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Article

Investigation and review of mirrors reflectance in parabolic trough solar collectors (PTSCs)

Energy Reports

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Elsevier

Suggested Citation: Jamali, Hamzeh (2019) : Investigation and review of mirrors reflectance in parabolic trough solar collectors (PTSCs), Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 145-158,
<https://doi.org/10.1016/j.egy.2019.01.006>

This Version is available at:

<https://hdl.handle.net/10419/243572>

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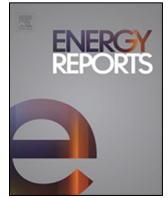
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Review article

Investigation and review of mirrors reflectance in parabolic trough solar collectors (PTSCs)



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ARTICLE INFO

Article history:

Received 25 September 2018
 Received in revised form 10 January 2019
 Accepted 14 January 2019
 Available online xxxx

Keywords:

Coating
 Mirror
 Reflectance
 Solar collector
 Substrate
 Thermal efficiency

ABSTRACT

As mirrors used in concentrating solar systems influence the thermal efficiency of the systems collectors to a large extent, the reflectance of mirrors plays a critical role in the thermal efficiency of parabolic trough solar collectors. The studies already done by scientists in terms of how to prepare mirrors of high reflectance and quality to be used in parabolic trough solar collectors are investigated in this review paper. In other words, the paper is aimed at investigating the reflectance of various mirrors already studied by researchers as an important parameter influencing the thermal efficiency of parabolic trough solar collectors. This influence is numerically shown through two instances applied in a case study. Many factors and preparation methods influencing solar mirrors reflectance and quality including mirror preparation technique, mirror material, and material configuration, which were studied by scientists, are investigated. In addition, the useful and important strategies, already studied, influencing the reflectors performance and quality are discussed within the paper sections and briefly through tables. Finally, although a nearly ideal reflectance of about 0.99 in both silver and aluminum mirrors – as the most common and efficient mirrors – has been achieved by scientists, it becomes evident that more work is still required to be done in the future in order to achieve mirrors of ideal reflectance and quality.

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<https://doi.org/10.1016/j.egy.2019.01.006>

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1. Introduction

Solar energy as a sustainable and environmentally friendly source of clean energy has continuously been center of attention in the recent decades. For many years, scientists have been making lots of efforts in order to improve concentrating solar power systems efficiency. Thermal efficiency of parabolic trough solar collectors is one of the research issues which has always been focused on as a matter of great interest. The radiation heat transfer in parabolic trough solar collectors (PTSCs) plays an essential role in this regard, which is directly concentrated on solar mirrors used in the collectors. Since the sunlight density is really low regarding the temperature needed for the heat transferring fluid (HTF) in a collector absorber tube, mirrors as solar thermal reflectors are used in a collector to concentrate high solar flux on a small area of absorber tube in order to attain higher fluid temperature. The ideal reflectors should have a high reflectance, low maintenance and initial cost, and a long life. There are many factors which could affect the reflectance and the economic lifetime of a solar reflector. Therefore, reflectors manufacturing methods, as the ways to determine the favorable properties for the reflectors, should keep these properties substantially intact during the time which the reflectors may get degraded and stressed by storm, temperature cycling, water, humidity, vapor, ultraviolet (UV) radiation, dust, and physical abuse (Silver/Glass Mirrors, 1985). Scientists have constantly been endeavoring to achieve a solar mirror with the ideal reflectance of 1. Although a solar mirror reflectance of 1 has not been practically achieved yet, scientists have already come up with various materials for the reflecting surfaces of mirrors through different methods each of which has its own advantages and disadvantages. Some of the mirrors prepared by them showed to have nearly ideal reflectance. However, corrosion as one of the most important problems causes degradation and consequently leads to a decrease in solar reflectance (Silver/Glass Mirrors, 1985). Silver and aluminum as the most common materials with high reflectance used for solar reflectors, if not properly protected, can undergo corrosion due to exposure to atmosphere, leading to a significant decrease in their reflectance (Silver/Glass Mirrors, 1985). Therefore, it really becomes crucial to prepare mirrors of not only ideal reflectance, but also durable and resistant to corrosive agents. The review paper investigates the various materials and methods ever chosen and studied by researchers in order to prepare mirrors of better reflectance and quality. In Section 1, an introduction is given through discussing the paper purpose and then investigating the previous researches already done by scientists in this regard. Section 2 discusses the influence of the reflectance of solar mirrors on the thermal efficiency of parabolic trough solar collectors through investigating two instances applied in a case study, accompanied with numerical results. In Section 3, the main conclusion is drawn from the two previous sections. And finally, Section 4 predicts the prospective studies in this regard.

1.1. Mirror preparation techniques

Although the article is not concentrated on mirrors preparation methods, it is worth reviewing the most common techniques already used by scientists in order to prepare mirrors with favorable properties needed for parabolic trough solar collectors. Below are mentioned the techniques:

1.1.1. Physical vapor deposition (PVD)

Physical vapor deposition (PVD) process is a deposition process in which atoms or molecules of a material are vaporized from a solid or liquid source, transported in the form of a vapor through a vacuum or low-pressure gaseous environment, and then condense on a substrate (Mattox, 2000). The process is also used to deposit films of elements, alloys, and compound materials as well as some polymeric materials (Mattox, 2000). Typically, PVD process is used to deposit films with a thickness range of a few to thousands of angstroms, with deposition rates varying from 10 to 100 Å/s (Mattox, 2000). There are various types of PVD process categorized as follows:

Vacuum evaporation is one PVD process in which material from a thermal vaporization source reaches the substrate without collision with gas molecules in the space between the source and the substrate (Mattox, 2000). Below are mentioned some of the most important advantages of vacuum evaporation process (Mattox, 2000):

- High-purity films can be deposited from high-purity source materials.
- High vaporization and deposition rates are possible.
- Deposition process can be easily controlled.
- The process is one of the least expensive processes of PVD ones.

Sputter deposition is another PVD process which is the deposition of the particles vaporized from a surface by physical sputtering process as a non-thermal vaporization process where surface atoms are physically ejected by momentum transfer from an energetic bombarding particle accelerated by a gun (Mattox, 2000). Below are mentioned some of the most important advantages of sputter deposition process (Mattox, 2000):

- It can be applied to elements, alloys, and compounds.
- The sputtering source and target can take a defined shape in some configurations.
- Reactive sputter deposition can be easily achieved.

Arc vapor deposition is also one PVD process in which vapor is formed from the anode or cathode of a low-voltage high-current DC arc, in a low-pressure gaseous atmosphere (Mattox, 2000). An arc can also be ignited in a vacuum, forming vacuum arc vaporization technique (Mattox, 2000). Below are mentioned some of the most important advantages of arc vapor deposition process (Mattox, 2000):

- Film-ions can be highly accelerated.
- A high vaporization rate can be obtained in anodic arc.
- There is low radiant heat load in cathodic arc.
- The arc plasma activates reactive species and makes them more chemically reactive.
- Alloy materials can be readily vaporized in cathodic arc.

Last but not least, ion plating is one PVD process which utilizes concurrent or periodic bombardment of energetic particles – which are usually ions of an inert or reactive gas – from the depositing film material to modify and control the composition and properties

of the depositing film (Mattox, 2000). Ion-plating can be done in a vacuum environment where the bombarding ions are produced from an ion gun, the process being called ion beam assisted deposition (IBAD) (Mattox, 2000). Below are mentioned some of the most important advantages of ion plating process (Mattox, 2000):

- Surface coverage can be improved.
- Film properties can be controlled.
- Film properties are less dependent on the angle of incidence of the flux of depositing material in comparison with sputter deposition and vacuum evaporation techniques.

