Selective Absorber Coatings and Technological Advancements in Performance Enhancement for Parabolic Trough Solar Collector

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Abstract: Parabolic trough solar collector systems are the most advanced concentrating solar power technology for large-scale power generation purposes. The current work reviews various selective coating materials and their characteristics for different designs in concentrating solar power. Solar selective absorbing coatings collect solar radiation and convert it to heat. To promote higher efficiency and lower energy costs at higher temperatures requires, this study aims to analyse the fundamental chemistry and thermal stability of some key coatings currently being used and even under investigation to find reasons for differences, information gaps and potential for improvement in results. In recent years, several novel and useful solar absorber coatings have been developed. However, qualification test methods such as corrosion resistance, thermal stability testing and prediction of service life, which have essential technical value for large-scale solar absorbers, are lacking. Coatings are used to enhance the performance of reflectors and absorbers in terms of quality, efficiency, maintenance and cost. Differentiated coatings are required as there are no uniformly perfect materials in various applications, working conditions and material variations. Much more knowledge of the physical and chemical properties and durability of the coatings is required, which will help prevent failures that could not be discovered previously.

1. Introduction

Due to the rise in carbon emissions and air pollution, the demand for renewable energy has risen worldwide. Various renewable resources and their related technologies are being investigated to reduce the use of fossil energy [1]. Solar energy is seen as a renewable alternative and a potential solution to conventional energy sources when considering the contentious global green energy criterion [2, 3]. Parabolic trough solar collector (PTSC) is one of the technologies used in solar applications. PTSCs reflect solar radiation using mirrors onto the receiver tube located at the focal point or focal line of the reflectors [4]. The fluid passes through

Nomenclature

A_a	aperture area of the collector/m^2
A_{co}	outer cover area/m^2
A_{ri}	inlet area of the receive tube/m^2
A_{ro}	outer area of the receive tube/m^2
C	concentration ratio
c_p	specific heat capacity/kJ·(kg·K)$^{-1}$
D_{ci}	inner diameter of the cover tube/m
D_{co}	outer diameter of the cover tube/m
D_{ri}	inner diameter of the receiver tube/m
D_{ro}	outer diameter of the receiver tube/m
f	collector focal distance/m
h	convection heat transfer coefficient/W·(m^2·K)$^{-1}$
h_{out}	cover to ambient heat transfer coefficient/W·(m^2·K)$^{-1}$
I_b	direct beam radiation/W·m^{-2}
K	incidence angle/(°)
k	thermal conductivity/W·(m·K)$^{-1}$
k_{eff}	effective thermal conductivity/W·(m·K)$^{-1}$
L	collector width/m
m	mass flow rate/kg·s^{-1}
Nu	Nusselt number
Pr	Prandtl number
Q_{abs}	absorbed thermal energy/W
Q_{conv}	convocation heat transfer/W
Q_{loss}	thermal losses of the absorber/W
Q_{rad}	radiation heat transfer/W
Q_s	solar radiation on the PTSC aperture/W·m^{-2}
Q_u	useful heat/W
Re	Reynolds number
T_{amb}	ambient temperature/°C
T_c	cover temperature/°C
T_{ci}	inner cover temperature/°C
T_{htf}	temperature of heat transfer fluid,/°C
T_{in}	inlet temperature of the heat transfer fluid/°C
T_{out}	outlet temperature of the heat transfer fluid/°C
T_{rm}	mean temperature of receiver/°C
T_{ro}	outer receiver temperature/°C
T_{sky}	sky temperature/°C
U_L	thermal loss coefficient/W·(m^2·K)$^{-1}$
V_{wind}	ambient air velocity/m·s^{-1}
W	collector width/m
x	coordinate in x-axis/m
y	coordinate in y-axis/m

Greek symbols

α	Absorptivity
γ	intercept factor;
ε_c	cover emittance
ε_r	receiver emittance
θ	angle of incidence of solar radiations/(°)
η	intrinsic viscosity
η_{opt}	optical efficiency of the collector
$\eta_{opt\text{-}max}$	maximum optical efficiency
η_{th}	thermal efficiency
μ	dynamic viscosity/kg·(m·s)$^{-1}$
ρ	reflectivity; density/kg·m^{-3}
σ	Stefan Boltzmann constant/W·(m^2·K^4)$^{-1}$
τ	Transmissivity
Φ_r	rim angle/(°)
φ	particle concentration/%
φ_{max}	maximum particle added to the fluid

Subscripts

a	aperture
amb	ambient
b	beam radiation
c	cover
f	fluid
hnf	hybrid nanofluid
htf	heat transfer fluid
in	inlet
max	maximum
nf	nanofluid
opt	optical
out	outlet
p	particle
ri	inner receiver
r	local mirror radius
ro	outer receiver
s	solar
th	thermal
tot	total
u	useful

Abbreviations

CFD	computational fluid dynamics
EXP	Experimental
NFs	nanofluids
PTSC	Parabolic Trough Solar Collector
TS	thermal stability

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the absorber tube and heated to approximately 400°C by radiation, producing steam, which enters the turbine to generate electricity [5]. The receiver tube is enclosed inside an oversized glass tube to enhance the convection's thermal conduction and loss. The absorber should be coated to enhance heat transfer. The coating should remain stable structurally and chemically at operating temperature through focusing of solar radiation [6, 7]. Several different types of coatings were researched for their ability to achieve high photothermal efficiency. Some examples of these coatings are cermet, semiconductor, multilayer coatings, dielectric-metal-dielectric stacks, and textured surfaces. Solar selective absorber coatings have been used for parabolic troughs for over 30 years. Several coatings are now used as solar selective absorbers for PTSC high-temperature operation: AlNi-Al$_2$O$_3$, Ni-SiO$_2$, Pt-Al$_2$O$_3$, NiCo$_2$O$_4$, Ni-5Al, Mo-Al$_2$O$_3$, TiAlN/TiAlON/Si$_3$N$_4$, CuCoO$_4$(NiFe)Co$_2$O$_5$, W-Al$_2$O$_3$, TiAlN/TiAlON/SiO$_2$, Au-MgO, HfMoN/HfON/Al$_2$O$_3$, Mo-SiO$_2$, and Ni-25 graphite [8, 9, 10]. The most widely used selective coatings were cermets used in PTSC trough heat collection devices. At 400°C, these selective surfaces absorb 0.96 and emit 0.1 [11]. Suriwong et al. studied the coating thickness effects of the solar absorber on the perforance of the collector with three layers of Ni-Al. The phase, morphology, and reflectance of Ni-Al coatings differ in several ways. The three Ni-Al coatings measured 195 μm, 215 μm and 299 μm. The result showed the thickest sample (299 μm) converts the most solar radiation into thermal energy [12]. The quality of the absorber coating layer deposited on the receiver also controls solar energy conversion to heat. The receiver tube is enveloped by solar selective coatings to achieve high solar absorbance and low emissivity value.

