyle\int_0^{2.5\mu m} Q_\lambda d\lambda} \tag{3}$$

$$\varepsilon = \frac{\displaystyle\int \varepsilon_\lambda E_{\lambda,T} d\lambda}{\displaystyle\int E_{\lambda,T} d\lambda}, \quad where\ \ \varepsilon_\lambda = 1 \ \text{ for } \lambda \le \lambda_{\mathrm{cutoff}} \tag{4}$$

$$\varepsilon_\lambda = 0 \ \text{ for } \lambda \ge \lambda_{\mathrm{cutoff}}$$

where α_λ is the spectral absorptivity, Q_λ is the spectral solar irradiance, $E_{\lambda,T}$ is the spectral emissive power for surface temperature T, and ε_λ is the spectral emissivity of the surface.

Figures 3 and 4 represent the maximum achievable thermal performance characteristics for an ideal solar selective surface, and these figures show that there exist theoretical limits for the absorptivity and emissivity of a solar selective coating. As stated above, however, real solar selective coatings do not have sharp cutoff wavelengths. But actual solar selective coatings are designed in such a way that they should have properties near to those of ideal solar selective coatings. The absorptivity and emissivity of some actual solar selective coatings are shown in Figs. 5 and 6, respectively.

The performance of solar thermal collectors can be enhanced by the following ways: (a) increasing the solar selectivity of the absorber [67,71], (b) reducing the thermal losses from the collector [72–75], and (c) increasing the heat transfer coefficient between the absorber surface and the working fluid (water, oil, molten salts, etc.) [76,77]. In order to increase the solar selectivity of the absorber and to reduce the thermal losses from the collectors [67], researchers are working on various types of solar selective coatings. In some cases, different materials are stacked over each other above the substrate in an optimized combination in order to achieve better optical and thermal properties. Various types of solar selective coatings on which recent research is being conducted are (a) dielectric-metal-dielectric (DMD) absorbers [78], (b) cermet composites [79–81], (c) multilayered absorbers [82–84], and (d) textured absorbers [85–87]. The details of these solar selective coatings are discussed in Sec. 2.1. This is followed by a discussion on advances in absorber geometry (Sec. 2.2) and glazings (Sec. 2.3). The optical properties of the system can also be improved by the use of nanoparticle-laden fluids (also known as nanofluids) [6,88,89]. Various experimental and numerical studies have been conducted with nanofluids-based solar thermal collectors, where the solar irradiation is directly absorbed by the nanofluid. The details of these studies are discussed in Sec. 2.4. Further, discussion regarding solar tracking devices is included in Sec. 2.5. In addition to that, Sec. 2.6 conveys a brief discussion on advances in modified solar receivers, i.e., evacuated tube collectors (ETC).

This paper presents a comprehensive review of the recent developments in solar thermal collectors along with the potential for PV/T systems. In this review paper, Sec. 2 focuses on technological advances in individual components of the solar thermal collector. It includes advances in different types of absorber coatings, geometrical improvisations of absorber shape, developments in glazing (glass cover), study of nanoparticle-laden fluids, advances in solar tracking systems, and advances in modified solar receivers. Section 3 presents the future outlook, which includes prospective directions and challenges for subsequent advances in solar receivers.

2 Advances in Solar Receivers

In order to increase the overall efficiency of solar thermal collectors, researchers have focused their attention on various aspects of the collector, such as use of better quality solar selective coatings, improvements in absorber geometry, and high efficiency glazing. Moreover, the use of nanoparticle-laden fluids as a direct absorption fluid in a solar collector has been considered in recent years. Also, solar energy collection by solar receivers can be increased by the implementation of solar tracking systems. Furthermore, the limitations of conventional flat plate solar collectors lead to modifications in their operational concept as well as their construction. Each of these aspects (solar selective coatings, absorber geometry, glazing, nanofluids, solar trackers, and modified solar receivers) is discussed in detail in the Secs. 2.1–2.6, respectively.

2.1 Solar Selective Coatings. Solar selective coatings can be gainfully employed in both solar thermal collectors and in photovoltaic modules. In both cases, the aim is to absorb the useful parts of the solar spectrum (e.g., shorter wavelengths), while controlling the IR radiation. In the case of PV, the excess energy, which is not extracted as electricity, leads to an increase in the surface temperature (and a subsequent reduction in efficiency) [27,90]. To address this issue, selective transmitter coatings can be introduced to the glass cover of the PV module. These coatings act as a filter, and allow only desired portions of the spectrum to be transmitted to the PV cells and can also be engineered to maximize infrared emission (to help cool the cells) [31,91]. There are two categories of such coatings—the first uses the principle of DMD coatings and the other one utilizes single-layer metal oxides [91]. Among the various DMD coatings, the ZnS-Ag-ZnS coatings are found to be quite efficient whereas, indium tin oxide (ITO) is best suited among the second category [92,93]. Due to tight tolerance requirements in ZnS-Ag-ZnS coatings, ITO is generally preferred. An antireflective coating over the ITO can further enhance the cell performance.

On the other hand, for solar thermal collectors, the absorber surface is the component where solar energy is absorbed (as thermal energy). Usually, the absorber itself is made of highly conducting metal (such as copper or aluminum) and has a solar selective coating on top of it to make it highly absorbing inside the solar spectrum. An ideal solar selective coating should have high solar absorptance (α) and low thermal emittance (ε) for efficient photothermal conversion. Therefore, it is desired that the optical properties of the surface be such that $\rho \approx 0$ for $\lambda \leq 3$ μm and $\rho \approx 1$ for $\lambda \geq 3$ μm [67], where $\alpha + \rho = 1$. Since the thermal radiative losses for solar absorbers are directly proportional to the fourth power of surface temperature (T^4), low thermal emittance is of paramount importance for high-temperature applications [94]. There are two main absorption mechanisms for the absorption of incident radiation: (a) intrinsic absorption and (b) interference-induced absorption. The intrinsic absorption is characterized by the extinction coefficient (κ) of the coating, whereas, the interference-induced absorption depends on the refractive index (n) and thickness of the coating as well as the substrate properties [95–97]. To achieve high absorption of solar radiation, the solar selective coatings are constructed with various combinations of these two absorption mechanisms. Based on their construction, there are different types of selective coatings and the details of these coatings are discussed subsequently. Further, the categorization of the absorbers on the basis of construction and working mechanism is listed below along with an explanation [67,78,87] and a schematic (Fig. 7):

(i) Intrinsic absorber [98–100]: An intrinsic absorber uses a single material with intrinsic selective properties of the material. Naturally occurring materials do not have ideal solar selective properties. A schematic is shown in Fig. 7(*a*).
(ii) Semiconductor metal tandem absorber [101–104]: It utilizes the property of semiconductor bandgap to absorb short-wavelength radiation and also achieves low thermal emittance (due to the metallic layers). A schematic is shown in Fig. 7(*b*).
(iii) Cermet absorber [80,81,105]: Also known as "multidielectric composite coatings." It consists of a dielectric or ceramic matrix holding nanoscale metal particles. They are generally stable for high-temperature (concentrated solar power ((CSP) applications. A schematic is shown in Fig. 7(*c*).
(iv) Textured absorber [85,87]: It achieves high solar absorptance with dendritic, porous, granular, or needle-like microstructures, capturing solar energy by multiple reflections. It is not very sensitive to the environmental effects (i.e., oxidation, thermal shocks). A schematic is shown in Fig. 7(*d*).
(v) Dielectric–metal–dielectric (DMD) absorber [78,95]: It absorbs the sunlight efficiently using multiple reflections between alternative layers of dielectric and metal. It is easily fabricated using only a small amount of material, resulting in lower consumable costs. A schematic is shown in Fig. 7(*e*).
(vi) Multilayer absorber [82–84]: It has several alternative layers of antireflective, dielectric, metal, IR reflector coatings, etc. Interference-induced absorption is dominant in this type of absorber. Its main disadvantage is costly fabrication. A schematic is shown in Fig. 7(*f*).
(vii) Selectively solar-transmitting coating on a blackbody-like absorber [67,106]: It is usually used for low-temperature applications as a blackbody-like absorber. It can be useful for high-temperature applications with highly doped semiconductors. A schematic is shown in Fig. 7(*g*).

Moreover, solar selective coatings can also be categorized on the basis of operational temperature [67]:

(a) Low-temperature solar selective coating: All the coatings used for temperatures less than 100 °C.
(b) Mid-temperature solar selectivity coating: These types of coatings have a stable temperature range from 100 to 400 °C. Here, selective coating materials like PbS, TiNxOy, NiCrOx, colored stainless steel (SS), black nickel NiS-ZnS, etc., are used. These selective coatings are used for industrial process heat and solar hot water desalination. In order to improve the overall efficiency of the system and to resist environmental degradation, midtemperature coatings should have properties like self-cleaning, transparent and superhydrophobic nature [67].
(c) High-temperature solar selectivity coating: These types of coatings are used for applications with operating temperatures greater than 400 °C. For this temperature range materials like Ni-Al_2O_3, Co-Al_2O_3, Mo-Al_2O_3, CuO, W-WOx,