1.1.2. Sol–gel deposition

The sol–gel process includes a number of stages such as gel formation, for synthesizing materials from solutions (Gaurav Bahuguna, 2016). The most popular type of sol–gel process is based on the phase conversion of a sol obtained from organometallic or alkoxide precursors (Gaurav Bahuguna, 2016). During the process, the above-mentioned sol gets polymerized at low temperature, and forms a wet gel (Gaurav Bahuguna, 2016). Finally, a dry gel can be formed by eliminating solvent through exposure to standard heating (Gaurav Bahuguna, 2016). The main advantages of sol–gel process over other conventional ones are low synthesis temperature, high purity, high homogeneity, better yield, novel materials, and low cost (Gaurav Bahuguna, 2016).

1.1.3. Lamination

Lamination is the technique of manufacturing a material in multiple layers, so that the composite material improves in terms of strength, stability, sound insulation, appearance or other properties through applying various materials (Wolf, 2010). There are two types of lamination which are extrusion-based lamination and adhesive-based film lamination, in order for making a composite construction (Wolf, 2010). The performance of the both types largely depends on the types of polymeric, adhesive, and surface treatment ingredients (Wolf, 2010). Adhesive-based laminates can be made by dry bonding, wet bonding, UV/EB curing, and hot melt adhesion processes (Wolf, 2010). Extrusion-based laminates are made by extruding a thin tie-layer of a plastic material to bond two other materials such as a polymer film, paper or foil (Wolf, 2010). Also, co-extrusion of materials can be done by extruding them at the same time and then pressing them together (Wolf, 2010). For incompatible layers, a thermoplastic adhesive as a tie-layer is used to laminate them together (Wolf, 2010).

1.1.4. Thermal decomposition of organometallic compounds

Thermal decomposition, or thermolysis of organometallic compounds is a chemical decomposition process in which the compounds are decomposed by heat. Organometallic compounds are those in which the carbon atoms of organic groups are bound to metal atoms (Hassan, 2002). As a result of the low electronegativity of metals, carbon–metal bonds are polarized so that carbon becomes the negative pole and metals tend to form positive ions (Hassan, 2002). Therefore, the bonds to carbon break with the electron pair remaining on carbon (Hassan, 2002). In reactions between organometallic compounds and compounds with electronegative substituent, attractive interaction between two carbon atoms is thus possible and reactions of this type lead to many useful and important carbon–carbon bond syntheses (Hassan, 2002). Accordingly, organometallic compounds are increasingly preferred as the precursors for depositing materials on various substrates via thermal decomposition of the metal compound (Crabtree, 2005).

1.2. Glass substrates and superstrates

Glass as a classic material has been being used in solar mirrors since long time ago. In first-surface solar glass mirror, glass plays the role of a substrate which is coated by appropriate protective films and the reflective film is positioned at the mirror front side, while in second-surface solar glass mirror, glass plays the role of a superstrate which is coated by appropriate protective films and the reflective film is positioned at the mirror back side and protected by other layers. In order to prepare both first-surface and second-surface glass mirrors, glass substrates and superstrates need to be coated by appropriate reflective and protective films through deposition processes. There are various types of glass used in many researches, including soda lime float glass used in the researches by Goodyear (1980), Coyle (1980), Dennis (1980), Correa (1998), Martinez (2000), and Almanza (2009), Corning Microsheet glass (Marion, 1980), aluminosilicate (Corning 0317) used in the researches by Coyle (1980) and Pitts (1984), borosilicate (Corning 7809) used in the researches by Pitts (1984) and Czanderna (1986), CGW-7809 (Coyle, 1980), microscopic glass substrate (Nwosu, 2017), and simple glass substrates used in the researches by Hass (1982), Pitts (1984), Silver/Glass Mirrors (1985), Susemihl (1987), Almanza (1988), Almanza (1992a), Almanza (1995), Fend (2003), Kennedy (2005), Hernandez (2007), and Ho (2013). Each glass type has its own advantages and disadvantages depending on technological applications and purposes researchers and manufacturers aim for. As the principal optical attributes of an ideal reflector are: (1) High optical performance, that is, ideal reflectance, specularity, and geometrical configuration (2) Low maintenance (3) Low initial cost (4) Long life, mirrors materials and manufacturing processes have always been undergoing modifications in order to achieve an ideal result. Below are mentioned two common types of glass mirrors:

1.2.1. Silver mirrors

In some researches, glass thickness and composition were modified in order to obtain new types of glass with favorable characteristics (Silver/Glass Mirrors, 1985). In terms of thickness, glass was produced as thin as possible to reduce double absorption during transmission of the incidental solar radiation over as wide a spectrum as possible, still keeping glass strength requirements fulfilled (Silver/Glass Mirrors, 1985). The reflectance of Soda Lime glass, Ford glass, SCHOTT B270 glass, ASG LUSTRAGlass, and Corning Type 0317 were studied regarding glass thickness reduction (Silver/Glass Mirrors, 1985). For most of the glass types studied whose thickness tended to be zero, the reflectance showed to be higher than 0.9 (Silver/Glass Mirrors, 1985). In terms of composition, purity of silica was heightened and glass reflectance was consequently increased by lowering the amount of unfavorable chemicals present in glass like iron and some oxides (Silver/Glass Mirrors, 1985). Then, the reflectance of Fused silica, 96% silica (Vycor), Borosilicate (Pyrex), Aluminosilicate, Soda-lime silica, and Lead-alkali was analyzed regarding their composition (Silver/Glass Mirrors, 1985). Likewise, In one study, John et al. prepared silvered mirrors using a high-transmittance low-iron glass manufactured at Ford Motor Company's Tula glass plant, discussing the influence of the presence of iron on the performance of the solar energy reflectors (Goodyear, 1980). It was demonstrated that low iron flat glass with relatively flat surface can be made by the float process and that this glass would make an excellent back-surface mirror with a solar reflectance of 0.896 (Goodyear, 1980). In another study, R. T Coyle et al. studied a new sheet glass (CGW-7809) manufactured by the Solar Energy Research Institute (SERI) at Corning Glass Works (CGW) (Coyle, 1980). By minimizing the total iron content, adjusting the conditions to oxidize all of the ferrous iron (Fe^{+2}) to ferric iron (Fe^{+3}), and also adjusting the levels of alumina and soda, the resulting CGW-7809 composition finally represented a

logical compromise among solar transmission (~ 0.91), thermal expansion, life, and cost, compared with soda-lime float glass and CGW-0317 aluminosilicate fusion glass (Coyle, 1980).

Glass substrates have always been being used for solar reflectors by researchers within various reflector configurations. Silver, vapor deposited on float glass, had specular reflectance ranging from 0.943 to 0.978 for various silicon resins, as protective coatings, tested by Dennis (1980). In a study, the mechanical and optical properties of silver/glass mirrors were reported in a study by Silver/Glass Mirrors (1985). The mirrors had high optical reflectance of 0.97 above (compared with aluminum which had reflectance of 0.91–0.92) within the wavelength band of $300 < \lambda < 700$ nm (Silver/Glass Mirrors, 1985). They also showed very good specularity, durability and ability to resist distortion from forces, and tolerance to impurities and mirror compositional variations (Silver/Glass Mirrors, 1985). In another study, regarding the fact that silvered mirrors with a solar reflectance of approximately 0.97 can degrade when exposed to terrestrial environment, Pitts et al. developed silvered mirrors by the thermal decomposition of organometallic resinate solutions, obtaining an adhesion between the silver and the glass substrates (Corning 0317 and Corning 7809) ten times as strong as silvered mirrors formed by evaporated silver, and improving the corrosion resistance of silver films (Coyle, 1980). As long as cost is one of the most important factors in mirrors design and configuration, C. Kennedy et al. reported a low-cost reflector material as an advanced solar reflective mirror (ASRM), developed by NREL (Kennedy, 2005). The mirror had a silvered glass substrate protected by an alumina coating several microns thick which was deposited by ion-beam-assisted deposition (IBAD) (Kennedy, 2005). They also tested some samples which maintained a hemispherical reflectance of 0.95 after more than 3 years accelerated and outdoor exposure, having the potential for a manufacturing cost lower than $\$10.76/\text{m}^2$ at the time (Kennedy, 2005). In addition, as a new mirror configuration, C. Nwosu et al. developed new reflectors by applying nanoscale thin films of Ag and Cu (Nwosu, 2017). Ag thin film of 100 nm was deposited by thermal evaporation onto a thin microscopic glass substrate while the Cu thin film (50 nm) was deposited on the Ag surface via sputtering (Nwosu, 2017). The deposited thin films were finally backed with 54 μm Pb based paint (Nwosu, 2017). As a result, the configuration of Pb-paint (54 μm)/Cu (100 nm)/Ag (50 nm)/glass showed an ideal reflectance of 0.96–0.99 (Nwosu, 2017).