Sandia National Laboratories is researching solar selective coatings for towers for enhancing optical properties. The absorptivity of various coatings was greater than 90% at 600°C and 700°C, with a thermal spraying coating with a laser having better properties for 480 h [13]. For perfect absorbance, the coating should absorb as much solar radiation as possible ($\alpha \geq 0, 95$). Therefore, the reflectance should be minimising in solar radiation. At the same time, heat loss by convection or conduction (including emission $\varepsilon \leq 0.05$) on the surrounding area should be minimal, with the thermal stability (TS) of up to the temperature of receiver operating (see Fig. 1) [14, 15]. The alternative to selective coating is to coat the inside glass envelop around the absorber tube by a dielectric material, which is transparent to the solar spectrum visible region and is well reflected in the infrared region [16, 17]. This type of coating is referred to as a 'hot mirror' and applied on energy-efficient windows in cars, buildings and

photovoltaic and thermophotovoltaic applications [18, 19]. Adding a hot mirror coating to the glass cover tube rather than a selective coating to the absorber tube because the glass envelop results in colder temperature [20].

This paper details the operational knowledge gained from using selective coatings to enhance PTSC performance. Current research and development efforts have rendered the most economically and scientifically advanced concentrating solar power technology available in this system. This extended analysis investigates the different selective coatings for enhancing heat transfer in the absorber tube by coating various components of the solar thermal system. The overall efficiency can be improved by using selective solar coating on absorber tubes, anti-reflective coating on glass tubes with borosilicate cover and protective cum coating on solar mirrors that are easy to clean.
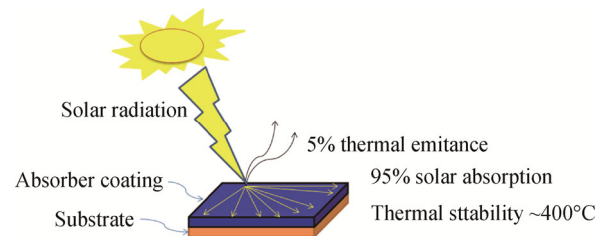

Fig. 1   Solar selective absorber [21]

2. PTSC System

PTSC consists of an absorber tube, reflector surface, and working fluid [22]. The absorber receives the solar radiation at the focus point of the parabolic concentrator, as shown in Fig. 2. The glass cover is used to protect the absorber tube from heat loss and maintain a vacuum pressure [23]. A fluid flowing inside the tube absorbs the heat energy that is generated by focused solar radiation, increasing its enthalpy and raising the temperature of the tube surface [1]. To reduce radiation heat losses, the absorber tube coated with an antireflective substance.

2.1 Geometry modelling

The parabolic form geometry in Fig. 2 is described as follows [24]:

$$y = x^2 / (4 \times f) \qquad (1)$$

The rim angle (ϕ_r) is determined as follows [25]:

$$\phi_r = \arctan \left[\frac{8(f/W)}{16(f/W)^2 - 1} \right] \qquad (2)$$

The total collector aperture calculated by multiplying the width (W) and the length (L) as follows [26]:
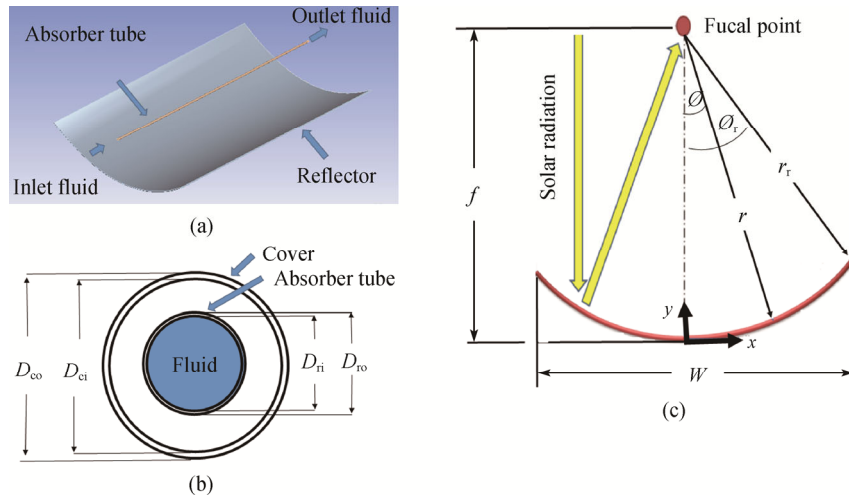
$$A_a = W \times L \qquad (3)$$

Fig. 2   (a) Schematic of a typical PTSC (b) Absorber tubes with cover (c) Parabolic concentrator [7]

The absorber area is the receiver tube outer area:

$$A_{ro} = \pi D_{ro} \times L \tag{4}$$

The concentration ratio is calculated from the ratio of the collector aperture area to the absorber area, so it determines the radiation flux incident on the receiver surface:

$$C = A_a / A_{ro} \tag{5}$$

2.2 Thermal modelling

The useful heat from the PTSC can be calculated based on the difference in the temperature of fluid that flows through the receiver tube, according to the following equation [24]:

$$Q_u = m_f \times c_p \left(T_{out} - T_{in} \right) \tag{6}$$

The solar irradiation on the collector aperture (Q_s) can be calculated by multiplying the aperture area by the direct beam solar irradiation as follows [26]:

$$Q_s = A_a \times I_b \tag{7}$$

The thermal efficiency of PTSC is calculated by the ratio of useful heat to available direct beam radiation:

$$\eta_{th} = Q_u / Q_s \tag{8}$$

The absorber tube thermal losses are calculated as:

$$Q_{loss} = A_{ro} \times U_L \left(T_{rm} - T_{amb} \right) \tag{9}$$

The thermal losses of the absorber tube to the cover are essentially radiation losses:

$$Q_{loss} = A_{ro} \times \sigma \times \frac{T_{rm}^2 - T_c^2}{1/\varepsilon_r + \left[(1-\varepsilon_c)/\varepsilon_c \right] \times \left(A_{ri}/A_{co} \right)} \tag{10}$$

Under steady-state conditions, it is assumed that the cover and absorber have the same thermal losses to the ambient. Thermal losses from the cover to the surrounding environment occur as a result of radiation and convection:

$$Q_{loss} = A_{ro} \times \sigma \times \varepsilon_c \left(T_c^2 - T_{sky}^2 \right) + A_{co} \\ \times h_{out} \left(T_{rm} - T_{amb} \right) \tag{11}$$
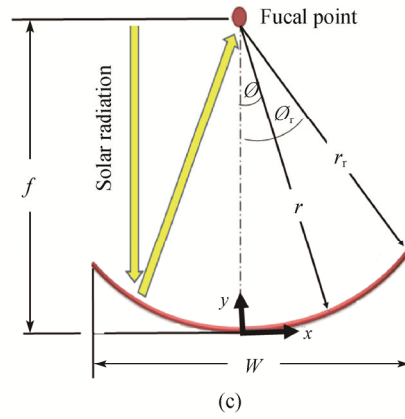
Heat transfer coefficient (h_{out}) and sky temperature (T_{sky}) are given by [27]:

$$h_{out} = 4 \times V_{wind}^{0.58} \times D_{co}^{-0.42} \tag{12}$$

$$T_{sky} = 0.0552 \times T_{amb}^{1.5} \tag{13}$$

2.3 Optical modelling

The energy balance equation can express the absorbed solar radiation (Q_{abs}) as thermal losses and useful heat:

$$Q_{abs} = Q_u + Q_{loss} \tag{14}$$

The absorbed solar energy depends on the solar collector optical efficiency and the solar irradiation:

$$Q_{abs} = \eta_{opt} + Q_s \tag{15}$$

The solar radiation incidence angle affects optical efficiency and is expressed as:

$$\eta_{opt} \left(\theta \right) = K \left(\theta \right) \times \eta_{opt\text{-}max} \tag{16}$$