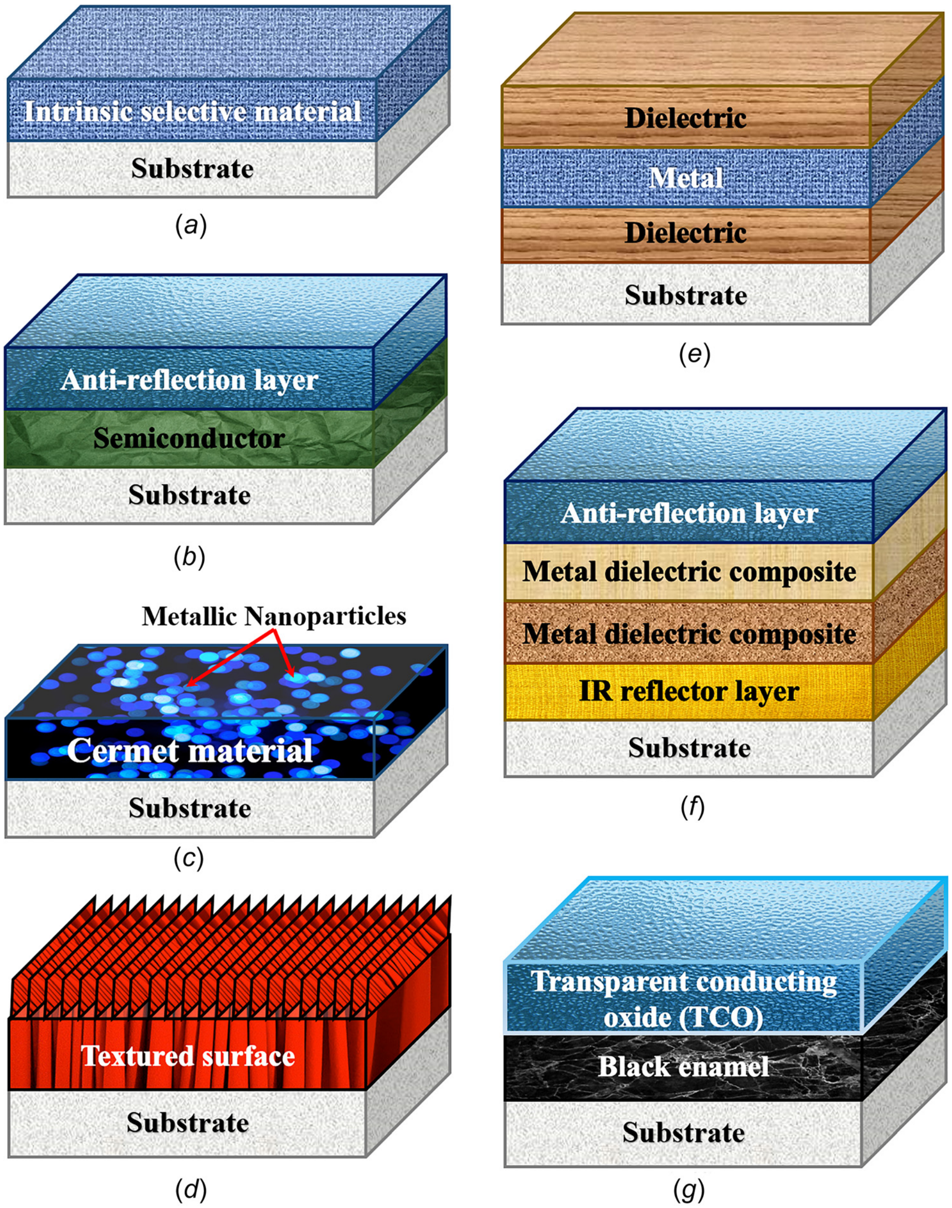

Fig. 7 Types of solar selective coatings: (*a*) intrinsic absorber, (*b*) semiconductor metal tandem absorber, (*c*) cermet absorber, (*d*) textured absorber, (*e*) DMD absorber, (*f*) multilayer absorber, and (*g*) selectively solar-transmitting coating on a blackbody-like absorber

Au/TiO_2, etc., are used [107]. Concentrating solar power systems can use this type of coating for solar thermal power generation. To develop selective coatings for high temperature, interlayer materials (Mo, Ta, Pt, etc.) are coated on the substrate in order to reduce the thermal emissivity. There are numerous factors [67] due to which high-temperature selective coatings start degrading, viz., pollution-induced atmospheric corrosion, hydratization of the selective coating surface due to condensation of atmospheric moisture, interlayer diffusion, oxidation due to intensive thermal conditions, poor interlayer adhesion, chemical reactions, etc.

Yet another method to enhance the short wavelength absorption is by "light trapping"—a phenomenon which utilizes multiple reflections in stacked absorber coating layers. The solar radiation absorptance of DMD coatings can be boosted by modifying the optical constants of metal and dielectric layers [78]. Many researchers have worked on improving DMD coatings in the past decade.

In order to investigate the principle mechanism of DMD coatings, Khelifa et al. [97] investigated the method of preparation as well as the structural and optical properties of a $Cr_2O_3/Cr/Cr_2O_3$ DMD solar absorber. It consists of a thin semitransparent metal layer of chromium sandwiched between two dielectric layers of chromium oxide deposited on SS substrate. In this case, the absorption due to interference is more dominant as compared to intrinsic absorption, since n is higher than the κ of the middle Cr layer and upper Cr_2O_3 layers. Whereas, for the bottom Cr_2O_3 layer, the κ values are higher than the n values, which shows that incident radiation absorption in this layer is mainly due to intrinsic absorption rather than the interference mechanism. This DMD coating has been shown to exhibit a good value of solar absorptance (α) of $\alpha = 0.89$ and thermal emittance (ε) value of $\varepsilon = 0.25$ at 100 °C. Similarly, Nuru et al. [96] investigated the microstructural, optical properties and thermal stability of a MgO/Zr/MgO DMD solar absorber. Magnesium oxide (MgO) was selected for high-temperature applications due to its properties like good thermal conductivity, high thermal stability and high melting point. The coating is thermally stable in vacuum up to 400 °C. However,

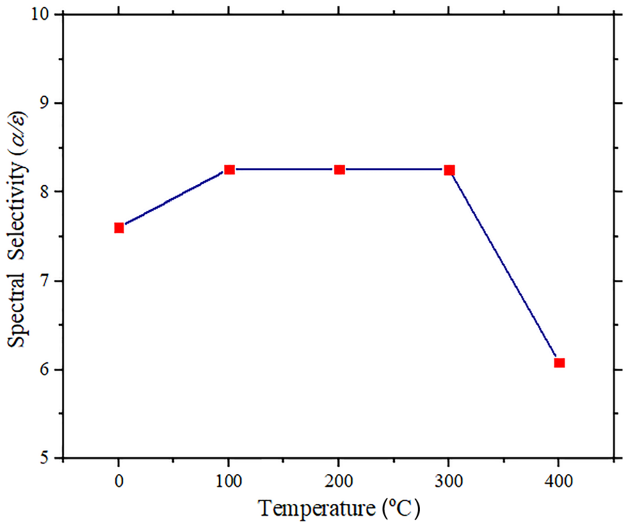

Fig. 8 Change in the spectral selectivity of coating due to annealing in air at different temperatures for 2 h (Adapted from Ref. [107])

the optical properties start to degrade around 500 °C, due to thermally activated atomic interdiffusion between the layers. This DMD coating has $\alpha = 0.918$ and $\varepsilon = 0.10$. Further in order to check the effect of annealing (in air) on the thermal stability of a MgO/Zr/MgO DMD solar absorber, Nuru et al. [107] also carried out an experimental study of the heat treatment of the selective coating (MgO/Zr/MgO) for 2 h and 24 h. The spectral selectivity of the coating after 2 h of heat treatment is shown in Fig. 8.

Figure 8 shows that there has been a negligible change in the optical properties (absorptance and emittance) for an annealing process up to 300 °C. Thus, it has been concluded that the coating is thermally stable in air up to 300 °C. However, at around 400 °C, a sudden reduction in solar selectivity ($\alpha/\varepsilon = 0.91/0.12$) occurs, due to the decrease in solar absorptance and the increase in thermal emittance. The authors inferred the reasons for degradation of coating properties at high temperatures (by the heavy ion elastic recoil detection analysis measurement) as follows: (i) outward diffusion of Zr layers toward the surface of the coatings, (ii) change in MgO chemical composition, and (iii) increment in oxidation of the base Zr metallic layer. Long-term thermal stability of the specified DMD coating is recorded up to 250 °C in air for 24 h, thus making it suitable for midtemperature applications.

From the previous references, the scope for subsequent research on improving the performance of DMD coatings for high-temperature applications can be easily identified. Thus, the succeeding review is focused on amplifying the thermal stability of DMD coatings. Selvakumar et al. [95] designed a DMD—HfO_x/Mo/HfO_2 solar selective coating for high temperatures with further utilization of an additional molybdenum layer in between the substrate and coating as a diffusion barrier. In this coating HfO_2 acts as an antireflective coating, Mo acts as a metal interlayer and HfO_x as an absorber. This coating primarily works on an interference-induced principal mechanism. They used Cu and SS substrates on which the HfO_x/Mo/HfO_2 coating was deposited. Molybdenum is a metal interlayer due to its low reflectance in the visible region, high infrared reflectance and good solar absorptance. High infrared reflectance results in low emittance in the infrared region, due to higher free electron density of Mo. In HfO_x, the oxygen content plays a crucial role; when HfO_x has lower oxygen content, it acts as an absorber which exhibits significant absorption in the visible region. On the other hand, when HfO_x has higher oxygen content, it acts as an antireflective coating which gives a great transparency over a wide spectral range (from ultraviolet to mid-IR region). The authors concluded that an optimized HfO_x/Mo/HfO_2 multilayer absorber on a Cu substrate exhibits high solar absorptance of $\alpha = 0.905$–0.923 and low thermal emittance of $\varepsilon_{82\,^{\circ}\mathrm{C}} = 0.07$–$0.09$, whereas on SS substrate, they achieved $\alpha = 0.902$–0.917 and $\varepsilon_{82\,^{\circ}\mathrm{C}} = 0.15$–$0.17$. HfO_x/Mo/HfO_2 coating on Cu and SS substrate can withstand temperatures $\geq$ 400 °C for 2 h, with no significant change in absorptance and emittance values. But, Cu substrate degradation starts after 350 °C because oxide formation starts after this temperature range. In order to overcome this issue, they introduced a thin Mo interlayer (40 nm) in the present coating (it acts as a diffusion barrier) so that a new four-layer (Mo/HfO_x/Mo/HfO_2) coating exhibits high solar selectivity ($\alpha/\varepsilon = 0.872/0.09$) with thermal stability up to 600 °C.