1.2.2. Aluminum mirrors

In one research, first-surface aluminum reflectors with float glass (soda lime glass) as substrate were studied by W. Dennis et al. using various silicone resins in order to be used as protective coatings (Dennis, 1980). Aluminum, vapor deposited on float glass had specular reflectance of 0.883, being protected by the best silicone resin tested (Dennis, 1980). However, vapor deposited silver on float glass with a higher reflectance than aluminum had much poorer adhesion to glass than aluminum and was more difficult to protect (Dennis, 1980). In another research, R. Almanza et al. studied first-surface mirrors obtained by using Si_2O_3 and SiO films as the front-surface over aluminum films thermally evaporated over soda lime glass substrates (Almanza, 1992b). An aluminum film was deposited on a clean 3-mm glass substrate (Almanza, 1992b). Then two types of first-surface mirrors were formed, one with SiO , and the other one with Si_2O_3 as the front-surface, each one with a thickness of 3000 Å (Almanza, 1992b). Finally, the reflectance values achieved were 0.82 and 0.86, respectively (Almanza, 1992b). In order to test the samples durability, after one year of exposure to the environment, no degradation was detected in them (as an advantage), but after two years a slight amount of corrosion appeared (as a disadvantage) (Almanza, 1992b). At the same direction, a research into production of aluminum first- and second-surface solar

mirrors by sputtering processes using linear magnetrons on soda lime glass substrate areas was done by Correa (1998). The goals of this technique were film purity, large areas coating capability, and good uniformity on deposition thickness (Correa, 1998). In these mirrors, there was a better adherence of aluminum to the glass compared to silver mirrors, a fewer corrosion problems, a higher reflectance compared with second-surface mirrors from the visible to far IR regions, and a UV reflectance higher than in silver mirrors (Correa, 1998). The aluminum was protected automatically by a silicon dioxide (SiO_2) front film (Correa, 1998). However, in preliminary stages, SiO_2 layer appeared yellowish affecting the mirror reflectance (Correa, 1998). To eliminate such color (as there is some absorbance on the visible spectrum), small amounts of O_2 was added to the sputtering gas (argon), so a reactive sputtering would achieve the purity (Correa, 1998). Therefore, a higher reflectance of ~ 0.89 was obtained (Correa, 1998). In a nearly different way, Iván Martínez et al. made aluminum first-surface solar mirrors over soda-lime glasses with concave geometry (Martinez, 2000). The glasses were thermally sagged in a furnace up to 600 °C for about 2 h (Martinez, 2000). The reflecting film was made with thermal evaporation of aluminum while the protective film Al_2O_3 was made through sputtering technology with a planar magnetron (Martinez, 2000). According to the tests, the mean life of each glass mirror was expected to be ten years or higher, with a reflectance of 0.85 (Martinez, 2000).

1.3. Substrates and superstrates of other materials

Metal substrates are other options selected and used by many researchers including stainless steel substrate used in the researches by Czanderna (1986), Ashley (1988), Reed (1988), Jorgensen (1993), Schissel (1994), and Brogren (2004), aluminum substrate used in the researches by Susemihl (1987), Schissel (1987), Jorgensen (1991), Jorgensen (1993), Morales (1999), Fend (2000), Fend (2003), and Good (2016), silver–aluminum substrate (Adams, 1979), and molybdenum substrate (Hass, 1982). In addition, many different types of polymer substrates have already been investigated by many researches, including polyester (EC534, cast polymer, extruded polymer films) used in the researches by Griffin (1980), Susemihl (1987), Jorgensen (1991), Kennedy (1997), and Good (2016), plastic used in the researches by Almanza (1988), Almanza (1992a), Jorgensen (1994), and Almanza (1995), and PET (polyethylene terephthalate) used in the researches by Jorgensen (1993), Jorgensen (1994), and Kennedy (1994). Both metal and polymer substrates were tested in the above-mentioned researches and mostly proved to be good substitutes for glass substrates in terms of cost reduction and durability in outdoor conditions. Metal substrates, in some researches, were painted and covered by special materials – as mentioned in the following sections of the paper in detail – in order to increase the substrates resistance to corrosion. Also, various polymer substrates were prepared and applied in the above researches – as mentioned in the following sections of the paper in detail – in order to reach one with best durability while maintaining the reflectance of the reflective material.

1.4. Silver-containing reflective and protective configurations

1.4.1. Aluminum–silver alloy as reflector material

Silver as a commonly used reflector material has a reflectance of 0.97 (Adams, 1979). However its reflectance, if not properly protected, could considerably decrease because of tarnishing in the atmosphere (Adams, 1979). On the other hand, the reflectance of aluminum, as another commonly used reflector material, hardly changes in atmospheric conditions (Adams, 1979). However, its reflectance is not as high as silver (Adams, 1979). Therefore, in

order to obtain desirable characteristics for solar reflectors made of either silver or aluminum reflectors, and reach a reasonable trade-off, films of aluminum–silver alloys (prepared once by Harris and Siegel in 1948) were used as reflective layers by Adams et al., overcoming silver corrosion problem, although not having as high a reflectance as silver (Adams, 1979). The reflectance of these alloys were in the range of 0.6 to 0.8 (Adams, 1979). All the films referred to in the study were produced using an argon pressure of 60 mTorr and target potentials of 2000 V on the aluminum and 1000 V on the silver (Adams, 1979).

1.4.2. Influence of lamination on reflectance

R. Marion investigated glass/adhesive/backing laminate referred to as a reflector laminate for silvered mirrors (Marion, 1980). Since the glass used in linear parabolic trough concentrators must be formed to curvature, a very thin sheet glass was used in order to elastically deform the glass without causing failure (Marion, 1980). However, thin glass is extremely fragile and would be difficult to handle in sheets reasonably sized for mirror use (Marion, 1980). The simplest way in order to overcome this problem was to laminate the glass to a backing material to form a flat laminate (Marion, 1980). In the study, the design, fabrication, and testing of reflector laminates using 0.25 or 0.51 mm Corning Microsheet glass was discussed (Marion, 1980). The solar average specular reflectance for the reflector laminate with either 0.25 or 0.51 mm thick glass was 0.93 to 0.95 (Marion, 1980). As a consequence, it was found that lamination concept not only facilitates handling of thin glass and allows it to be bent to a small radius of curvature, but also increases the glass resistance to fracture and abrasion, by the compression it brings about throughout the glass (Marion, 1980).