The incidence angle modifier is:

$$K \left(\theta \right) = \cos \left(\theta \right) - \frac{f}{L} \left(1 + \frac{W^2}{48 f^2} \right) \times \sin \left(\theta \right) \tag{17}$$

The optical efficiency of a PTSC is the ratio of energy absorbed by the receiver to that collected by the aperture. To express the maximum available optical efficiency, the used formula is:

$$\eta_{opt\text{-}max} = \rho \tau \gamma \alpha \tag{18}$$

2.4 Heat transfer analysis

Convective heat rate for unit length inside the absorber tube between the heat transfer fluid and the absorber:

$$Q_{conv} = \pi D_{ri} \times h_{htf} \left(T_{ri} - T_{htf} \right) \tag{19}$$

The heat transfer coefficient (h_{htf}) can be calculated as:

$$h_{htf} = Nuk / D_{ri} \tag{20}$$

For laminar flow: Nu=4.36 and for turbulent flow:

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4} \tag{21}$$

Convective heat rate in the annulus and free molecular

convection heat rate in the annulus [28]:

$$Q_{conv} = \frac{2\pi k_{eff}}{\ln(D_{ci} - D_{ro})}(T_{ro} - T_{ci}) \quad (22)$$

The radiative heat transfer rate from the outside wall of the absorber to the inner wall of the glass cover:

$$Q_{rad} = \frac{\sigma \pi D_{oa}(T_{ro}^4 - T_{ri}^4)}{(1/\varepsilon_a) + \{[(1-\varepsilon_c)D_{ro}]/\varepsilon_c D_{ri}\}} \quad (23)$$

Convective heat rate for unit length over the glass envelope:

$$Q_{conv} = \pi D_{co} \times h(T_{co} - T_{amb}) \quad (24)$$

Radiative heat rate for unit of length from the glass envelope:

$$Q_{rad} = \pi D_{co} \times \varepsilon(T_{co}^4 - T_{sky}^4) \quad (25)$$

3. Thermal Enhancement Techniques of PTSC

Enhancing the thermal performance of the receiver is essential for PTSC efficiency improvement. This increases the heat transfer from the receiver's inside surface to the thermal fluid, resulting in lower heat losses and improved thermal performance. The most important aspects of thermal enhancement are below.

3.1 Mono and hybrid nanofluids

Nanofluids (NFs) play a significant role in improving the thermophysical properties of working fluids [29]. The NFs improve the heat transfer performance of the absorber. Increasing the volume concentration of hosted nanoparticles enhances the collector thermal performance but reduces the stability of the NFs and causes agglomeration [30]. The pumping power requirements increase because of the use of nanoparticles in the base fluid. As a result, the nanoparticle volume percentage should be tuned for the increasing efficiency of PTSC.

The thermophysical properties for mono NFs calculate density, viscosity, specific heat capacity, and thermal conductivity, for any nanoparticle and fluid [31]:

$$\rho_{nf} = \rho_f(1-\varphi) + \rho_p \times \varphi \quad (26)$$

$$c_{p,nf} = \frac{\rho_{nf} \times c_{p,f}(1-\varphi) + \rho_p \times c_{p,p} \times \varphi}{\rho_{nf}} \quad (27)$$

The viscosity of the nanofluid can be estimated with the existing relation:

$$\mu_{nf} = \mu_f(1 + \eta\varphi) \quad (28)$$

The equation above for calculating the kinematic viscosity applicable to $\varphi \leq 2\%$ linearly, viscous fluid having diluted, suspended, and spherical particles (Einstein, 1906).

Modified Einstein's model is applicable to high particle concentrations up to $\varphi \leq 4\%$:

$$\mu_{nf} = \mu_f(1-\varphi)^{-\eta} \quad (29)$$

Modified the equation for highly concentrated suspensions with uniform solid spheres [31]:

$$\mu_{nf} = \frac{9}{8}\mu_f\left[\frac{(\varphi/\varphi_{max})^{1/3}}{1-(\varphi/\varphi_{max})^{1/3}}\right] \quad (30)$$

where φ_{max} represents the maximum particle concentration that can be added to the fluid.

Nanoparticles enhance thermal conductivity in a conventional fluid. The expressions of the conventional models of the effective thermal conductivity of a solid/liquid suspension are as follows (Maxwell) and the spherical particles and $\varphi < 1\%$:

$$k_{nf} = k_f\frac{k_p + 2k_f + 2\varphi(k_p - k_f)}{k_p + 2k_f - \varphi(k_p - k_f)} \quad (31)$$

Modified Maxwell's model and applied to spherical inclusions:

$$k_{nf} = k_f\left[1 + \frac{3(\alpha-1)\varphi}{\alpha+2} + O(\varphi^2)\right] \quad (32)$$

where $\alpha = k_f/k_p$.

The updated Jeffery's equation is:

$$k_{nf} = k_f\left[1 + \frac{3(\alpha-1)}{\alpha+2-(\alpha-1)\alpha}\left[\varphi + f(\alpha)\varphi^2 + O(\varphi^3)\right]\right] \quad (33)$$

Hybrid nanofluid is a new type of nanofluid that is made by dispersing two (or more) different nanoparticles into a working fluid [31]. Hybrid nanofluids have better thermal performance fluids and thermophysical properties than convectional working fluids such as ethylene glycol, oil, water, and nanofluids with mono nanoparticles. The effective properties of hybrid nanofluid are defined as follows:

$$\rho_{hnf} = \rho_f(1-\varphi_{tot}) + \rho_{p1} \times \varphi_1 + \rho_{p2} \times \varphi_2 \quad (34)$$

$$c_{p,hnf} = [\rho_f \times c_{p,f}(1-\varphi_{tot}) + \rho_p \times c_{p,p2} \times \varphi_2 + \rho_p \times c_{p,p2} \times \varphi_2] \times \rho_{hnf}^{-1} \quad (35)$$

$$\varphi_{tot} = \varphi_1 + \varphi_2 \quad (36)$$

$$\mu_{hnf} = \mu_f(1-\varphi_{tot})^{-\eta} \quad (37)$$

where φ_{tot} is the combined concentration of volume in the hybrid nanofluid of two different types of nanoparticles (φ_1 and φ_2) as measured.