Similarly, Nuru et al. [108] checked the effect of tantalum (Ta) as a diffusion barrier on the optical properties and thermal stability of a Cu/Ta/Al_xO_y/Pt/Al_xO_y solar absorber. The reasons for choosing tantalum as a diffusion barrier are good adhesion, high melting point (3017 °C), and chemical stability with copper substrate. The current solar absorber is thermally stable up to 700 °C in air, whereas without the Ta diffusion layer, it was stable for temperatures below 500 °C. Long-term annealing showed that the multilayer coating was stable up to 550 °C in air for 24 h; it was previously stable up to only 450 °C without a Ta layer [109].

On the other hand, for multilayer or tandem coatings, multiple layers of various materials are stacked over each other to produce a specific characteristic, which will subsequently enhance the performance of the absorber. Each layer added in a tandem absorber either improves the solar selectivity or amplifies the thermal stability so that the absorber will absorb more radiation and dissipate it less at comparatively higher temperatures (around 500 °C and beyond that).

Jyothi et al. [83] fabricated a TiAlC/TiAlCN/TiAlSiCN/TiAlSiCO/TiAlSiO tandem absorber coating designed for high-temperature solar thermal power applications. The design of the tandem absorber from bottom to top layer includes three absorbers: (TiAlC/TiAlCN/TiAlSiCN), a semitransparent layer (TiAlSiCO), and an anti-reflective layer (TiAlSiO) sequentially. From the bottom (TiAlC) to the top layer (TiAlSiO) reduction of the metal volume fraction is modulated in order to maintain the gradient refractive index to achieve high absorptance. A new type of tandem absorber was deposited on tungsten-coated SS substrate, yielding a solar absorptance of $\alpha = 0.961$ and a thermal emittance of $\varepsilon_{82^{\circ}\mathrm{C}} = 0.07$. The coating is also thermally stable in vacuum up to 650 °C for 100 h under cyclic heating conditions.

Consequently, some of the research work has also been focused on reducing the thermal losses in the form of IR emission from the absorber substrates. Sibin et al. [110] experimentally attempted to control the thermal emittance of the SS substrate by varying the thickness of a tungsten (W) layer. An IR reflecting tungsten layer was deposited beneath an AlTiN/AlTiON/AlTiO tandem absorber using direct current (DC) magnetron sputtering. The variation in solar selectivity (α/ε) for different thickness of tungsten coating is shown in Fig. 9.

From Fig. 9, it was observed that the spectral selectivity increases with an increase in the coating thickness (in the range 100–900 nm). Sibin et al. [110] also concluded that the low thermal emittance of the tungsten thin film depends on the low resistance of the same layer. The sheet resistance decreases with an increase in tungsten film thickness. The microstructural defects in the tungsten layer like dislocations, pin holes, vacancies, interstitials, etc. lead to the increase in resistivity. They have observed good thermal stability at high temperatures (up to 750 °C) in vacuum. During the annealing process, the tungsten coatings were thermally stable in air up to 300 °C; the thermal emittance increases as the operational temperatures go beyond 350 °C. Solar selective coating of W/AlTiN/AlTiON/AlTiO tandem absorber exhibited absorptance of 0.955 and emittance of 0.08.

In addition to the IR reflector, it can be observed that research must be done on the antireflective properties of the coating, as the antireflection layer on top enables the coating to absorb the maximum solar spectra. Dan et al. [111] have also fabricated W/

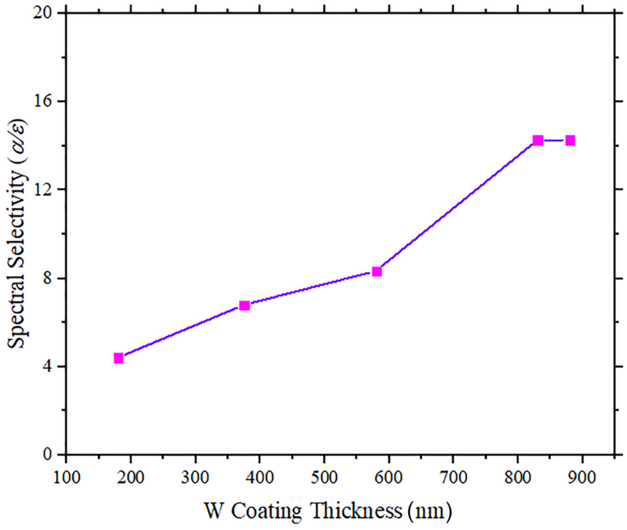

Fig. 9 Solar selectivity versus tungsten (W) coating thickness on SS substrate (Adapted from Ref. [110])

WAlN/WAlON/Al_2O_3 coatings on SS substrates to absorb the maximum possible solar radiation with minimal thermal emittance. As per the construction of the coating, tungsten acts as the IR reflection coating, the main absorber layer is WAlN, WAlON acts as the semi absorber layer and the top layer of aluminum oxide (Al_2O_3) works as the antireflection layer. Different values of optical properties for various combinations of coating layers are shown in Fig. 10.

From Fig. 10, it can be concluded that after deposition of Al_2O_3 as an antireflection layer, tandem absorber coatings exhibit a high absorptance of 0.958. The coating is thermally stable in air up to 500 °C for 2 h with negligible changes in the spectral selectivity. The long-term thermal stability results show that the coating is thermally stable up to 350 °C and 450 °C for 550 and 150 h, respectively, and there was no significant degradation in the optical properties of the coating. The mentioned tandem absorber can exhibit a solar absorptance of 0.958 and thermal emittance of 0.08.

Furthermore, Dan et al. [112] have found that for a wide range of incidence angles from 18 deg to 58 deg, a (W/WAlN/WAlON/Al_2O_3 coating) tandem absorber exhibits a high solar absorptance. Also, Dan et al. [113] confirmed that in order to maintain a high selectivity, it is desirable to obtain a colored appearance of the coating.

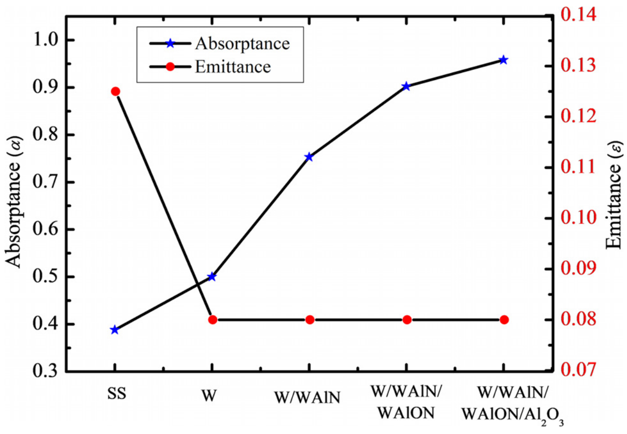

Fig. 10 Absorptance and emittance values for SS substrates with different combinations of the solar selective coating (Adapted from Ref. [111])

Similarly, Selvakumar et al. [114] developed a novel solar selective coating (HfMoN/HfON/Al_2O_3) on a SS substrate, which has high solar selectivity and good thermal stability in vacuum. It uses a combination of absorber–reflector tandem and double layer antireflection coating (DLARC) concepts. In DLARC, the bottom layer must have high refractive index relative to the top layer in order to get promising results. The reduction in reflectance over a broad wavelength range can be achieved with the help of double reflectance minima, which becomes the major advantage for DLARC. The details of each layer of this coating are shown in Fig. 11.

A gradual reduction of refractive index from the substrate to top layer leads to the high absorptance of the tandem absorber (confirmed by ellipsometric measurements). The absorptivity of a tandem absorber increases from 0.92 to 0.95 under identical conditions, due to the addition of an Al_2O_3 coating on top of the three-layer tandem absorber. The interference-induced and intrinsic absorption are dominant in this coating with DLARC, due to the increase in refractive index (n) in subsequent layers from top to bottom. The multilayer coating is thermally stable in air at 475 °C for 34 h, whereas it is thermally stable in vacuum at 600 °C for 450 h and at 650 °C for 100 h with no change in the emittance and 1% decrease in the absorptance.

In recent years, cermets are being extensively researched in order to achieve the properties like higher solar selectivity and enhanced thermal stability. The cermets coatings are composites of metal nanoparticles enclosed in a dielectric or ceramic matrix (e.g.—oxide, nitride, oxynitride, etc.). It should have metallic properties in the infrared (IR) spectrum, and ceramic properties in the remaining spectrum.

Barshilia has filed a patent [105] for a cermet-based solar selective coating, which can be used for high temperature applications like concentrated solar power. The coating (Ti/AlTiN/AlTiON/AlTiO on SS substrate) has been prepared to obtain excellent thermal and mechanical properties, like long thermal stability in air as well as in vacuum, high surface uniformity, high hardness, scratch resistance, higher humidity resistance, chemical inertness, etc. From this selective coating a solar absorptance ($\alpha = 0.927$) and thermal emittance ($\varepsilon = 0.16$) can be achieved. The author inferred that the coating is thermally stable in air up to 350 °C for a duration of 1000 h and in vacuum up to 450 °C for a duration of 1000 h as well, under cyclic heating conditions.