1.4.3. Incidence angle effect on reflectance

Since the reflectance weighted by solar irradiance spectrum strongly affects solar concentration ratio, some researches were done into this subject as one of great interest. In a research, absolute reflectometers such as the one by NIST was developed to measure bi-directional reflectance in the range 200–2500 nm (Proctor, 1996). In a couple of studies, measurements of specular reflectance were reported for several reflective materials including back-silvered glass, metallized polymer films, and polished aluminum (Pettit, 1977; Susemihl, 1987). Since in none of the previous researches is the measured spectral data over the solar spectrum at various incidence angles generally available for defined acceptance angles suited for solar applications, P. Good et al. in a recent work within Monte Carlo ray-tracing simulations employed a spectroscopic goniometry system that enables the spectral and directional measurement of reflectance, transmittance, and scattering with high accuracy over a wide range of wavelengths and incidence angles relevant for solar concentrating applications (Good, 2016). They showed that the solar-weighted specular reflectance at near normal incidence and an acceptance half-angle of 17.5 mrad was 0.941 for back-silvered glass, and 0.908–0.926 for silvered polymer films, and 0.939–0.954 for silvered aluminum sheets (Good, 2016). The angular scattering, quantified in terms of the standard deviation of a Gaussian distribution, was found to be negligible for back-silvered glass (<0.07 mrad), and noticeable for silvered polymer films (0.27–1.12 mrad) and silvered aluminum sheets (0.12–1.66 mrad). In addition, the spectral transmittance of semi-transparent materials suitable for protective covers was measured, yielding solar-weighted normal transmittance values of 0.913 and 0.946 for 100 μm thin films of ETFE (ethylene-tetrafluoroethylene) and FEP (fluorinated ethylene propylene), respectively (Good, 2016). Consequently, it was found that the optical efficiency and the solar concentration ratio are strongly dependent on the reflectance and transmittance of materials, while the effect of non-specularity is secondary and affects the solar flux distribution to some extent

(Good, 2016). In another study, H. Liang et al. proposed a novel optical simulation method which combined the advantages of two models, Monte Carlo Method (MCM) and Finite Volume Method (FVM), in order to optimize optical efficiency of parabolic trough solar collectors with a cavity receiver (Hongbo Liang, 2017). They investigated the CSP optical efficiency regarding the parameters such as rays number, rays relative error, inclination angle of side absorber of cavity, and absorber tube depth (Hongbo Liang, 2017). The optical efficiency showed to be insensitive to the inclination angle between 0° and 15° (Hongbo Liang, 2017). The highest optical efficiency of the whole receiver they obtained was 85.30% at the highest absorber tube depth (Hongbo Liang, 2017). The results also showed that inclination angle of side absorber of cavity was not a sensitive factor for optical efficiency of the cavity receiver, but for heat transfer and concentration ratio within the absorber tube (Hongbo Liang, 2017).

1.4.4. Sol-gel method effect on silver reflectors production

C. Ashley et al. investigated the planarizing effect of sol-gel films on several stainless steel substrates for solar silvered mirrors (Ashley, 1988). By first planarizing the metal substrate using sol-gel derived films, the ultra-smooth surface required for high specular reflectance was obtained (Ashley, 1988). Through the study, a new configuration of Sol-gel overcoat/Primary protective coat/Silver layer/Sol-gel planarizing layer/steel substrate was evaluated, which gave a highly improved reflectance of ~ 0.93 (Ashley, 1988). S. Reed et al. also studied and designed front-surface silver mirrors coated with sol-gel derived films as protective coatings for silver (Reed, 1988). Regarding the fact that silver can be degraded by any subsequent processing (heating, coating, outdoor exposure, or H_2SO_4 exposure), sol-gel films proved to be dramatically reducing the thermal degradation of silver (Reed, 1988). In addition, a primary protective layer of SiO_2 was sputter-deposited before sol-gel film application onto a 2000 Å thick 403 stainless steel in order to minimize damage to silver from sol-gel deposition and subsequent heating (Reed, 1988). Finally, the results also showed that silver degradation seemed to originate at the edges suggesting that less degradation would be observed in mirrors with sealed edges (Reed, 1988). In another study, A. Morales et al. also investigated sol-gel front-surface silvered mirrors (Morales, 1999). Sol-gel thin and thick silica protected silvered mirrors presented reflectance values of 0.96 and 0.93 and outdoor durabilities of over 4 and 5 years measured in a QUV weathering chamber, respectively (Morales, 1999). In consequence, all the above researches showed how an ultra-smooth reflecting surface could be obtained using sol-gel method which yielded a good reflectance, also suggesting protective layers as a solution to the problem of unfavorable effects on silver layer caused by the method (if any).

1.4.5. Silvered polymer reflectors

As an appropriate option for constructing durable, low-cost, light-weight solar concentrating collectors, silvered polymer reflectors have been being studied by many researchers since long time ago. In one study, silvered polymer reflectors were prepared by A. Czanderna et al. through the multilayer mirror configuration of polymer/silver/backing adhesive/substrate by thermal evaporation and dc sputtering onto 3-M ECP-300XP polymer, where Inconel or aluminum as backing materials, 3-M Doublestick-SPR as adhesive, and 316 stainless steel and Corning 7809 glass as substrates were applied (Czanderna, 1986). Among all silvered polymers samples tested, 3-M ECP-300XP had maintained the best specularity of over 0.9 at 7 mrad for 65 weeks of outdoor weathering, because of topographical roughness of the polymer sheet before metallization (Czanderna, 1986). In another study, silvered polymer reflectors were produced in a different way; I. Susemihl

et al. investigated silvered transparent cast polymer sheets and silvered extruded polymer films (Susemihl, 1987). Applied with an adhesive onto aluminum or glass substrates, or suspended as a membrane, silvered polymers showed a reflectance of over 0.9 (Susemihl, 1987). The quality of the mirrors did not change significantly over the wavelength ranging from 400 to 1000 nm and incidence angles between 20 and 60 degrees (Susemihl, 1987). In a nearly similar work, P. Schissel et al. studied thin, flexible silvered polymers mounted on aluminum substrate with a significant cost reduction and an acceptable performance (Schissel, 1987). The mirrors maintained a reflectance greater than 0.9 for one year outdoor exposure (Schissel, 1987). They also studied polymeric stabilizers and stabilizers that do not absorb UV light to improve mirror durability, regarding the fact that conventional stabilizers – needed to maintain the reflectance of silver – may limit mirror durability (Schissel, 1987). In a creative research, in terms of tunneling problem as a common problem in silvered polymer mirrors, G. Jorgensen et al. developed ways to improve tunneling resistance of silvered-polymer reflector materials (Jorgensen, 1991). A set of measures were taken including either thermal treatment of ECP-305/Substrate construction (after lamination) at °C for 40 h or application of Tedlar tape (a polyvinyl fluoride from DuPont) to protect all edges, thermal treatment of reflector elements, avoiding bare aluminum substrate material to prevent aluminum

hydroxide formation which can initiate tunneling, and using alternative deposition methods like sputtering rather than evaporation of silver onto the polymer film (Jorgensen, 1991). In nearly same direction, as a state-of-the-art research, P. Schissel et al. studied ECP-305 as silvered-PMMA film commercially available from the 3M Company and developed in collaboration with the National Renewable Energy Laboratory (NREL), in order to make progress in overcoming the three primary mechanisms causing ECP-305 to lose reflectance: (1) Photon-induced silver corrosion, (2) surface soiling, and (3) a form of delamination called tunneling (Schissel, 1994). For the problem of silver corrosion, UV absorbers like opaque layers, or a dielectric paint layer were added to polymer glazing to block the light and finally avert or slow corrosion (Schissel, 1994). In terms of soiling problem, non-contact cleaning could regularly return the reflectance to more than 0.9 over a two-year period (Schissel, 1994). Finally, for the delamination or tunneling problem, annealing the reflector materials and protecting the mirror edges dramatically reduced tunneling in test samples (Schissel, 1994). The test results also showed that edge-taping and thermal heat treatment before curving would provide protection against the mechanical stresses introduced into the reflector film during the bending process (Schissel, 1994). In another research, however, regarding the two drawbacks of ECP-305 – the price of the material and the loss of reflectance during service – which kept it suspended from being employed on a wide-scale basis in solar industry, C. Kennedy et al., with the cooperation of NREL, introduced some advanced reflector materials including a commercial silvered-polymer solar reflector designated ECP-305+ by 3M Company, all-polymeric reflector material prepared by Dow Chemical Company of Midland-Michigan, and silvered Teflon, all of which maintained a specular reflectance above 0.9 for a lifetime of ten years under outdoor conditions (Kennedy, 1994). Among all, the exciting design which used ECP-305+ laminated to a 4-mil-thick polyethylene terephthalate (PET) substrate, was to be promising for wide-scale usage in solar industry, especially for offering increased durability in terms of corrosion degradation and delamination resistance (Kennedy, 1994). Additionally, C. Kennedy et al. studied a low-cost durable reflector of a silvered polymer mirror protected by an optically transparent alumina coating applied by ion-beam-assisted physical vapor deposition (IBAD) technique, in order to achieve a specular reflectance above 0.9 (Kennedy, 1997).