If the thermal conductivity of hybrid nanofluid is defined according to the Maxwell model, it must be employed for this purpose:
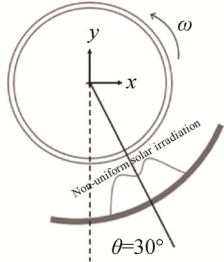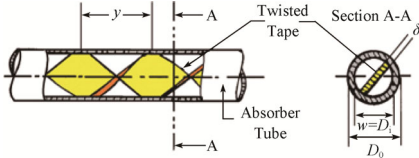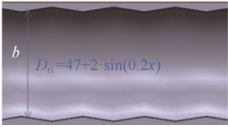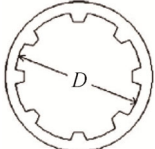
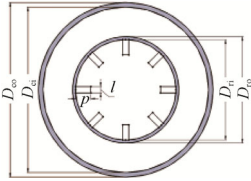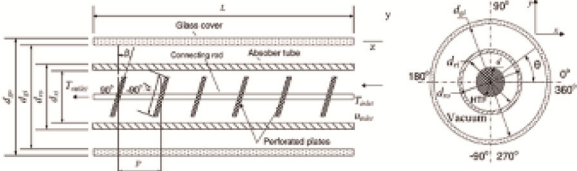$$k_{hnf} = k_f\left[\frac{[(\varphi_1 k_{p1} + \varphi_1 k_{p1})/\varphi_h] + 2k_f +}{[(\varphi_1 k_{p1} + \varphi_1 k_{p1})/\varphi_h] + 2k_f -} \rightarrow \frac{2(\varphi_1 k_{p1} + \varphi_2 k_{p2}) - 2\varphi_h k_f}{2(\varphi_1 k_{p1} + \varphi_2 k_{p2}) - 2\varphi_h k_f}\right] \quad (38)$$

3.2 Modifications to the receiver tube

Inserts are utilised within the absorber tube to improve collector thermal efficiency. This is a passive method of increasing heat transfer. Using varied inserts disturbs the usual flow pattern of heat transfer fluid, causing turbulence. Turbulence causes Brownian motion of

Table 1   Summary of insert types used to enhance the thermal efficiency of PTSC

Insert type	Method	Working fluid	Model	Thermal eff./%	Ref.
Metal foam	EXP	Cu/water		14	[33]
Rotating tube	CFD	Al$_2$O$_3$/therminol-VP 1		15	[34]
Twisted tape	Model	Water		10	[35]
Wall-detached twisted tape	CFD	Syltherm 800	–	27	[36]
Converging-diverging absorber	CFD	Thermal oil		4.55	[18]
Helical fins	CFD	Syltherm 800		3	[37]
Longitudinal fins	CFD	Syltherm 800		1.4	[38]
Longitudinal fins	CFD	Syltherm 800		1.27	[39]
Perforated plate	CFD	Syltherm 800		8	[40]
Porous discs	EXP	Water		7	[41]

nanoparticles and mixing of fluid, increasing the heat transfer property of the working fluid. Various researchers are currently concentrating on improving the heat transfer properties of fluids to improve PTSC efficiency. Table 1 explains some of these studies.

3.3 PTSC coating materials

The coating of the absorber tube of PTSCs showed a remarkable enhancement of thermal efficiency by decreasing thermal losses [32]. In the following chapters, we will discuss in detail the most important characteristics of the coatings used in terms of thermal and optical properties, their operating principles, advantages, and disadvantages.

4. Classification of Selective Solar Coatings

The preparation and development of coatings have attracted considerable interest since Tabor put forward the idea of solar selective absorbing coatings (SSACs) in the 1950s [42]. The design process of solar coatings in solar thermal systems is more complicated than designing protective and anti-reflective coatings in mirrors, polymeric sheeting and glass because absorption and emission depend on the wavelength, temperature and microstructure of the coating. Selective coatings are applied on the reflector surface and absorber tube to enhance the efficiency of PTSCs.

4.1 Selective reflector coating

Aluminium or thin silver coatings are widely used as reflectors for the concentration of the solar thermal systems. The reflectivity highly depends on their surface material, which also depends on the deposition, production and polishing method [43]. In general, silver and aluminium have 98% and 88% reflectivity, respectively [44]. They can be oxidised quickly and effectively by the surrounding environment; therefore, coatings are mostly applied on mirrors to protect the reflective surface from environmental effects such as oxidation and corrosion [45]. This is a specific issue with silver mirrors given that silver can be easily tarnished. Silver is applied on the back of the glass to protect it from environmental conditions. To protect silver from mechanical damage and corrosion, a copper layer is typically used on the silver coating due to its smaller standard electrode potential than silver. A material layer is then added to provide mechanical strength [46] (see Fig. 3).

Corrosion of aluminium is typically prevented by using an aluminium oxidation layer or silica-based coatings [47] (see Fig. 4).

Coatings can help avoid reflector corrosion. However, corrosion persists when the protective layers are penetrated by air or moisture. Losses can be on the order of 10% or more, even using silver and aluminium mirrors [48]. Glass mirrors are good reflectors for PTSCs because they have high reflectivity and minimum loss throughout the lifetime of PTSCs. However, glass mirrors are limited by their fragility, weight and cost-effectiveness. These limitations could be overcome by using mirrors manufactured from polymer because it is lightweight, flexible and inexpensive. The technological advances in the manufacture of reflectors have developed reflector materials [49]. Reflectors are manufactured from material by directly deposited, silvered Teflon, and polymer multilayer (see Fig. 5).
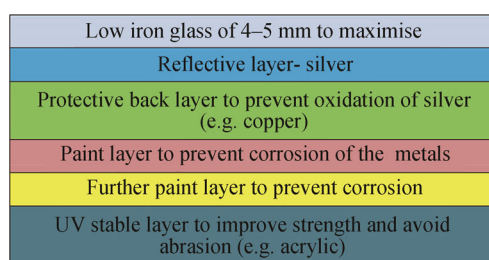

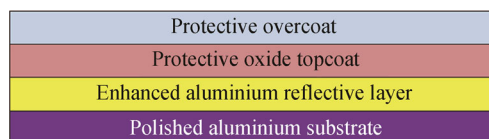**Fig. 3**　Coating layers for silver mirror protection against corrosion [32]

Fig. 4　Coating layers for aluminium corrosion protection and reflection enhancement [32]
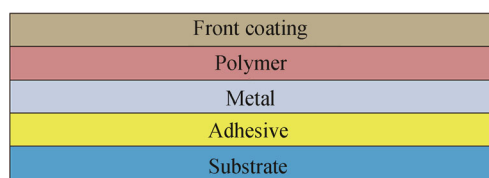

Fig. 5　Structure of metallised polymer reflectors [50]

Materials for reflectors are directly deposited, and the structure of the reflector is composed of various layers: topcoat, reflective layer, levelling layer and substrate. These types of reflectors minimise the requirement for adhesives and lamination [51]. Silver Teflon reflectors use Teflon, which is an intrinsically weather-proof and non-hygroscopic material with excellent barrier properties. Additionally, Teflon has low surface energy to minimise soil retention resistance. In polymer multilayer reflectors, the material layers are composed of Si_3N_4 and Ag-polymer multilayer-Substrate. These reflectors have a high production capacity, reducing production cost [52].