Furthermore, Nuru et al. [80] studied the optical properties and thermal stability of a multilayer of Pt and Al_2O_3, as well as a single layer of Pt-Al_2O_3 cermet. In this study, they concluded that the selection of Mo as the IR reflector material will enhance the solar spectral selectivity. Ideally, the optimized Pt-Al_2O_3 double cermet will be stratified as: Mo ~ 100 nm/Pt-Al_2O_3 ~ 60 nm/Pt-Al_2O_3 ~ 40 nm/Al_2O_3 ~ 80 nm. The double cermet coating exhibits a solar absorptance (α) of 0.97 and thermal emittance (ε) of 0.05.

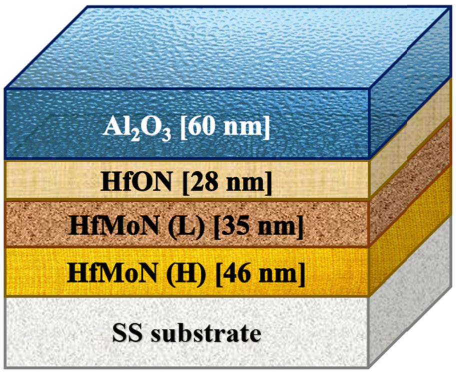

Fig. 11 A schematic of tandem absorber along with the absorptance and emittance of different layers of the tandem absorber (Adapted from Ref. [114])

As a novel attempt to achieve combined properties of cermet as well as textured absorbers, Karoro et al. [87] designed and investigated the microstructural and optical properties of laser nanostructured cobalt (Co) nanocylinders-Al_2O_3 cermets. This coating can be comprehended as a new family of solar selective coatings as it can be classified as a textured surface as well as a cermet composite due to its unique fabrication details. This kind of coating works on three different mechanisms of light absorption, viz., anti IR reflection and plasmonic effects, entrapment of light into surface irregularities and/or Fresnel angular reflection dependence. Enhancement in the optical absorptance of nanostructured cermet coating can be observed when compared to the conventional Co-Al_2O_3 cermets with a value of α (λ) above 0.98 and a thermal emittance ε (λ) of 0.03. This coating results in a flexible, attractive, and cost-effective application for solar selective absorbers.

There are numerous researchers who have shown novelty in their research of solar selective coatings for solar collectors—absorbers. Some of them innovated new methods to produce various coatings or individual layers, in order to achieve cost-effectiveness, ease in manufacturing method and in some cases to make the method environmental friendly [115,116]. Wang et al. [117] experimentally demonstrated a solar selective meta-material coating with nanostructured titanium gratings deposited on an opaque tungsten film and an ultrathin MgF_2 spacer. In order to minimize the possibility of cracks at the interface of two layers at high temperatures, MgF_2 with better coefficient of thermal expansion was the perfect match with tungsten as well as with the titanium layers. No degradation of optical properties occurred up to 350 °C, which showed that the coating is thermally stable. The solar-to-heat conversion efficiency for this solar selective coating was predicted to be 78% at 100 °C without optical concentration, or 80% at 400 °C under 25 suns.

Furthermore, Wu et al. [118] investigated the effect of silicon (Si) doping on the thermal stability (in air and in vacuum) of an individual absorber layer consisting of Al/NbTiSiN/NbTiSiON/SiO_2 solar selective coating deposited on a SS substrate. The thermal stability depends on the coating materials and the properties can be improved with the addition of materials like Si, Al, or Cr. Among these materials, Si is more efficient than the others due to its higher oxidation resistance and anti-diffusion ability. When this Si coating is aged at 500 °C in air for 2 h, the absorptivity and emissivity values are maintained at 0.922 and 0.13, respectively.

To summarize, it is observed that for high-temperature applications, e.g., CSP, cermet-based composite selective coatings are most promising. In order to enhance the performance of solar thermal collectors, additional layers (like Mo, Ta, Al_2O_3, etc.) having properties like antireflective (solar spectrum), antidiffusion, IR reflective, etc. can be used. In future, more novel attempts should be made in order to produce coatings like metamaterials in which two different categories of solar selective coatings are combined so as to meet the required optical and thermal properties. Finally, the details of all compositions of the materials and preparation methods discussed here are summarized in Table 2.

2.2 Absorber Geometry.

While the selective coatings can provide excellent radiative control, those techniques are limited by their additional cost. Modifying the geometry of a solar collector, on the other hand, provides a low-cost mechanism to control heat removal from the solar absorber. Numerous studies have also been carried out to optimize the geometry and orientation of solar thermal and PV collectors, along with studies on the best geometric configuration for thermally coupled and decoupled configurations of PV/T hybrids. For all cases, the geometry plays a critical role in terms of heat removal to a passive (e.g., air) or active (e.g., water, oils, nanofluids) heat transfer fluid. All of these designs work by either disturbing the fluid flow (e.g., to create mixing) or by enable the flow to pass by more easily (e.g., passively enhancing natural convection in building integrated PV systems or by reducing pumping power in a thermal collector).

Research work in absorber geometry alterations can be broadly categorized into two categories, viz. microscale and macroscale alterations. In microscale alterations, artificial roughness and micro channels beneath the absorber surfaces have been studied. This kind of corrugation on the absorber surface results in an increase in heat transfer coefficient by increasing the surface area, leading to turbulent flow. Bisht et al. [77] presented an intensive review of various techniques to produce artificial roughness on the underside of the absorber surface in order to improve the performance of solar air heaters. They described the effects of various roughening styles like V-shaped ribs, grooves, arc-shaped ribs, arc-shaped dimples, S-shaped ribs, hyperbolic ribs, etc. on the enhancement of heat transfer. They concluded that the multi V-shaped ribs with gap is the most effective roughness style which offers higher heat transfer enhancement and lower pressure drop in heat transfer flow. Oyinlola et al. [121] experimentally investigated the effects of micro channel geometry on the absorber of a compact flat plate solar collector. From the results, the authors stated that considerable improvements in thermal performance can be achieved by increasing the fluid velocity with a corresponding increase in pumping power input. The micro channels with 0.25 mm-deep grooves were concluded to be the most efficient and optimized construction for an absorber plate.

Macroscale alterations in the absorber geometry can be carried out by changing the effective area, shape, or orientation of the absorber. The comprehensive PV thermal management review by Du et al. provides details for numerous proposed geometric designs which effectively increase natural/forced air cooling and optimized hydraulic cooling designs for PV [122]. In general, the same forced convection techniques work for removing heat from both PV and solar thermal absorbers, including incorporating internal fins, varying cross section of the absorber throughout the length, changing the nature of the absorber tube axis, etc. Bellos et al. [123] investigated the thermal performance of internally finned absorbers of parabolic trough collectors (PTCs) with twelve different fin geometries. The fins were rectangular, constructed on the inside periphery of the absorber tube, along the length of the absorber tube and toward the center of the absorber cross section. They also compared the finned geometries with smooth (conventional) absorber tubes on the basis of parameters like thermal efficiency, Nusselt number, pressure losses, etc. The objective of this research was to examine different constructions of fins with the help of computational fluid dynamics analysis and to determine the optimum fin dimensions or aspect ratio for maximum thermal efficiency with lowest possible pressure losses. The authors concluded that the length of fin is the more dominant factor compared to fin thickness in order to get higher thermal efficiency with lower pressure drops. Moreover, Bellos et al. [76] theoretically analyzed the effect of different types of HTF and altered the absorber geometry on the overall thermal performance of PTC. This research demonstrated an enhancement in the performance of PTC by changing the shape of the absorber tube in the form of wavy inner surface (converging-diverging absorber tube), as shown in Fig. 12.

Such a design increases the heat transfer surface area and moreover the flow becomes turbulent, which results in higher heat transfer coefficients (leading to a 4.55% increase in collector efficiency).

Demagh et al. [124] numerically investigated the use of an S-curved/sinusoidal absorber for the PTC instead of a conventional straight absorber tube along the absorber axis with the help of the Monte Carlo ray tracing method. The schematic of the sinusoidal absorber is shown in Fig. 13.

The authors concluded that the proposed design offers higher intercept factor and better average flux distribution all around the absorber tube, along with a few limitations like reduced temperature gradient and decrease in heat flux maxima. Pavlovic et al. [125] experimentally developed a lightweight structure of a spiral