1.4.6. Reflectance-enhancing double layers effect

As the application of metal reflecting coatings may be followed by some problems – mainly, poor adherence between the metal reflector and the substrate, and poor durability of the metal reflector, the usage of some reflectance-enhancing double layers as a solution to the above-mentioned problems can maintain a satisfactory adherence between the metal reflector and the substrate, protect the reflecting material and consequently increase its durability, and most importantly increase the reflectance by using them with alternately low and high indices of refraction (Hass, 1982). Regarding the issue, G. Hass et al. studied the UV, visible, and IR reflectance behaviors of the most frequently used mirror metal coatings Al, Ag, Au, Cu, Rh, and Pt at various angles of incidence, and also protective layers SiO, SiO₂, SiO_x, and Al₂O₃, in order to be used in front-surface mirrors (Hass, 1982). They also presented new deposition techniques such as electron gun evaporation and electron beam evaporation for the deposition of high-melting-point metals and oxides (Hass, 1982). The coatings were deposited by evaporation in high vacuum (Hass, 1982). With the reflectance-enhancing double layer of Al₂O₃ + CeO₂, the reflectance of Ag mirrors increased from 0.983 to 0.993 (Hass, 1982). Al₂O₃ was used as an adherent layer, by electron beam evaporation onto Ag mirrors (Hass, 1982). Evaporated nichrome was also a good adherent layer to be used between the substrate and the Ag film (Hass, 1982). In another study, a reflectance-enhancing pair of aluminum oxide and tantalum oxide with controlled thickness was used by M. Viswanathan et al. to improve the silver mirrors reflectance in the visible region (Viswanathan, 1988). They developed front and rear-surface mirrors with a reflectance greater than 0.95 in the visible and IR regions, and an excellent mechanical and environmental durability obtained by the thickness control of appropriate binder film and protective film materials (Viswanathan, 1988). The mirrors were prepared using a binder layer and protective overlayer materials like aluminum oxides, tantalum oxide, yttrium oxide, silicon dioxide, and magnesium fluoride (Viswanathan, 1988). A thin layer of chromium and a composite layer of chromium and silver as the binder coating for the front-surface mirrors and tantalum oxide for the rear-surface mirrors were used (Viswanathan, 1988). The films were deposited by a vacuum evaporation technique (Viswanathan, 1988).

1.4.7. Comparative discussion of some reflectors

G. Jorgensen reported a study into low-cost (likely to be less than \$11/m² at the time), durable solar reflectors, done by National Renewable Energy Laboratory (NREL) and 3M Company (Jorgensen, 1993). In the early 1980s, a number of candidate metallized reflector materials were evaluated by many researchers, including acrylic,¹ silicone, fluoropolymers, polyacrylonitrile (PAN), polycarbonate, and polyester films, among which acrylic was determined to be the most promising polymer candidate from a cost-performance perspective, considering both silver and aluminum as reflective layers (Jorgensen, 1993). A chronological cost-performance ratio of silvered polymer reflector materials was reported to be Scotchcal 5400 > FEK-244 > ECP-300x > ECP-300 > ECP-300A > ECP-305 by Jorgensen (1993). G. Jorgensen also evaluated both organic and inorganic candidate coat materials (Jorgensen, 1993). Organic layers of organosilicone, polyurethane (PUR), and acrylic, and inorganic coatings of Si₃N₄, diamond like carbon (DLC), SiO_x, Al₂O₃, and other oxides were tested along with organic/inorganic composite coatings (Jorgensen, 1993). In their study, G. Jorgensen reported the substrate materials such as sheet stainless steel or aluminum or a polymer film such as polyethylene terephthalate (PET) used for front-surface reflectors (Jorgensen,

¹ Polymethylmethacrylate.

1993). In addition, fire protective and scratch-resistant top coatings (SRC), a UV-cured acrylic, a low emissivity coating, a thermal-cured organosilicone, and a UV-cured organosilicone provided and tested by NREL were reported (Jorgensen, 1993). Moreover, silvered polymers reflectors as candidate advanced material reflectors were studied by the NREL (Jorgensen, 1993). In terms of durability, ECP-305 reflector degraded a little after more than 2 years of outdoor exposure, while ECP-300A reflector degraded a lot after 1 year of outdoor exposure. Additionally, silvered PMMA (Polymethylmethacrylate) reflectors with back protective copper layers of various thicknesses (0 Å, 100 Å, 300 Å, and 600 Å), regarding the mirror configuration of PMMA/Ag/Cu/adhesive/substrate (Al or stainless steel), were examined, where the reflectance for 0 Å thickness significantly degraded after 300 h of exposure, while the reflectance for other thicknesses was maintained greater than 0.9 after 2000 h of exposure (Jorgensen, 1993). A new silver mirror configuration, Top protective film (2 mil Teflon^{TM2})/Metal interlayer (Au, Cu, Cr, Ti)/Reflective layer (Ag)/Back protective layer (Inconel, Cu, Cr, Nichrome), was also investigated aiming to minimize corrosion problems, top protective coats being deposited via a low-voltage, ion-plating process (Jorgensen, 1993). Among all of the samples tested for the above-mentioned configuration, the samples with copper back protection and either no interlayer or a titanium interlayer exhibited the best optical durability after 1 month exposure in Weather-Ometer (WOM) (Jorgensen, 1993). In another comprehensive study, a research and development program by NREL into advanced reflector materials was reported by Jorgensen (1994). As one of the ways to reduce the cost of solar mirrors is to metallize an appropriate and inexpensive substrate material such as a polyethylene terephthalate (PET) film and then overcoat the reflector with an abrasion-resistant, durable, protective top layers, such as organosilicones, polyurethanes, or acrylics as organic layers, and Si₃N₄, diamond-like carbon, SiO_x, Al₂O₃, and other oxides as inorganic layers, NREL has done some durability tests on some reflectors with this construction (Jorgensen, 1994). Following sputter deposition of SiO_x over silver, and the configuration PET/Ag/Si_yO_x, the silvered mirrors optical durability and performance showed to be dependent on the stoichiometry and thickness of Si_yO_x (Jorgensen, 1994). Polyurethane (PUR) was also evaluated on both glass and PET substrates, with and without copper protective layers behind the silver; where the silvered mirrors reflectance degraded during accelerated exposure testing (Jorgensen, 1994). Directly deposited reflector materials, following the configuration of Top coat/Reflective layer/Levelizing layer/Substrate, were also investigated, the advantage of such materials being that they eliminate the need for adhesives and lamination during the manufacturing process (Jorgensen, 1994). Samples severely degraded in accelerated exposure testing at NREL showing problems of interlayer adhesion and top coats showed to be turning yellow during weathering, as limitations of this method for solar applications (Jorgensen, 1994). Additionally, a silvered TeflonTM reflector material was developed, whose advantage was that TeflonTM is inherently weatherable and nonhygroscopic, while the reflectance was generally low (0.8 at 650 nm and 8–12 mrad) (Jorgensen, 1994). In the same work, a polymer multilayer reflective material (PML) was used by the Pacific Northwest Laboratory (PNL), under a subcontract with NREL, following the configuration of Si₃N₄ and-or PML/Ag/PML/Substrate, where Si₃N₄ is protective hard coat, and the PML encapsulates the silver reflective layer to prevent corrosion (Jorgensen, 1994). The PML was deposited by a vacuum flash-evaporation technique having the potential for extremely high production-line speeds and consequent low production cost (Jorgensen, 1994). A variety of ion-assisted sputter-deposited hard coats were also introduced to be applied to silvered