Titanium dioxide (TiO_2) provides photocatalytic properties that can address soiling and cleaning problems

related to the concentration of solar energy technology. The photon is excited in the high-level energy of the bandgap of TiO_2 can catalyse or speed up the organic matter conversion to water and carbon dioxide. This specific property of TiO_2 is applied in reflectors of PTSCs [32]. Performance loss and surface cleaning cost are two major factors reducing maintenance costs and operation of PTSCs in the long term [53]. For example, reduced solar mirror reflectivity related to soiling will lead to 8%–12% decreased performance [54].

Addressing cleaning problems is crucial for concentrating solar plants on a large scale due to the low amount of water in desert-type conditions [55]. Metallising a suitable and affordable substrate material using polyethylene terephthalate film is one of the most promising methods to minimise the cost of solar mirrors. Then, the reflector's coating by a protective layer in the top for enhancing resistant abrasion and durable [32].

4.2 Selective absorber coating

Selective solar absorbers harvest solar energy in the form of heat. The selective solar coating should be structurally and chemically stable at the operational temperature [56]. Therefore, the maximum absorption is hard to obtain on a single layer from the coating [1]. The spectral selectivity of SSACs may generally be improved by changing the composition of coatings, selecting different materials or utilising depositing methods [57]. On the basis of the mechanisms of absorption and principles of design (see Fig. 6), five types of selective solar absorbers are defined: (1) intrinsic absorber, (2) semiconductor metal, (3) multilayer interference stacks, (4) cermets and (5) textured surface [58].

The absorption of light depends on many factors such as the material's electronic structure wavelengths and specific surface features including pits, peaks or voids. Coatings are utilised on glass cover tubes to enhance light transmission in glass [59]. In general, the glass cover tube is coated by anti-reflective coatings which have been improved and used to the optical industry to enhance by reducing the reflection. Their characteristics depend on several factors such as composition, shape, wavelength, thickness and temperature [60]. For example, borosilicate glass tubes improved from 92% to 96% [4] or more. Thin-film coatings improve collectors' performance by protecting the receiver tube from dirt or corrosion by glass tube cover. Therefore, the glass cover tube reduces convection and corrosion [61] (see Fig. 7).

Plastics can also be used to improve the performance, reduce operational and maintenance costs and increase the life of materials in solar collectors [54]. In addition, the solar collector frame should be made from high-entropy alloys because they have superior corrosion resistance, hardness and intense strength [62]. Some of the systems used at present and their operating principles, advantages and disadvantages are reviewed below.

4.2.1 Intrinsic absorbers

Transition metals and semiconductors have selective intrinsic solar characteristics. Therefore, they have to be specifically optimised for intrinsic absorption. No single material exhibits a perfect solar selectivity in its natural form. The structural stability of intrinsic absorbers on the absorber surface is optically inefficient compared with multiple layer absorbers [23]. Examples of intrinsic absorption materials include Al_2O_3 [63], Fe_3O_4 [64], V_2O_5 [65] and LaB6 [21]. Ceramics are used in intrinsic absorption materials for ultra-high temperature operations, including SiC, ZrB_2, HfB_2, [66], HfC, TaC, ZrC [67] and ZrB_2 [68].

These materials have attracted interest as potentially desirable candidates for selective solar applications. Transitional metals can better absorb solar radiation at the visible region of the electromagnetic spectrum when their empty orbitals combine with oxygen and nitrogen.
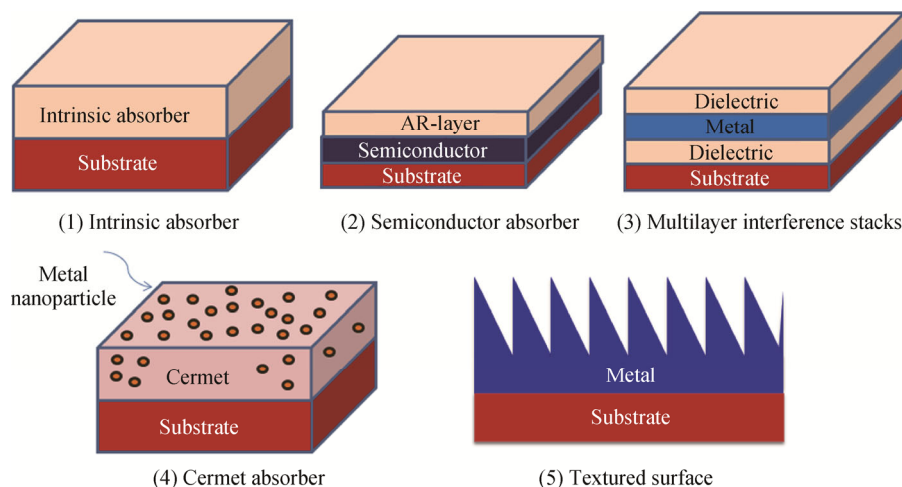

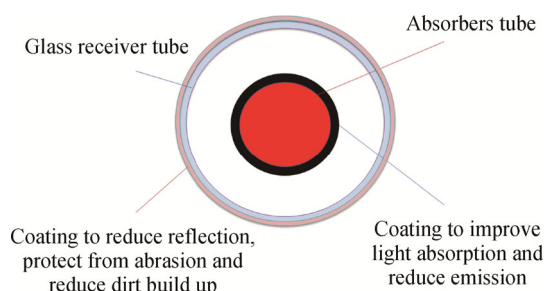**Fig. 6**   Five types of selective absorber coatings [21]

Fig. 7 Absorber tubes with a glass cover tube [32]

In this method, intrinsic absorbers will become a possible filter for a solar thermal system when making certain modifications, their properties. The selectivity of tungsten (W) was investigated by laser sintering method in micro- and nano-particles of W with stainless steel substrate. The coating exhibited good efficiency even after thermal processing at 650°C in air for about 36 h [69]. Some of the coating materials or electrodeposited coating are made from spinel powders, including Cu1.5Mn1.5O$_4$ [70], CoCuMnO$_x$ [71], CuAl$_2$O$_4$ [72] and CuCr$_2$O$_4$ [73].

A downside to using much for the intrinsic absorbers is according a crossover happens at too short-wavelength of solar radiation from short to high wavelengths of electromagnetic spectrum, i.e. which phase in the spectral reflectance and the drop in the change wavelength just isn't very steep. In addition, to absorb the maximum amount of sunlight, the intrinsic material layer needs to be thick because the increase in thickness increases the emittance [74]. The introduction of a compositional or structural improvement within a lattice from these same materials will solve these problems.

The properties of intrinsic materials should be optimised to fulfil particular requirements by doping the suitable material element to a substance or preparing composite metals from other materials. Less attention has been paid to research on intrinsic absorbers because intrinsic materials cannot be found in nature. However, it is receiving increasing interest, and considering one of the components of multilayer absorbers.