Table 2 Summary of the advancements in solar selective coatings

Sr. No.	Author (year)	Composition	Preparation method	Development
1	Selvakumar et al. [95]	HfO_x/ Mo/ HfO_2	Reactive DC unbalanced magnetron sputtering system	Solar absorptance (α) = 0.905–0.923 Thermal emittance (ε) = 0.07–0.09 Thermally stable up to 800 °C (in air)
2	Nuru et al. [109]	Al_xO_y/ Pt/ Al_xO_y	High vacuum e-beam evaporation system	Thermally stable up to 500 °C (in air) Long-term thermal stability up to 450 °C in air for 24 h
3	Nuru et al. [108]	Ta/ Al_xO_y/ Pt/ Al_xO_y	High vacuum e-beam evaporation system	Thermally stable up to 700 °C (in air) Long-term thermal stability up to 550 °C in air for 24 h Using a Ta thin layer as a diffusion barrier proves to be an effective method to improve the thermal stability of the coatings
4	Nuru et al. [96]	MgO/ Zr/ MgO	High vacuum e-beam evaporation system	Solar absorptance (α) = 0.918 Thermal emittance (ε) = 0.1 Thermally stable up to 400 °C (in vacuum)
5	Nuru et al. [107]	MgO/ Zr/ MgO	High vacuum e-beam evaporation system	Thermally stable up to 300 °C (in air) Long-term thermal stability up to 250 °C in air for 24 h
6	Khelifa et al. [97]	Cr_2O_3/ Cr/ Cr_2O_3	High vacuum e-beam evaporation system	Solar absorptance (α) = 0.89 Thermal emittance (ε) = 0.25
7	Dan et al. [111]	WAlN/ WAlON/ Al_2O_3	Reactive DC/RF magnetron sputtering system	Solar absorptance (α) = 0.958 Thermal emittance (ε) = 0.08 Thermally stable up to 500 °C (in air) for 2 h Long-term thermal stability up to 350 °C and 450 °C for 550 h and 150 h, respectively
8	Jyothi et al. [83]	TiAlC/ TiAlCN/ TiAlSiCN/ TiAlSiCO/ TiAlSiO	Four-cathode reactive unbalanced DC magnetron sputtering system	Solar absorptance (α) = 0.91 Thermal emittance (ε) = 0.07 Long-term thermal stability up to 650 °C in vacuum for 100 h
9	Selvakumar et al. [114]	HfMoN/ HfON/ Al_2O_3	Reactive pulsed DC unbalanced magnetron sputtering system	Solar absorptance (α) = 0.95 Thermal emittance (ε) = 0.14 Long-term thermal stability (in vacuum) up to 600 °C and 650 °C for 450 h and 100 h, respectively Long-term thermal stability (in air) up to 475 °C for 34 h.
10	Wu et al. [119]	Al/ NbMoN/ NbMoON /SiO_2	Magnetron sputtering system (Vacuum)	Solar absorptance (α) = 0.948 Thermal emittance (ε) = 0.05 Thermally stable up to 400 °C (in vacuum)
11	Song et al. [120]	Al/ NbMoN/ NbMoON /SiO_2	Magnetron sputtering system (Vacuum)	Thermally stable up to 300 °C (in air) Long-term thermal stability up to 450 °C in air for 200 h and up to 500 °C in air for 240 h
12	Barshilia [105]	Ti/ AlTiN/ AlTiON/ AlTiO Cr/ AlTiN/ AlTiON/ AlTiO	Sol-gel deposition method	Solar absorptance (α) = 0.927 Thermal emittance (ε) = 0.16 Solar absorptance (α) = 0.935 Thermal emittance (ε) = 0.09
13	Nuru et al. [80]	Mo/ Pt-Al_2O_3/ Pt-Al_2O_3/ Al_2O_3	Reactive DC/RF magnetron sputtering system	Solar absorptance (α) = 0.97 Thermal emittance (ε) = 0.05
14	Karoro et al. [87]	Co nanocylinders-Al_2O_3 cermets	Laser surface structuring and Electrodeposition of nanocylinders	Solar absorptance (α) = 0.98 Thermal emittance (ε) = 0.03 (For solar spectrum range of 200–1100 nm)

Table 2 (continued)

Sr. No.	Author (year)	Composition	Preparation method	Development
15	Wang et al. [117]	Ti grating on Ti/MgF_2 layer	E-beam evaporation and fabrication of Ti followed by lift-off process	Solar absorptance $(\alpha) = 0.9$ Thermal emittance $(\varepsilon) = 0.2$ Thermally stable up to 350 °C (in air)
16	Wu et al. [118]	Al/ NbTiSiN/ NbTiSiON/ SiO_2	Reactive magnetron sputtering method	Solar absorptance $(\alpha) = 0.922$ Thermal emittance $(\varepsilon) = 0.13$ Thermally stable up to 500 °C (in air) for 2 h

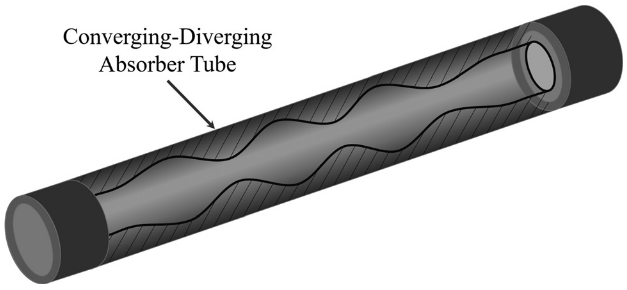

Fig. 12 Schematic of convergent-divergent absorber tube (Adapted from Ref. [76])

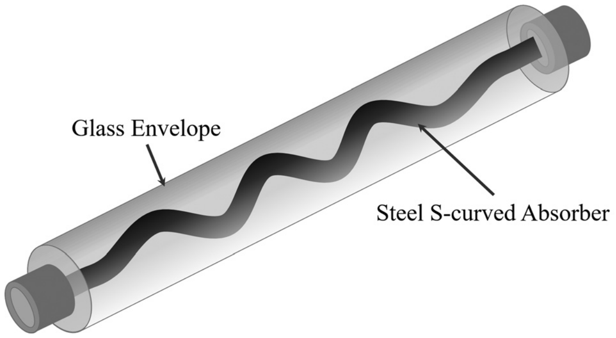

Fig. 13 Schematic of the S-curved/sinusoidal absorber tube (Adapted from Ref. [124])

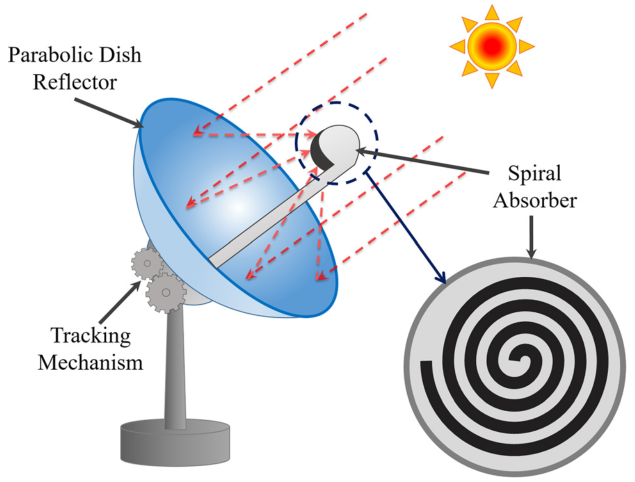

Fig. 14 Schematic of solar thermal dish collector with a spiral absorber (Adapted from Ref. [125])

absorber for a point-focusing solar paraboloid dish collector. The schematic of the setup is shown in Fig. 14.

The experimental results were validated using a numerical model. The authors claimed that this point-focusing solar collector achieved a thermal efficiency of around 34% when water is used as the heat transfer fluid. This kind of compact, low-cost solar collector is best suited for high-temperature applications over 100 °C, like solar power plants, solar heating and cooling, etc.

Many researchers are also working on altering absorber geometries in other solar applications such as solar stills (desalination) and solar air heating. Samuel Hansen et al. [126] experimentally analyzed the effect of using absorbers with special construction (attached with fins or engraved with grooves) on the performance of an inclined solar still. This hybrid solar desalination system has three different configurations, with flat, grooved and fin-shaped absorbers, respectively. It was concluded that the fin-shaped absorber gives 25.7% higher distillate output than that of the conventional flat plate absorber. Similarly, Velmurugan et al. [127] compared the experimental results of a solar still having redesigned basin absorber with fins to that of an ordinary solar still. Due to the increased exposure area in the case of the fin-integrated absorber, the solar still productivity increased by 45.5%. Some of the researchers also tried to achieve higher performance from a solar still by altering the shape of the absorber. Arunkumar et al. [128] experimentally studied a solar still design having hemispherical absorber shape with hemispherical concentrator. The authors concluded that the greater surface area of the absorber leads to higher productivity. Whereas, Ayoub et al. [129] carried out a modification in conventional solar still design in order to enhance its productivity significantly. They installed a partly submerged slowly rotating hollow drum inside the still instead of the conventional flat absorber. The authors claimed that this kind of modification will promote the evaporation process rapidly, since a thin layer of saline water is continuously getting formed and evaporated on a large circumferential area of drum. The performance of solar air heaters can also be enhanced using similar techniques like ribbed absorber surfaces [130–132], winglets, and wavy grooves on the absorber [133–135], fins with various designs [68], etc. The key point for enhancing the performance of solar stills and solar air heaters is to increase the heat transfer coefficient by making the flow of working fluid turbulent or to increase the exposure area.

In summary, the alterations made in the absorber geometry, whether it is microscopic or macroscopic, have enhanced the thermal performance of collectors. This is due to a combination of factors such as increased absorber surface area and higher heat transfer coefficient. Various types of shapes, which have been considered, are spiral, S-curved, converging-diverging, etc. From the review of developments in absorber geometry, it has been found that this field must be focused for research work to be carried out in the upcoming future. Furthermore, in order to further improve the performance of solar thermal collectors, it is of paramount importance to cutoff the thermal losses. Glazings are proven to be one of the most prominent solutions to reduce the thermal losses to a considerable amount. Discussion of recent progress in solar collector glazings is presented in Sec. 2.3.

2.3 Glazing. Glazing in solar thermal collector and solar PV helps in improving the overall efficiency of the system. The first role of glazing can be depicted as a transparent covering plate of the solar collector due to which the absorber and PV panel are protected from the outside atmosphere including dust, moisture, etc. When the solar irradiation is incident on the glazing, attenuation of the irradiation takes place due to three different processes, viz. absorption, reflection, and transmission. A high value of the glazing transmittance is required. For maximum transmittance, antireflective coatings of transparent conducting oxide (TCO) are preferably incorporated. The roughening of the TCO surface can make it work like an antireflective coating. Another alternative for antireflective coatings, other than TCO, is multilayer antireflection (MAR) coatings [136]. MAR coatings use destructive interference of light in order to prevent reflection. The interference is controlled by the refractive indices of the layers as well as the thickness of the layers. One of the examples, meeting all the requirements of MAR coatings, is a combination of zirconium dioxide (ZrO_2) with high refractive index and silicon dioxide (SiO_2) as low refractive index material. Furthermore, in case of STC, convective and radiative losses get suppressed with the presence of glazing. In STCs, the absorption of the incident radiation, by the glazing, should be minimum or negligible, within the visible and near infrared (NIR) region. Further, this absorption depends on the iron content (Fe_2O_3) in the glass. If the Fe_2O_3 content is high, then the glass will be able to absorb more in the IR region of the solar spectrum [56]. The spectral transmittance curve of glass for 6 mm thickness at different iron contents is shown in Fig. 15.