PET film, and intended to result in an improved optical durability (Jorgensen, 1994). In another part of the study, all-polymeric reflector materials were produced by Dow Chemical Company, having the advantages that degradation of optical performance caused by corrosion of metallic reflecting layers is no more a concern, and such materials can be directly thermoformed into usable structures, thereby reducing costs associated with support elements (Jorgensen, 1994). NREL characterized an approximate reflectance of 0.9 for some samples of the all-polymeric reflector materials, 60 mils thick and comprising 5000 alternating coextruded layers having a tailored gradation in layer thickness (Jorgensen, 1994). As the final part of work, adhesively bonded reflector materials, with a matrix of TefzelTM/Silvered PET laminated samples bonded to tension frames, were developed, the advantages being that the material construction were low-cost, and the problems with poor specular reflectance associated with metalizing fluoropolymer films could be avoided (Jorgensen, 1994); however, the main concern was the durability of the adhesive layer during weathering (Jorgensen, 1994). In a comparative and comprehensive research, T. Fend et al., with the cooperation of NREL, introduced some low-cost reflectors with long durability and reflectance values up to 0.96, including Flabeg, Miro2, Naugatuck, SolarBrite95, Glaverbel, and Erie-Electroverre, among which Flabeg demonstrated the best optical durability (Fend, 2003). Flabeg mirrors were produced by applying a silver reflective layer and an adhesion-promoting layer (usually copper) onto relatively thick (> 1 mm) glass using wet chemistry processes followed by protective backside paint (Fend, 2003). SolarBrite95 mirror construction developed by Alco and evolved from EverBrite95 was a UV-stabilized polyester film having a metallic back-protective layer (Fend, 2003); the film was laminated using a thermoset adhesive to a chemically pretreated aluminum substrate (Fend, 2003). A painted coating was applied to the backside of the metal substrate for added durability (Fend, 2003). Consequently, the reflectance achieved was ~ 0.92 and the cost ranged between 17 and 52 e/m^2 at the time (Fend, 2003). The Naugatuck thin glass mirror showed a reflectance loss of 0.95 to 0.92 after 5.5 years exposure in Texas, 0.95 to 0.89 after 6.5 years exposure in Sacramento, and similar reflectance after 6 years in the WOM (Fend, 2003); however, a negligible loss in reflectance occurred (after cleaning, and having the correct choice of adhesive to bond the thin glass to the substrate) in Phoenix and Florida after 7 and 5 years exposure, respectively (Fend, 2003).

As shown in Table 1, various silver mirror materials along with configurations have been studied by a lot of researchers in order to obtain silver mirrors with better reflectance and durability, and low cost. In some of the researches, there was a trade-off between the three factors of reflectance, durability, and cost, while in some other researches, one or a pair of factors were prioritized through the application of specific mirror materials and configurations regarding the demands made in solar industry.

1.5. Aluminum-containing reflective and protective configurations

1.5.1. Electron gun usage

R. Almanza et al. obtained some advances in first-surface mirrors using SiO, SiO₂, and Si₂O₃ films as front-surface over an aluminum film thermally evaporated by an electron gun over a glass or plastic substrate 3 mm thick (Almanza, 1988). The SiO₂-protected mirrors were obtained by evaporating pirex glass with an electron gun in a small evaporator (Almanza, 1988). In order to obtain a higher reflectance in the mirrors, the SiO was evaporated in an atmosphere of oxygen at pressure 10⁻⁴ Torr to produce a coating of Si₂O₃ (Almanza, 1988). Finally, the highest measured specular reflectance was 0.86 (Almanza, 1988). In another study, R. Almanza et al. presented more advances in aluminum first-surface mirrors regarding their previous studies (Ref. Ho, 2013)

² Polytetrafluoroethylene.

Table 1
Brief data collection on configuration and reflectance of various silver-focused mirrors.

Mirror material or configuration	Reflectance	Comment
Aluminum–silver alloy mirror	0.6 to 0.8	This mirror type was produced in order to overcome silver corrosion problem, although not having as high a reflectance as silver (Adams, 1979).
Low-iron-glass mirror	0.896	Iron minimization improved the mirror reflectance (Goodyear, 1980).
Glass/adhesive/backing laminate	0.93 to 0.95	Corning Microsheet glass was used in this mirror (Marion, 1980).
Silicon resin-protected mirror	0.943 to 0.978	Silver was vapor deposited on float glass, then protected by silicon resin (Dennis, 1980).
Silver/glass mirror	≥ 0.97	The reflectance was measured within the wavelength band of $300 < \lambda < 700$ nm (Silver/Glass Mirrors, 1985).
Silver/corning glass 0317 or 7809	0.97	The mirror was produced by thermal decomposition of organometallic solutions (Guenther, 1990).
ASRM silver/glass mirror	0.95	The mirror was protected by alumina coating (Kennedy, 2005).
Pb-paint/Cu/Ag/glass	0.96 to 0.99	Nanoscale thin films of Ag and Cu were applied on a microscopic glass substrate (Nwosu, 2017).
Silver/glass	0.941	The reflectance was measured at near normal incidence and an acceptance half-angle of 17.5 mrad (Good, 2016).
Silver/polymer	0.908 to 0.926	The reflectance was measured at near normal incidence and an acceptance half-angle of 17.5 mrad (Good, 2016).
Silver/aluminum	0.939 to 0.954	The reflectance was measured at near normal incidence and an acceptance half-angle of 17.5 mrad (Good, 2016).
Sol–gel overcoat/primary protective coat/silver/sol–gel planarizing layer/steel substrate	0.93	An ultrasurface was obtained using sol–gel derived films (Ashley, 1988).
Sol–gel silvered mirror	0.93 and 0.96	The reflectance was measured after 5 and 4 years of QUV weathering chamber (Morales, 1999).
PMMA/Ag/Cu/adhesive/Al or stainless steel substrate	> 0.9	The reflectance was measured after 2000 h of exposure, for different thicknesses of Copper layer (Jorgensen, 1993).
Silvered polymer (3-M ECP-300XP) Mirror	> 0.9	The mirror maintained reflectance for 65 weeks of outdoor weathering (Czanderna, 1986).
Silvered polymer mirror	> 0.9	Silvered cast polymer sheet and silvered extruded polymer films were used (Susemihl, 1987).
Silvered polymer mirror	> 0.9	The reflectance was measured after one year of outdoor exposure (Schissel, 1987).
Silvered polymer mirror	> 0.9	The mirror maintained reflectance for ten years under outdoor conditions (Kennedy, 1994).
Silvered polymer mirror	> 0.9	The mirror maintained reflectance by overcoming three corrosion inducing mechanisms (Schissel, 1994).
Silvered polymer mirror	> 0.9	Protective alumina coating was used by IBAD technique (Kennedy, 1997).
Silvered mirror/reflectance-enhancing double layers	0.993	The reflectance increased from 0.983 to 0.993 by using reflectance-enhancing double layers (Hass, 1982).
Silvered mirror/reflectance-enhancing double layers	> 0.95	The films were deposited by vacuum evaporation technique (Viswanathan, 1988).
SolarBrite95	0.92	The mirror evolved from EverBrite95 (Fend, 2003).
Naugatuck	0.95	The reflectance decreased from 0.95 to 0.92 after 5.5 years of exposure in Texas (Fend, 2003).