4.2.2 Semiconductor metal

Semiconductor absorbers comprise an underlying metal sheet to maintain the emission of the heated substrates and focus on the semiconductor and bandgap. They usually have a bandgap ranging from ~0.5 eV to 1.26 eV (2.5–1.0 mm). Semiconductors can absorb solar radiation at a greater wavelength than the bandgap energy [21]. Theoretically, semiconductor absorbs the radiation at the visible and near-infrared spectrum region.

Semiconducting materials are being used as anti-reflective coatings [75]. Therefore, the high reflectance of surface light, which is due to its higher refractive index, leads to low absorption of solar radiation, thereby affecting the photothermal conversion performance. The disadvantage of semiconductors is that they are not stable at high temperature due to their high refractive index, which causes significant reflectance losses. For this purpose, a deposited anti-reflection layer is needed.

4.2.3 Multilayer interference

Multilayer absorbers include several alternate layers of anti-reflective layer, metallic layer, infrared reflector coating layer and dielectric layer [76]. The anti-reflective layer is added on the upper coating to accelerate the propagation to the absorber surface (see Fig. 8).
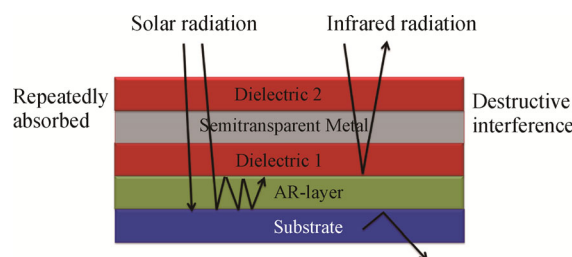

Fig. 8 Selective multilayer solar coating for an absorber [75]

The bottom layer is made of a reflective material. Many multilayers for dielectric-metal interference stacks are made of various dielectrics (e.g. MgF$_2$, SiO$_2$, Al$_2$O$_3$, CeO$_2$, AlN). Different metals are also used (e.g. Au, Ag, Al, Ti, Cr, Cu, Ni, and Mo) [77]. However, the disadvantage of these stack coatings is the manufacturing cost. Although many researchers attempted to reduce the cost by using wet chemical methods, this coating is ineffective at high temperatures (more than 400°C) [78, 79]. The reason is that using a wet chemical method leads to many structural defects in the coating, especially in its density and purity. Therefore, these disadvantages limit the development of these coatings.

4.2.4 Cermet or metal-dielectric composite coatings

Cermet absorbers and multilayer interference stacks are commonly used in composite coatings [80]. In general, the infrared reflective surface layer consists of the typical double cermet coating with a substrate, the solar absorption layers with a low and high metal volume fraction, and anti-reflective ceramic layer (see Fig. 9) [81].
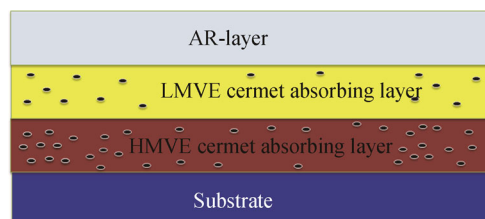

Fig. 9 Double cermet absorber coating [75]

The improvement of double cermet coatings focuses on layer thickness, number of layers, composition of each layer and gradation of metallic from the substrate to an anti-reflection layer [82]. The cermet layer consists of nano-particle metal at ceramic matrix or the dielectric, whilst the metal is utilised as an infrared reflector. Such type of cermets, like AlNi-Al$_2$O$_3$ [83], Ni-NiO [84], W-Al$_2$O$_3$ [8], W-Ni-YSZ [85], Ag-Al$_2$O$_3$ [86], Mo-SiO$_2$ [87, 88], Pt-Al$_2$O$_3$ [9] and Mo-Al$_2$O$_3$ [89]. The metal particles in the absorption layer affect the ceramic phase's optical response. Generally, Cr, Pt, Mo and W are used as metallic components with Al$_2$O$_3$, SiO$_2$, Cr$_2$O$_3$, AlN and TiO$_2$ matrix.

Solar radiation scatters via into phases: metallic and dielectric [90]. Dielectrics with low refractive index can effectively decrease surface reflectance and improve the absorption of solar spectrum coatings [86]. Cermet coatings are more suitable for convection or higher thermal resistance. During sudden large temperature changes, cermet coatings have greater stability at the substrate interface.

4.2.5 Absorbers with textured surfaces

Selective solar absorbers with textured surface can be used to enhance solar spectral absorption by multiple reflection or absorption effects of concentrated solar radiation [91]. The textured surface of porous, granular, dendrite or needle-like microstructures may produce very high absorption and catch several solar reflections, whereas lower emittance can be obtained when the surface appears to be smoother for long wavelengths [92]. Chen developed an electrode location tapered aluminium doped nanorod covered with zinc oxide, which exhibited absorption in the solar radiation of 0.95 [93]. A selectivity of 0.95/0.07 was exhibited by nanoneedles and nanofibers made using chemical oxidation of Cu [94]. Wang simulated the optical properties of the surface of a two-dimensional molybdenum photonic crystal, which showed a high absorption of 0.919 and a low emission of 0.149 at 1000°C [95].

5. Methods for Preparing Selective Coating

Coating preparation is an ageing process that is practised worldwide for different purposes, such as insulation, thermal barrier, corrosion safety and thermal absorber. This paper will not explain the various coating techniques available and their advantages and disadvantages, as these are discussed in broader literature. To make the tube surface of PTSCs absorbent, certain selective absorptive coatings must be prepared and applied in the system. A solar absorber needs to absorb the radiation whilst minimizing losses to increase the receiver temperature. These coatings are dependent on

combinations of metal-metal, metal-ceramic and metal-metal oxide [91]. Different types of coatings are prepared using techniques such as physical vapour deposition, thermal chemical coating, spray pyrolysis, electrochemical coating, mechanical coating, and dip coating cathodic and sputtering vacuum deposition and various sputtering techniques. The selection of the deposition technique depends on the requirement of the coating material's specific properties, working conditions and manufacturing cost.

The physical and chemical properties of coatings depend on many factors including substrate structure, layer thickness, cleanliness, purity, substrate temperature, film structure, grain size, void formation and subsequent treatments. The following methods are used to prepare selective coatings [96, 42]:

(1) Physical vapour deposition is principally a vaporisation coating technique by transferring vapour particle materials to travel directly to the substrate. The whole process is conducted at vacuum conditions by thermal evaporation or electron beam method. For example, a coating material is vaporised by intense thermal from tungsten filament [97].

(2) Chemical vapour deposition is a deposition process performed under vacuum conditions to manufacture high-quality, reliable materials with high performance. This process involves a chemical reaction between the materials deposited by halide or an organometallic with other gases to fabricate solid thin films on the substrate surface [98].

(3) Sputtering is a technique that involves the ejection of the coating to the substrate by high-energy particles deposited using bombardment. Inert gas ions have been used to bombard the coating to transmit momentum and energy to the metal substrate [99].