From Fig. 15, it can be clearly observed that low iron content glass (water white glass with 0.02% Fe_2O_3) has excellent transmission within the visible to NIR region of the solar spectrum. On the other hand, glass with high iron content (0.50% Fe_2O_3) has a greenish appearance and has very low transmittance in the NIR region of the solar spectrum.

An ideal solar selective glass should fulfill the following requirements: high value of solar transmittance, economical cost, long-term chemical stability, and heat trapping capability [74]. In order to significantly reduce the thermal losses, heat trapping capability is a must and it can be achieved by applying a selective coating over the glass surface, which reflects the most in the IR spectral region. Adding an anti-reflection (AR) coating on a single side of the glazing could reduce the reflective thermal losses by four times. Moreover, if the AR coating is deposited on both sides of the glazing, it can result in the reduction of reflective losses by 8–9 times as compared to uncoated or untreated glazings [56]. Nostell et al. [137] described and investigated antireflection coatings for solar collector glazing applications. Their AR treatment of the glazing uses an interference effect based on the Fresnel formalism, which can enhance the fraction of glazing transmittance. AR treatment of glass can be done by three different methods, viz., dip-coating, etching and the third method involves an alternative execution of the first two methods. For the dip-coating method, the lowest value of reflectance recorded for the best film is 0.8%, whereas the solar reflectance decreased from 8% to 2.8%. The coating made with dip-coating method encountered the drawback of poor adhesion between the substrate and the film. This problem of poor adhesion can be solved by heat treatment, i.e., baking of the film at around 500–550 °C for 30 min. Due to this kind of heat treatment, solar reflectance increases but it enhances the thermal and mechanical properties. Further, Nostell et al. [138] investigated the optical and mechanical properties of a sol-gel prepared antireflective coating for solar energy applications utilizing a modified dip-coating method. The resulting coating shows higher transmittance values above 96%, which more or less satisfies the theoretical limit of transmittance for homogeneous films. Baking of the film improves the mechanical properties like adhesion, scratch resistance, etc. of the film significantly.

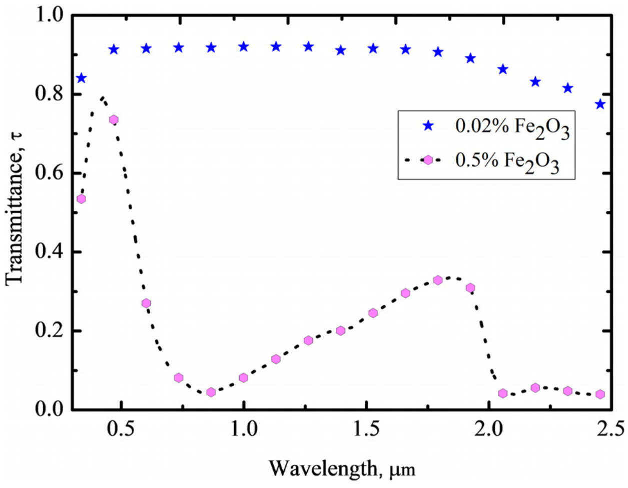

Fig. 15 Spectral transmittance of 6 mm-thick glass with various iron oxide contents for incident radiation at normal incidence (Adapted from Ref. [56])

Hody-Le Caër et al. [139] developed and analyzed a coating material on solar collector glazing having lower refractive index. Lower refractive index is achieved with the introduction of voids or combining two dissimilar metal oxides (making clusters). Thin film materials with lower refractive index allow a larger spectral region of antireflection. This requirement can be simply acquired by the direct use of materials having much lower refractive indices, like silicon dioxides (SiO_2) and magnesium fluoride (MgF_2) with refractive indices of 1.38 and 1.47, respectively. Another way is to combine two different materials with low refractive index to make a new material with even lower refractive index than the parent materials. For instance, Mg-F-Si-O films have a refractive index around 1.26 in the range of 300–900 nm, which is considerably lower than that of SiO_2 and MgF_2. Due to the development of this kind of novel combination, new areas of research–multilayered AR coatings, coloration of glazing, etc. have been initiated for further developments.

The performance of the solar collector can also be enhanced by varying the number of glazings. Many researchers have studied the effect of glazing on the solar collector. Youcef-Ali [140] investigated and compared the experimental results for solar collectors with double as well as triple glazing systems. In this study, cellular polycarbonate sheets with improved impact resistance were used as the transparent glazings. Double-glazed systems have higher solar energy transmittance than triple-glazed systems; thus, the thermal heat losses are considerably more with double-glazed systems as compared to triple-glazed systems. The effective heat gain by the absorber will therefore be higher with a triple-glazed system.

A new area of research in the field of colorization of glazing was discovered by researchers to improve the architectural integration of solar collectors with the buildings. Schüler et al. [141] established and investigated a colored reflection from the glazing so that the artistic look of the solar collector with black absorber will be improved. The motive of this research was to make the collector glazing more energy efficient by fulfilling the architectural integration using unique coloration techniques. All the solar energy should be transmitted through the glazing instead of getting absorbed; thus, numerous stacks of thin transparent materials are best suited for the cause. Two- and three-layered glazing systems are analyzed in this paper. The results obtained convey that the higher reflectance of blue and green colors at short wavelengths was achieved in combination with a good solar transmission. An additional third layer increases the colored reflection. It is advantageous to use materials with lower refractive indices to achieve considerable anti-reflective properties. Later, Schüler et al. [142] experimentally demonstrated a unique technique of glazing colorization, in which $SiO_2/Ti_{1-x}Si_xO_2$ interference stacks were deposited by a sol-gel dip-coating method with alternative tempering cycles. Silicon-oxide (SiO_2) and $Ti_{0.5}Si_{0.5}O_2$ were the best suited materials due to low and high refractive indices, respectively, and due to the thin film design. Improvised transmittance (around 95%) along with a bright colored reflection was recorded for the mentioned multilayered glazing coating as compared to the uncoated substrate having lower transmittance (92%). This kind of novel glazing multilayered coating opens up new possibilities for architectural integration of solar thermal collectors.

Giovannetti et al. [74] examined the potential of innovative collector design with a glazing coating having high solar transmittance and low emissivity properties. It uses suitable active materials like metals (Ag, Au, Cu, etc.) or metal oxides (tin oxide, indium oxide, etc.), also known as TCO. Metal coatings (mainly silver) have the limitation of corrosion sensitiveness, thus TCO are more suitable for the purpose. Transparent conductive oxides, like tin doped ITO, exhibit low value of emissivity and thus provide good thermal insulation with effective chemical inertness. But due to its lack of availability, aluminum-doped zinc oxide coating is usually preferred. Analysis of these glazed collectors conveys that the improved performance of solar collectors at high temperatures can be achieved using these low-emission TCO-coated glazings, which reduces the overall thermal losses. Further, Ghosh et al. [143] revealed the possibility of using another TCO–antimony doped indium oxide (IAO) coating as a potential application in the field of solar thermal devices. It was an improvisation over the evacuated uncoated glazing based solar cooker. When IAO-coated single glass was compared with uncoated double glass, it was found that the use of this TCO leads to a considerable reduction of thermal losses. Antimony-doped indium oxide (IAO)-coated glazing has better thermal performance with additional advantages, like light construction, easy manufacturing (as compared to evacuated devices), easy handling, and better thermal shock resistance.

It can be inferred from the Stefan–Boltzmann law that the emissive losses are directly proportional to the fourth power of temperature; thus, with the rising temperature of the solar collector, thermal emission from the absorber becomes significantly higher. Fan and Bachner [72] investigated the possibility and effect of using glazing films which transmit solar radiation but also reflect IR radiation, popularly known as transparent heat mirror films. Due to their high IR reflectivity, thermal insulating properties of the heat mirrors are equivalent to several inches of asbestos (or any other conventional insulator). These heat mirror films are coated on the glazing system and can be used as a promising way to reduce the radiation losses. There are number of materials, which can be considered as the heat mirror films–Au, Ag, Cu, etc. among which Ag has the best potential. Several researchers are still making efforts to develop novel materials whose performance is close to the ideal heat mirrors. Khullar et al. [73] analyzed a combination of two different geometries of metal nanoparticles and transparent heat mirrors. To enhance the IR reflectivity, two major variables were emphasized, viz., free charge (electron/hole) concentration and thickness of the film. From the results, they concluded that the low thermal emissivity in the mid-IR spectral region can be ensured with the use of nanoparticle dispersion (in HTF) with semiconductor-based heat mirrors. This proposed design for solar selective volumetric receiver gives 6–7% higher thermal efficiencies compared to conventional surface absorption-based collectors.

This subsection (on glazing) can be summarized by considering different techniques, which fulfill all the requirements of an efficient solar collector glazing. The utilization of TCO-coated glazing reduces the emissive losses and thus enhances the thermal performance of the solar collector. The glazing coated with heat mirror films satisfies the high solar transmission and negligible IR transmission requirements due to which thermal radiative losses are reduced [144]. Moreover, the performance of the solar thermal collector can be enhanced by improving the thermal properties of the working fluid which can be identified as another major component of a solar thermal collector system. An increase in the heat carrying capability of the working fluid due to nano-sized metal particles will result in superior thermal transport, and a discussion of the same is presented in Sec. 2.4.