(Almanza, 1992a); first it should be noted that although silver mirrors have higher reflectance than aluminum mirrors, to obtain a good silver mirror five layers are needed compared with aluminum mirrors which need two layers (aluminum film and a protective transparent film) (Almanza, 1992a); In addition, less corrosion is observed in aluminum mirrors than in silver mirrors, because the adherence to the glass in aluminum mirrors is better and the sulfide tarnishing does not occur (Almanza, 1992a). As a new approach in their study, two electron guns were used in order to obtain higher quality in aluminum first-surface mirrors; one gun for aluminum evaporation permitting to eliminate or to minimize the pinholes, and the other one to allow the evaporation of SiO without any mirror contamination (Almanza, 1992a). The second advantage was a better adherence achieved between the aluminum film and the Si₂O₃ obtained by oxidization of SiO with some oxygen inside the evaporation chamber (10^{-4} Torr), due to the use of two e-guns that permit not to open the chamber (Almanza, 1992a). Through the same way and in another creative work, a research and development of aluminum first-surface solar mirrors was done by Almanza (1995). They used two protective films for the aluminum layer: Si₂O₃ and SiO₂ (Almanza, 1995). In the first-surface mirrors, the substrates were chosen to be glass, metals, or plastic (Almanza, 1995). Then, two electron guns were used to manufacture aluminum first-surface solar mirrors (Almanza, 1995). With the two electron guns, there was no need to open the

chamber during aluminum evaporation with tungsten filaments, and consequently, better adherence between the aluminum film and Si₂O₃ or SiO₂ was obtained (Almanza, 1995). The optimum thickness was 1000 Å or higher for the aluminum layer, about 2500 Å for Si₂O₃, and 3200 Å for the SiO₂ (Almanza, 1995). The mirrors were tested in the environmental chamber for accelerated weathering (Almanza, 1995); in consequence, SiO₂ and Si₂O₃ proved to be corrosion resistant and protective, especially regarding the preparation process of Si_yO_x layer beside the thickness of the layer (Almanza, 1995). The mirrors possessed high specular reflectance (0.89) and high environmental stability (Almanza, 1995).

1.5.2. Integration of aluminum first- and second-surface mirrors

R. Almanza developed new solar aluminum mirrors by integration of aluminum first- and second-surface mirrors, composite aluminum first-surface mirrors with double layer, and combination of integrated and composite mirrors (Almanza, 1999). As a consequence, the reflectance of the mirrors were 0.85–0.86 before and after aging tests for first-surface films and 0.73 for second-surface films (Almanza, 1999). In the same direction, the optical parameters of double first-surface aluminum mirrors i.e. Glass/Al/SiO₂/Al/SiO₂ produced using magnetron sputtering method were studied by C. Hernandez et al., in order to develop the mirrors of longer life (Hernandez, 2007). The manufactured mirrors showed a reflectance of 0.81–0.82 (Hernandez, 2007). Through a new work,

R. Almanza et al. studied the aluminum first-surface solar mirrors which, after twelve years of exposure to the aggressive weather conditions of Mexico City, had a reflectance decrease of only 0.03 (from 0.85 to 0.82), with only small scratches on the SiO₂ layer (Almanza, 2009). They also introduced two new concepts for aluminum mirrors: (1) First- and second-surface integrated mirrors. (2) First-surface compound mirrors. The configuration of Epoxic paint protection /Al layer/Soda-lime glass/Al layer/SiO₂ protection layer was presented for the former, which consists of an aluminum deposit in the frontal and back part of the floating glass substrate (Almanza, 2009); the aluminum at the front part is protected by SiO₂, whereas the aluminum at the back part is protected by epoxy paint (Almanza, 2009). With this configuration, if corrosion occurs on the first-surface mirror, it is replaced with the second-surface mirror (Almanza, 2009). Regarding the fact that the corrosion type was big holes with a diameter two times the thickness of the substrate, the integrated mirrors gave a reflectance of the order of 0.8 or less (Almanza, 2009). Although the reflectance was relatively low and it could also be lower, the mirrors could have a longer life (Almanza, 2009). For the latter, the configuration of Soda-lime glass/Al layer/SiO₂ protection layer/Al layer/SiO₂ layer was presented, which consists of evaporated Al and SiO₂ over an Al first-surface mirror (Almanza, 2009). Therefore, these mirrors could be more resistant to corrosion than simple first-surface mirrors, because if corrosion develops in the upper mirror layer, then the lower one replaces it, so that the reflectance does not get affected; and consequently, the mirrors remain in good condition and could have longer life (Almanza, 2009).

1.5.3. Miro2 reflector

T. Fend et al. studied four types of highly reflective coil materials (Fend, 2000). The first two were standard anodized aluminum coil-coated (STAAC) produced on a coil, and standard anodized aluminum coated piece-by-piece (STAAP) produced by anodizing single pieces (Fend, 2000). The other two were physical vapor deposition (PVD)-coated types of aluminized sheets Miro2 and Miro2+ (Fend, 2000). The standard anodized materials (STAAC and STAAP) showed a severe decrease in specular reflectance after outdoor exposure, which made them unpredictable for concentrating solar technologies such as parabolic troughs (Fend, 2000). On the other hand, Miro2 as a PVD-coated material was first appealing because of its enhanced reflectance in visible spectrum (Fend, 2000). It was produced by applying a two-layer coating deposited on standard aluminized coils as substrate (Fend, 2000); the first layer was an opaque pure aluminum layer sputtered by DC magnetron at 10⁻³ mbar, and the second layer was an oxide layer system like TiO₂ and SiO₂ layers which can both be produced by an industrial process conducted with reactive e-beam evaporation (Fend, 2000). One year outdoor weathering test of Miro2 resulted in a decrease in solar hemispherical reflectance from 0.886 to 0.826 (Fend, 2000). This degradation was the result of pitting corrosion taking place at the outermost interface of the sputtered aluminum layer, as the porosity of TiO₂ and SiO₂ was too large to prevent penetration of humidity and corrosive salts through the coating and to the sensitive Al/SiO₂ interface (Fend, 2000). To solve this problem, a protective lacquer (an additional polymer coating) with a very high transmittance, a very good stability against UV radiation, good adhesion to the oxide coating, and only a negligible effect on the reflectance was applied as the third layer on Miro2, which produced a new coated material named Miro2+ (Fend, 2000). Finally, tests with severe simulation of climates with atmospheric and rain water pollution and salt spray test showed no visible and optical degradation for the Miro2+ having the reflectance of 0.893 after 1000 h (Fend, 2000). Generally, first-surface aluminized reflectors typically start with a polished aluminum substrate onto which a reflective layer of aluminum is electrochemically deposited and a

protective oxidized top coat (alumina) is allowed to form (Fend, 2003); however, a new formulation (Miro2) produced by T. Fend et al. (Ref. Adams, 1979), in which the aluminum reflective layer was deposited by physical vapor deposition and a thin protective polymeric overcoat was used to protect the alumina layer, survived after more than 4 years of outdoor exposure in Cologne, Germany (Fend, 2003). Using a fluoropolymer overcoat, the researchers came up with another new formulation (Miro2/4270kk) demonstrating a better durability, a cost of <23 €/m² at the time, and a reflectance of ~ 0.89–0.9 (Fend, 2003).