6. Thermal Stability and Lifetime of Selective Absorber Coatings

The selective coatings should be thermally stable because they experience rapid and cyclic temperature variations over operation time. High temperature to coating surfaces in air/vacuum can cause surface degradation and oxidation, hence thermal stability is a crucial factor to consider [100]. The coating properties should have stable absorptivity and emissivity. Therefore, the coating properties should be investigated during testing and accelerated ageing. Qiu et al. studied the deposition of titanium diboride on stainless steel, which has a strong solar absorptance (α=0.93) and low thermal emittance (ε=0.11). The tandem absorber coating is characterized by SEM, UV-vis-NIR spectrophotometer, FTIR, XPS, and Micro-Raman methods. The results showed the thermal stability of the SS/TiB$_2$/Al$_2$O$_3$

tandem absorber coatings in vacuum was investigated at 400°C–800°C for 2 h and 100 h, respectively [101]. Palomo et al. examined a $MoSi_2$-Si_3N_4-based selective coating and showed that the addition of Al_2O_3 increases the thermal stability of the composite even when it is operated continuously for 100 h at 600°C [102]. By using a magnetron sputtering technique, they deposited a solar selective ZrB_2/Al_2O_3 coating on stainless steel. The coating had α=0.92 and ε=0.11. The sample was annealed for 100 h at 500°C and 600°C to test the coating's thermal stability. The results showed that the coating was thermally stable at 500°C [103]. Magnetron sputtering method was used to prepare a solar selective absorbing coating of NbTiON/SiON on Cu. To achieve high solar selectivity, the new coating's absorptance (α=0.95) and emittance (ε=0.07) were optimised. The results showed the coating on Cu substrate has steady spectral properties (α/ε=0.94/0.08) after 40 h at 500°C in vacuum, but reduces at 600°C [104]. Cheng et al. prepared a Mo-Al_2O_3 solar selective absorption layer on stainless steel. As seen by AES and SEM with etching depth, the Mo diffuses easily at 400°C, as seen by AES and SEM. Optimising the deposition conditions resulted in a denser Mo-Al_2O_3 layer with better thermal stability [105]. Meng et al. prepared the Cu/Zr0.3Al0.7N/Zr0.2Al0.8N/Al34O60N6 cating by ion beam deposition. That has α=0.953 and ε=0.079 at 400°C. An annealing test at 400°C in a vacuum shows the deposited coating is thermally stable. The photothermal conversion efficiency decreases from 12.1 to 6.86 at 600°C annealing due to increased emittance [106].

As shown above, most present study on spectrum coatings focuses on enhancing optical properties and thermal stability, with little study on evaluating and predicting service life. Researchers should study the factors of accelerated ageing coating performance tests for accuracy, stability, and design. So, investigation of coating applications are required to elucidate the failure mechanism of absorption coatings and establish accelerated ageing, life evaluation, and prediction approaches.

7. Comparison of Data for Selective Absorber Coatings

Concentrated solar power plants are currently used for large-scale production in electrical plants to supply approximately 400 MW of power. PTSCs have represented a critical economic investment and are thus projected to be operational for at least 25 years. Therefore, it is essential to continue maintaining the cost-efficiency of the installation and high performance rate [107, 108].

The ageing or lifetime mechanisms induced by oxidation, diffusion, grain size change, micro-defects and optimised ingredients complicate the efforts of scholars to improve the efficiency of solar absorber coating [109, 110].

In typical PTSCs, the receiver/absorber is essentially one of the main important components of a collector. Therefore, the coating lifetime should be stable to enhance the efficiency and reduce maintenance cost [111]. This is because the coating is in contact with the absorber tube and solar radiation. Moreover, PTSCs can receive about 850 kW/m^2 of heat flux and achieve an outlet working temperature of 600°C or higher for a fluid receiver [74]. The coating should be protected from extreme abrasion loss due to environmental conditions [112].

As it is difficult to thoroughly document the exact shape, surface composition, properties and manufacturing method of absorbers, many mid- and high-temperature solar absorber coatings have been studied (see Table 1). The table provides some physical and chemical details for selected transition metal components and compounds and lists various references of compounds as a potential absorber coating.

8. Discussion and Future Research

A recent studies general revision was investigated, considering the coating types and methods. Different types of coating materials are used in reflectors and absorber tube to protect and improve the solar collector's optical efficiency. The high thermal efficiency of PTSCs depends on selecting an appropriate design of the receiver and the selective coating. Modelling and simulation are conducted to enhance the performance factor for designing a reliable system. PTSCs have an operating temperature of about 400°C in the absorber tube. Recent designs are expected to increase the temperature range to 600°C and improve efficiency by 5%–10%.

Several studies have been invested in the coatings utilised in the layered structure and have revealed their significance. In Table 2, some essential selectivity parameters are explained: chemical stability, emissivity, absorption, and stability at high temperatures. The various coatings used by researchers are listed, along with their associated results. Table 2 and Table 3 summarise various selective coatings, their corresponding application processes, coating characterisation methodologies, and specific results/remarks. Many coatings require other materials to attain desired properties, such as raising incompatibility with each other and costs. In order to achieve solar coating

Table 2 Physical and chemical properties of selective absorber coatings

Selective coating	Substrate	Method	Absorptivity (α)	Emissivity (ϵ)	Findings	Ref.
AlCrSiN/AlCrSiON/AlCrO	Stainless steel	Ion plating	0.96	0.14	TS at 600°C for 600 h in air. Chemically inert, high oxidation resistance and stable microstructure	[113]
CuCr2O4, CuFeMnO4, Cu0.5Cr1.1Mn1.4O4	Copper	Spray-coating	0.972	–	TS at 800°C for 2000 h in air	[114]
AlxOy/Pt/AlxOy	Copper	Electron beam evaporation	0.94	0.06	TS at 500°C for 2 h in air, and 450°C for 24 h	[115]
MoSi3N4	–	Sputtering	0.926	0.017	TS at 600°C for in vacum	[116]
Ni-CrOx	Stainless steel	Sputtering	0.8	0.14	high spectral selectivity, ranging of solar absorption (0.88 to 0.94) and ranging of thermal emissivity (0.15 to 0.04)	[117]
ZrOx/ZrC-ZrN/Zr	Stainless steel	Sputtering	0.88	0.04	TS at 700°C in vacuum	[118]
ZrOx/ZrC-ZrN/Zr	Copper	Sputtering	0.85	0.1	TS at 600°C in vacum	[118]
Mo/HfOx/Mo/HfO2	Copper	Sputtering	0.90	0.07	TS at 400°C for 2h in air, and 600°C for 2h in vacuum	[119]
Mn-Cu-Co-Ox-ZrO2/MgF2	Stainless steel	N/A	0.97	0.17	TS at 700°C for in the air	[120]
ZrB2/Al2O3	Stainless steel	sputtering	0.92	0.11	TS at 600°C for 100 h in vacuum	[103]
W/WeAl2O3/Al2O3	Stainless steel	Sputtering	0.93	0.14	TS at 580°C for 30 days in vacuum	[8]
SS/Cr/TiAlCrN-G/TiAlN/AlSiN/AlSiO	Stainless steel	Physical Vapor Deposition	0.949	0.122	TS at 300°C for in the air	[121]
MnCo3O4	Inconel 625	Spin coating	0.918–0.894	0.87–0.88	TS at 600°C for 480h in air	[13]
W/WAlN/WAlON/Al2O3	Stainless steel	Sputtering	0.958	0.08	High TS and the results show that each layer decreases its refractive index and extinction coefficient from the substrate to surface	[90]
TiAlN/AlON	Copper	Sputtering	0.93	0.05	TS at 550°C for 2h in air, and 800°C for 2h in vacuum	[122]
AlxOy/Ni/AlxOy	Stainless steel	Sputtering	0.932	0.038	TS at 400°C for 12 h in air	[123]
TiSi2	–	Spray coating	0.898	–	TS at 750°C for 1000 h in air	[124]
W/CrAlSiNx/CrAlSiNxOy/SiAlOx	Stainless steel	Electron beam	0.951	0.097	TS at 400°C for 650 h in air	[82]
AlxOy-Pt-AlxOy	Copper	Electron beam	0.92	0.1	TS at 550°C for 2h in air, and 450°C for 4 h in vacuum	[115]
Mo/HfOx/Mo/HfO2	Stainless steel	Sputtering	0.9	0.15	TS at 550°C for 2 h in air	[119]
MoSi2-Si3N4	–	Sputtering.	0.88	0.11	TS at 300°C in vacuum	[125]
CrAlSiNx/CrAlSiOyNx	Stainless steel	Sputtering	0.959	0.097	TS at 600°C for 650 h in a vacuum	[100]
W/WSiAlNx/WSiAlOyNx/SiAlOx	Stainless steel	Sputtering	0.96	0.096	TS at 450°C for 400 h in air	[100]