2.4 Nanoparticle-Laden Heat Transfer Fluid (Nanofluids).

The overall efficiency of solar energy devices can also be enhanced by increasing the heat transfer coefficient of the fluid, as well as by improving the optical properties of the system (high absorptivity and low emissions). Addition of nanoparticles in the base fluid at low volume fractions (around 0.05%) would not enhance the thermal properties (thermal conductivity, specific heat, etc.) of nanofluid significantly when compared to that of the basefluid [145–147]. Thus, the focus is instead directed to changing the optical properties due to the addition of nanoparticles. In the case of PV, nanofluids help in improving the efficiency of the system by dissipating produced heat. The nanofluid will act as an optical filter, which "precools" the solar PV, by selective absorption, as well as by convective cooling. In these systems, the fluids need not necessarily be water-based (although hydrogen bonding is nice for stability, but an organic fluid could be easy to use). A suitable example of such an organic fluid is Therminol® VP-I as a base fluid [6,148]. The nanofluids are also used as a selective filter to prefilter out the wavelengths that are not useful to the PV cell (because PV performs well for a selected wavelength band).

Furthermore, in the case of solar thermal collectors, application of nanofluids leads to an increase in heat transfer and solar heat absorption, which will result in enhancement of the overall efficiency of a solar power plant [149]. The nanofluids offer numerous advantages: they can be optically solar selective (high solar absorption and low thermal emittance), and exhibit enhanced absorption efficiency due to tunable nanoparticle (NP) shape and size corresponding to the application [149,150]. The amount of NP present within the nanofluid is usually quantified by the parameter called volume fraction. The value of volume fraction plays a very important role. If the volume fraction of nanoparticles is very high, it may lead to the maximum absorption of solar radiation in thin top layer of the nanofluid whereas, at lower volume fractions, most of the radiation may get transmitted through the fluid without being absorbed. Both these cases result in the loss of a significant portion of absorbed thermal energy to the surrounding environment [147,149]. By the use of optimum value of nanoparticle volume fraction, up to 10% improvement in overall efficiency of solar power plants is reported and thus the electricity production cost can be expected to reduce accordingly [147,151]. However, the use of nanofluids comes with some difficulties which should be addressed, namely agglomeration and instability, high pumping power required due to enhanced viscosity, complex manufacturing processes, high capital costs, etc. [57].

The high temperature applications (e.g., solar tower) generally use a molten salt type of HTF, due to the specific requirement of stabilized thermophysical properties at elevated temperatures. In order to enhance the thermophysical properties of molten salt HTFs, Zhang et al. [152] attempted to improve the thermal properties of a carbonate ternary using lithium fluoride (LiF) with the use of the static melting method. Additionally, Zhang et al. [153] prepared and carried out enhancements of the molten salt thermal properties by adding Al_2O_3 NPs with three different sizes, viz., 20 nm, 50 nm, and 80 nm. This type of nanofluid can be a potentially attractive candidate for high-temperature CSP and thermal energy storage applications. Further, a novel way to use nanofluids in solar collectors utilizes the principle of direct absorption of solar energy.

2.4.1 Direct Absorption Solar Collectors. As the name suggests, direct absorption solar collectors (DASC) aim to absorb sunlight directly by the HTF. This kind of volumetric solar thermal collector has been found to be more efficient than conventional solar collectors due to higher absorption and lower reflectance [154,155]. DASC eliminates the intermediate heat transfer step in conventional solar collectors like absorption of sunlight into the absorber surface first, and then transferring that energy to the HTF. Also, the heat transfer mechanism in a surface-based solar collector has a greater involvement of conduction heat transfer, which makes heat transfer process ineffective due to the low thermal conductivity of HTF [156]. Overall, it is observed that surface-based solar collectors have lower efficiencies compared to the DASC [157,158]. This can be observed from the following reviewed articles related to nanofluid-based DASC.

Phelan et al. [55] categorized the DASC on the basis of its operational temperature, viz., low temperature (<250 °C), medium temperature (250–500 °C), and high temperature (>500 °C). Tyagi et al. [159] theoretically investigated a low temperature non-concentrating DASC with a mixture of aluminum nanoparticles and water, which was later compared to a typical flat plate collector. Theoretically, the nanofluid-based DASC has 10% higher absolute efficiency when compared to the conventional flat plate collector, which uses pure water as HTF. Further, Milanese et al. [160] investigated the optical properties of a number of nanofluids made up from different metal oxide nanoparticles having water as the base fluid, with variations in its NP volume fraction. Among different NPs, TiO was found to be the best NP as it can completely absorb the solar radiation within 1 cm of depth.

Many researchers have also been working in the area of high temperature (>500 °C) DASC in order to enhance the performance of solar collectors, by alternating the HTF properties with optimized volume fraction of the best suited NPs. Lenert et al. [146] experimentally analyzed the effect of varying optical thickness on thermophysical properties of nanofluid (made up from a mixture of 28 nm sized carbon coated nanoparticles and Therminol® VP-1 as a base fluid). Additionally, Khullar et al. [161] analyzed the thermal aspects of a nanofluids-based concentrating collector with parabolic reflectors focused on a transparent glass pipe trough through which nanofluid flows (direct absorption). It was concluded that the proposed idea shows 5–10% increase in the efficiency when compared to that of a conventional parabolic solar collector, so it has the potential to absorb the solar thermal radiation in a more efficient manner. Similarly, Taylor et al. [149] also carried out a comparative investigation of the performance of nanofluids-based high flux DASC and a conventional solar collector with similar design. Due to its very high absorption peak, which fairly matches with the solar spectrum irradiance, silver nanoparticles were selected in this research. From analysis, it was found that the efficiency of the specified solar collector was enhanced by approximately 10%. Furthermore, Milanese et al. [162] investigated the optical properties of nanofluids with water basefluid for high-temperature CSP applications. Three metal oxide NPs were found to be unaffected by the higher operational temperatures and thus these NPs are best suited for CSP plants.

Researchers are continuously searching for novel and effective NPs to optimize DASC systems. Otanicar et al. [155] experimented with DASC using various nanoparticles like graphite (spherical), carbon nanotube and silver (spherical) in varying concentrations or varying sizes of nanoparticles. Numerous researchers, including Muraleedharan et al. [163] with Al_2O_3 nanoparticles and Therminol® 55, and Bhalla et al. [157,164] with cobalt oxide as well as aluminum oxide nanoparticles, have already claimed an enhanced DASC thermal efficiency. Further, Khullar et al. [89] experimentally attempted to identify the promising HTFs along with the most suitable NPs, which can be used for practical applications in solar thermal applications. From the results of the optical and thermal characterization, it was concluded that amorphous carbon-based nanofluids are of significant importance in solar thermal applications because they have very high solar absorption at low NP volume fraction.

The concept used for direct absorption of light can be a breakthrough if it is implemented carefully in various solar thermal applications. Phelan et al. [55] suggested some novel ideas regarding the same, which includes solar-assisted chemical reactions, remediation of waste water, use of binary fluids for solar absorption refrigeration, etc. Researchers are working on the integration of the direct absorption of light into different fields other than just solar water heating, such as steam generation [154,165] and desalination [166].

In summary, it has been seen in several studies that the use of appropriate size, material, and volume fraction of nanoparticles may lead to an increase in the overall performance of solar collectors. Moreover, depending on the temperature range of the application, factors such as nanoparticle size, volume fraction/concentration, and nanoparticle material require detailed optimization for achieving the best operational efficiency. On the other hand, to increase the output of solar receivers (both PV and thermal), solar tracking devices are very important to enhance the solar energy collection for receivers. Over the past two decades, researchers have been attempting to make these solar tracking technologies more economical and more reliable. In Sec. 2.5, some of the recent advances in the field of solar tracking systems are briefly discussed.

2.5 Solar Tracking Systems. Numerous studies show that the solar energy collection of solar PV systems as well as solar thermal systems can be enhanced by around 20–50%, with the utilization of solar tracking [167–169]. By facing the sun, the apparent area of the receiver surface is at a maximum (i.e., $\cos\theta \sim 1$), but the most viable tracking technology to achieve this is much less clear [170,171]. Solar tracking systems are mainly categorized on the basis of their degrees-of-freedom, namely single-axis trackers [172,173] and dual-axis sun trackers [174–177]. These can be subcategorized on the basis of control strategies, i.e., open-loop and closed-loop sun trackers [178,179]. Single-axis tracking systems can follow the sun in a north-south direction, an east to west direction (most common), or a rotational/azimuth track (least common). Researchers have carried out various studies to simplify the operation and power consumption of these systems. For example, Sefa et al. [172] experimentally studied the application of a single axis solar tracking system with the help of a programmable controller and a microcontroller. The designed system was limited to single-axis tracking so as to eliminate the difficulties of handling heavy solar collectors whereas, Lamoureux et al. [180] investigated a novel idea of utilizing the origami and kirigami principles (the art of folding and cutting of paper) into single-axis solar PV tracking to make it highly efficient. The authors have claimed that such dynamic kirigami trackers are electrically and mechanically sustainable enough to maintain their performance for more than 300 cycles.

Dual-axis solar tracking systems enable nearly perfect tracking of the sun, due to having two degrees-of-freedom, which allows variations in slope as well as azimuthal angle [56]. In recent years, numerous studies on dual axis solar tracking have attempted to improve the accuracy and precision of these systems. Rubio et al. [179] demonstrated a hybrid solar tracker, which combines open-loop and closed-loop control strategies using simulation as well as experimental studies. This tracking system was reportedly cost-effective and could minimize the ordinary open loop errors due to utilization of hybrid strategies. Yao et al. [181] studied a solar tracker, which uses two different automatic tracking strategies. The first one works just like an ordinary sun tracker, controlling both primary as well as secondary axes to maintain a small tracking error for the period of a whole day, and later one adjusts the primary axes at the end of the daily solar tracking cycle.

In summary, solar tracking systems can certainly enhance solar collection efficiency in both PV and solar thermal collectors, and a lot of work is on-going to obtain cost-effective, easily producible, and accurate/precise tracking systems.

2.6 Advances in Modified Solar Receivers. Although they have been around for some time, research is on-going to modify conventional solar thermal collectors to enhance their performance. Thus, the focus of this final subsection is to present recent advances in one of the most prominent solar technologies, namely, ETC.

As per observations drawn from researchers working on solar thermal collectors [1,60], when compared to flat plate collectors, ETC have higher efficiency. ETC are made of two coaxial and concentric pipes with different diameters; the inner one is of metal or glass covered with a solar selective coating, and the outer pipe is a glass pipe. In between these two, vacuum conditions are created inside the annular space and maintained. Due its unique construction, ETC has two major advantages over the flat plate collector, viz., the vacuum space eliminates the convective losses from the absorber (inner tube) and its tubular design eliminates the need of sun tracking, unlike in flat plate collectors. Some researchers have also reported that maintenance of ETC is easy and inexpensive [1,182].

In the last decade, researchers have made considerable efforts to enhance the thermal performance of ETC by combining various devices [183–185], by modifying its applicability [186,187], etc. Bataineh and AL-Karasneh [187] studied and investigated the system performance numerically for direct steam generation in ETC. ETC can also be combined with heat pipes in order to reach higher thermal efficiency [183] and to be utilized in applications like desalination effectively [188]. In addition to that, the integration of latent heat storage using phase change materials (PCM) with ETC has produced better results in recent years [184,189]. Papadimitratos et al. [189] carried out several experiments with integrated PCMs with ETC for the purpose of solar water heating. The heat pipe immersed inside PCM enables the latent heat storage to store the energy effectively. This study showed that the system improved efficiency by 26% compared to a conventional system without PCM. Similarly, Feliński and Sekret [190] utilized paraffin as the PCM inside ETC for the purpose of experimentation. Additionally, Abokersh et al. [191] experimentally analyzed an integrated ETC with paraffin used as PCM in a solar water heater comparing two different constructions, viz., with fins and without fins. Furthermore, Sobhansarbandi et al. [192] proposed an evacuated tube solar collector, which utilizes the concept of carbon nanotube sheets as multifunctional absorber layers with heat accumulator using paraffin as PCM.

Evacuated tube solar collectors with various modifications mentioned above are effectively used in different applications like desalination [186,188,193,194], solar pressure cookers [195], solar-assisted chemical heat pump dryers [196], etc.

3 Outlook

Research on components such as glazing, absorber geometry, and solar selective coatings is going to be influential in the future as well for the overall improvement in efficiency of solar receivers (both PV as well as solar thermal collectors). The performance of solar photovoltaics will continue to be limited by several factors. Significant among those is the effect of substrate temperature on the PV cell efficiency. This requires efforts to remove heat from the cells (especially for CPVs), in a similar way as currently being done in electronic packaging. Efforts are expected to continue to improve the performance of optical filters, which could reflect/transmit the desired wavelength irradiation on the PV surface, while diverting the remaining spectrum away (preferably to a heat transfer fluid, which could allow beneficial use of this thermal energy for other purposes). Moreover, efforts will also continue to develop better PV/T systems where the fluid comes in contact with the hot PV substrate and then transfers the heat away from it.

Similarly, it is expected that a lot of attention must be given to imminent improvements in the performance of solar thermal systems. In order to enhance the performance of a solar thermal collector, it is of utmost importance to increase the solar selectivity of the absorbers. Solar selectivity can be improved using novel solar selective coatings, which offer higher solar absorptivity and lower thermal emissivity. In other words, the solar radiation-absorbing surface must have lower value of reflectance in the solar spectrum range and higher reflectance in the IR spectrum range. Most research about absorber coatings is focused on achieving this outcome. There are several ways researchers have achieved it, like adding an extra layer of tungsten on the substrate surface, which will be acting as an IR reflector, thus the controlling factor for thermal emittance [110], or using specifically improvised materials offering enhanced optical properties. DMD coatings can be considered as a potential candidate for further research work in order to improve its solar absorption and thermal stability so as to make it succeed commercially [78]. DMD coatings offer enhanced optical absorptance and reduced complexity in manufacturing techniques, thus making them potentially economically viable. Similarly, due to promising properties like strong absorption in the visible region, which occurs because of surface plasmon resonance phenomena, also known as quantum confinement effect, nanocermets are becoming more suitable candidates for the purpose of solar energy absorption. Pt-Al_2O_3 double cermet coating using molybdenum metal as an IR reflector would be a significant example for the potentially best suited cermet-based coatings, which show improved optical properties, viz., solar absorptance of 0.97 and thermal emittance of 0.05 [80]. Another outstanding attempt for producing a novel coating based on two different types of coatings, e.g., textured surfaces and cermet composites, have been made in the form of co-nanocylinders—Al_2O_3 cermets coating [87]. This type of hybrid coating offers absorptance of 0.98 and emittance of 0.03, which are superior to conventional co-based surface absorbers.

In addition to the optical properties, another major requirement for the absorber coating is to have a thermal stability for a longer time at higher operational temperatures. Due to concentrated solar radiation, heat accumulates at the intermediate contact surfaces; the metal substrate oxidizes and thus diffuses into the coating layer at higher temperature. This effect of deterioration of coating can be reduced by introducing a diffusion barrier on the substrate surface with properties like higher melting point, good adhesion, and lower reactivity with substrate material. Tantalum has been proven as a diffusion barrier, which enhances the thermal stability in air, in the short as well as long term [108]. The addition of an extra layer of antireflective material will reduce the reflectance as well as control the oxidation to the surroundings from the topmost layer of the coating. Also, to enhance the in-air thermal stability of cermet-based coatings, research has been carried out in order to develop high-temperature solar selective coatings based on transition metal nitride/oxynitrides/oxides and silicides [94]. Utilization of doped coating layers with doping materials like silicon, aluminum, or chromium will improve the thermal stability of the coating significantly. According to the literature, silicon is proven to be the most suitable doping material among the three materials mentioned [118], due to better optical properties, enhanced oxidation resistance, and improved structural stability. Researchers must focus on similar novel ways, which will extend the thermal stability of absorber coatings used for concentrated solar collectors.

Combining these different ways of increasing the efficiency of selective coatings can be an optimum way of designing a selective coating. Also, the manufacturing methods must be improved in order to produce low cost—high quality selective coatings, which can be commercialized on a mass scale.

In recent years, developments in absorber geometry have proven that it can be the next most promising area of research after solar selective coatings. Researchers must focus on different techniques of increasing absorber surface area by altering the surface roughness or by incorporating fins, using various shapes of the absorber tube, etc. Integrating obstructions in the flow path inside the absorber produces greater heat transfer due to turbulent mixing effects.

4 Conclusion

The paper has presented a comprehensive review about the issues related to the use of solar receivers (both PV as well as thermal collectors). The various factors, which affect the overall performance of solar receivers—solar selective coating, absorber geometry, glazing, role of heat transfer fluid, and solar tracking systems, have been covered in extensive detail. This includes recent developments in selective coating materials like cermet-based composite coatings, dielectric-metal-dielectric coatings, and multilayered coatings. Many exciting possible paths are also available as future research areas that offer enhanced performance of solar selective coatings, such as using Mo as an IR reflector, Ta as a diffusion barrier, Al_2O_3 as an antireflective layer, etc. Furthermore, it has been observed that the advancements in absorber geometry are a potential research area in which prominent results regarding performance enhancement of solar collectors have been achieved in recent years. In the interest of enhancing the heat transfer in solar thermal collectors, changes in absorber shape result in increases in convective heat transfer coefficient or enlarging the absorber surface area. Whereas, other likely research areas include developments in glazings and heat transfer fluid. The functional performance of glazings can be augmented with the application of heat mirror films, while the optical properties of heat transfer fluid can be amplified using suitable nanoparticles. All the aforementioned factors (selective coating, absorber geometry, glazing, heat transfer fluid, and utilization of solar trackers) are expected to improve the efficiency of solar receivers, as they involve principles similar to those used in electronic packaging, albeit at small flux but at higher scales (around 100× larger area). This shows that electronics packaging in the case of PV can also include optics along with thermal issues (like waste heat management). All these technical developments in various aspects of solar receivers can soon be worked into the electronics package of a PV system. One of the modified solar receivers, evacuated tube collectors, is also discussed along with recent advances in the corresponding areas.

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Nomenclature

A = absorptivity of ideal solar selective coating
b, C = constants
E = emissive power, W/m^2
h = convective heat transfer coefficient, W/m^2-K
k = thermal conductivity, W/m-K
L = length, m
n = index of refraction
q = heat flux, W/m^2
Q = solar irradiance, W/m^2
R = resistance, K m^2/W
T = temperature, K

Greek Symbols

α = absorptance
ε = emittance
κ = index of absorption
λ = wavelength, μm
ρ = reflectivity
τ = transmittance

Subscripts

c = cutoff
m = measured
s = simulated
sa = solar absorption
T = surface temperature, °C
λ = wavelength, μm

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