Table 3 Summary of the studies with selective coating

Selective coating type	method	Main Findings	Ref.
Ni-Al	Spray coating	Increasing the Ni-Al coating thickness increases PTSC thermal performance while decreasing heat transfer from PTSC to its surroundings	[12]
Cu CoO$_x$	Spray coating	The stability of a solar receiver coating at high temperatures of 750°C lasts for 1000 hours	[51]
Fe$_3$O$_4$ Nanoparticles	Electron beam	The results show the influence of thickness on selectivity (α/ε), with 15.2 being the best value at one layer coating	[64]
ZrC	N/A	It has a low emissivity, allowing for good thermal energy storage with minimal radiative losses	[66]
CoCuMnO$_x$	Spray coating	The findings show that coatings can be used safely in solar collectors for a long time	[70]
Cu-CuAl$_2$O$_4$	Sputtering	The coating showed high selectivity (α/ε) of 0.87/0.04	[71]
W/WSiAlN$_x$ /WSiAlO$_y$N$_x$/SiAlO$_x$	Sputtering	The coating showed high selectivity (α/ε) of 0.96/0.104 with high TS at 600°C in vacuum for 300 hours	[82]
AlNi-Al$_2$O$_3$	sputtering	The coating showed high selectivity (α/ε) 0.95/0.078 high TS at 500°C in vacuum for 240 hours	[83]
W-Al$_2$O$_3$	sputtering	High TS at 580°C in vacuum for 30 days	[8]
W-Ni-YSZ	sputtering	The coating showed high selectivity (α/ε) 0.91/0.13 high TS at 600°C in a vacuum	[85]
Ag-Al$_2$O$_3$	sputtering	The coating showed high selectivity (α/ε) of 0.93/0.04 with high TS at 400°C in a vacuum	[86]
Mo/Mo-SiO$_2$/SiO$_2$	sputtering	The coating showed high selectivity (α/ε) 0.96/0.097	[87]
Mo-SiO$_2$	sputtering	The efficiency of photothermal conversion has increased by 0.6%	[88]
W/WAlN/WAlON/Al$_2$O$_3$	sputtering	The coating showed high selectivity (α/ε) 0.958/0.08.	[90]

selectivity, stable solar selective coatings may need to be made from chemically and structurally stable materials. According to data on absorptance and emittance for such coatings, many metals and their compounds may be suitable for use in PTSC systems.

Developing new coatings requires materials with high TS at high temperatures, good optical properties, and resistance to oxidation, corrosion, and abrasion. Many of the investigations in Tables 1 and 2 used the sputtering method to cover cermet materials. The emissivity and absorptivity of all sputtering coatings range from 0.05 to 0.17 and 0.8 to 0.96, respectively, at a stable temperature of 300°C to 750°C. Table 3 shows that high absorptivity and low emissivity magnetron sputtering coatings can be utilized for high annealing temperatures, and other coatings methods can produce hazardous emissions. Spray coating is a reliable method for getting good properties, highly adhesive and anticorrosive coatings over the substrate. Therefore, the coating method must be chosen based on the application area, availability, and cost criteria.

The enhancement and modification of coatings for PTSC should be done in the context of manufacturing -making components efficiently, cheaply, and reliably; assembly or construction making systems simpler, cheaper, and easier to integrate with the relevant application (generation of electricity, cooking, desalination, process plant, heating, etc.). Thermal analysis on PTSC shows that improving main influencing parameters such as absorber tube materials, coatings, and working fluid can improve thermal efficiency. According to the research, coatings are more effective for improving system performance.

The literature review of PTSCs provided an in-depth insight into the research work conducted to enhance optical and thermal performance. Future work should focus on the following research gaps to improve the performance of PTSCs.

(1) Investigation of coatings in the reflector and absorber tubes for minimising dust particle adhesion.

(2) Investigation of advanced composites (cermet) with enhanced transmittance, better absorptivity and negligible emission.

(3) Enhancement of TS for selective coatings to prevent environmental degradation.

(4) Different coatings need to be mixed with other materials for better properties.

9. Conclusion

PTSCs for large-scale electricity generation are most advanced in terms of technological research, development and practical experience. This study present the current scenario of PTSC technology as well as its various improvements. The current work reviews various selective coating materials and their characteristics for

different designs in concentrating solar power. The coating of the absorber tube of PTSCs showed a remarkable enhancement of thermal efficiency by decreasing thermal losses.

The study describes a wide variety of selective absorber coatings that can be used to improve the receiver's absorptivity, thereby increasing the system's thermal performance. These systems are expected to operate for 20–25 years. The main outcomes are summarised below:

(1) The performance of PTSCs depends on many parameters such as working fluid, thermal conductivity, coating absorptivity, heat flux, optical performance and collector size of the system.

(2) Mixing of nano-particles to the working fluid is an effective method to increase the thermal energy collected and nanofluid's thermophysical properties such as enthalpy, specific heat capacity, thermal conductivity and density.

(3) Hybrid nanoparticles bear excellent physical characteristics as compared to mono nanoparticles.

(4) The thermal modifications in the absorber tube are able to enhance the efficiency and increase the useful output.

(5) Selective coatings may experience corrosion at high operating temperatures; thus, certain anticorrosive materials need to be added to preserve their optical and thermal behaviour.

(6) Coating performance analysis can help analyse physical and chemical properties that can reduce failures.

(7) The sputtering coating method has certain significance for depositing films on the substrate and is economic and environmentally friendly.

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