1.5.4. Influence of lamination on reflectors

As mentioned above in the previous sections, the simplest way in order to overcome some problems with mirrors was to laminate the mirrors substrate to a backing material to form a flat laminate. A newly developed aluminum-polymer-laminated steel reflector was evaluated by Brogren et al. with respect to its optical properties, durability, and reflector performance in solar thermal systems (Brogren, 2004). The durability of the reflector was tested in a climatic test chamber as well as outdoor exposure (Brogren, 2004). Before aging, the total and specular reflectance were 0.82 and 0.77, respectively (Brogren, 2004). After one year of outdoor exposure, the total and specular reflectance were decreased by less than 0.01 (Brogren, 2004). However, after 2000 h in damp heat and 1000 W/m² simulated solar radiation, the total and specular reflectance significantly decreased to 0.75 and 0.42, respectively, because of degradation of the protective polyethylene terephthalate (PET) layer, caused by UV radiation and high temperature (Brogren, 2004). The results also showed that PET was not suitable under extreme climatic conditions, but in a normal Swedish climate (Brogren, 2004). In a later work, G. Jorgensen et al. reported a research into abrasion resistant hard coats for polymer film laminated reflectors done by NREL (Jorgensen, 2010). ReflecTech mirror film was first laminated to standard mill-finished aluminum and finally hard polymer coats were applied (Jorgensen, 2010). In consequence, among many tested abrasion resistant coatings (ARCs) identified and deposited onto ReflecTech Mirror film pre-laminated to aluminum sheet substrates, a UV curable acrylic formulation from Red Spot Paint & Varnish Company, Inc. as an advanced ARC product demonstrated excellent abrasion resistance, adhesion, and weatherability (Jorgensen, 2010). Within the tests, the product showed resistance to Taber and scrub brush abrasion to the extent that visual effects were nearly imperceptible and the measured specular reflectance was virtually unchanged and kept over 0.9 (Jorgensen, 2010). Resistance to Taber abrasion was maintained after exposure to UV light, condensation cycling, and thermal cycling (Jorgensen, 2010). The weatherability included highly accelerated exposure to over 10 years equivalent outdoor UV (Jorgensen, 2010). In another study, Solar Mirror Film 1100 (SMF1100) from 3M Company, produced by lamination process, was evaluated by C. Ho et al. for its potential advantages over silvered glass mirrors including lower weight, easier application, larger continuous reflective area, and competitive costs, commercially available for application in concentrating solar power towers (Ho, 2013). The SMF1100 mirror film was applied to a 0.508 mm painted aluminum substrate with an acrylic adhesive on the back side of the aluminum substrate, both laminations being performed under controlled conditions at 3M (Ho, 2013). The tests showed that after cleaning each facet using a damp cloth wipe, the specular reflectance and the total hemispherical reflectance of SMF1100 were 0.86 ± 0.026 and 0.93 ± 0.014, respectively, while the specular reflectance and the total hemispherical reflectance of the 3-mm silvered glass were 0.9 ± 0.012 and 0.94 ± 0.026, respectively (Ho, 2013). It was resulted that the clean specular reflectance (at 660 nm) of SMF1100 was lower than that of silvered glass for angles ranging from 25 to 15 mrad, respectively (Ho, 2013). However, the

measurements from reflectance and beam quality tests to evaluate the soiling impact revealed that there was no discernible difference in soiling rates between silvered glass and SMF1100 samples when exposed to outdoor conditions for over one year (Ho, 2013).

1.5.5. Reflectance under various conditions

R. Griffin did research in the reflectance of aluminized plastic film reflectors under various conditions, investigating first-surface and second-surface mirrors (Griffin, 1980). A single roll of polyester EC534 was metalized under a variety of conditions such as angle of deposition, vacuum level, and rate of motion of the film through the metallizer, in order to show the effect of deposition conditions on aluminum reflectance of a first surface mirror (Griffin, 1980). The results of their study showed that under good commercial production conditions, neither rate of deposition, and system pressure, nor angle of incidence has any detectable effect on the reflectance of vapor-deposited aluminum (Griffin, 1980). It was also shown that the choice of substrate is critical to the performance of the reflector in both first-surface and second-surface reflectors (Griffin, 1980). R. Griffin investigated various candidates of first-surface and second-surface reflectors as well as new samples selected for weathering tests, which gave different results (Griffin, 1980). Regarding Monte Carlo ray-tracing program, a study was done into the optical properties of various materials for solar concentrators measured over the wavelength ranging from 300–2500 nm and as function of incidence angle ranging from 15° to 60° using a spectroscopic goniometry system, by Good (2016). In their study, the effects of solar-weighted specular reflectance, narrow-angle transmittance, and angular scattering on the optical performance of solar concentrators were investigated (Good, 2016). They showed that the solar-weighted specular reflectance at near normal incidence and an acceptance half-angle of 17.5 mrad was 0.895 for aluminized polyester film, and 0.86 for aluminized aluminum sheet (Good, 2016). The angular scattering, quantified in terms of the standard deviation of a Gaussian distribution, was found to be negligible for aluminized polyester (< 0.05 mrad) (Good, 2016). In consequence, it was found that optical efficiency and solar concentration ratio are strongly dependent on the reflectance and transmittance of materials (Good, 2016).

1.5.6. Dielectric usage in reflectors

A dielectric mirror is a type of mirror composed of multiple thin layers of dielectric material, typically deposited on a substrate of glass or some other optical materials via thin-film deposition methods such as physical vapor deposition (which includes evaporative deposition and ion beam assisted deposition), chemical vapor deposition, ion beam deposition, molecular beam epitaxy, and sputter deposition. Dielectric mirrors are used to produce ultra-high reflectance mirrors; reflectance values of 99.999% or better over a narrow range of wavelengths can be produced using the above-mentioned techniques. K. H. Guenther et al. reported a research done into the development of front-surface aluminum mirrors with dense, dielectric overcoats deposited by low-voltage reactive ion plating (RLVIP) (Guenther, 1992). The mirror coatings were expected to have an ideal reflectance over 0.9 in the spectral band of 300–400 nm (Guenther, 1992). For this, they used dielectric thin films which were tested in outdoor weathering condition and accelerated weathering in lab, in order to reduce some absorption in the dielectric overcoat (Guenther, 1992).

1.5.7. Sol-gel method in aluminum reflectors production

Sol-gel technique as a method to yield a high quality aluminum reflector was used in a research by Morales (1999). In their research, they investigated sol-gel front-surface aluminum mirrors (Morales, 1999). Sol-gel front-surface aluminum mirrors protected

with alternating layers of titania (TiO_2) and silica (SiO_2) over an aluminum sheet demonstrated a reflectance of 0.895 (Morales, 1999). In addition, Selective Au/TiO₂ absorber cermet were produced with the same technique with quite promising optical properties (Morales, 1999). Sol-gel mirrors presented an outdoor durability over 4 to 5 years measured in a QUV weathering chamber (Morales, 1999).

1.5.8. Reflectance-enhancing double layers effect

Reflectance-enhancing double layers as a means of enhancing mirrors reflectance were used in a study by G. Hass in order to increase the reflectance of Al mirrors (Hass, 1982). Moreover, Rh mirrors were also studied and examined in their research. The most frequently used reflectance-enhancing film combinations in order to increase the reflectance of metals in the range of UV to IR were $\text{MgF}_2 + \text{CeO}_2$, $\text{Al}_2\text{O}_3 + \text{TiO}_2$, and reactively deposited $\text{SiO}_x + \text{TiO}_2$ (Hass, 1982). A film pair of $\text{MgF}_2 + \text{CeO}_2$ and two film pairs of them increased Al mirrors reflectance to 0.97 and 0.99, respectively (Hass, 1982). With evaporated $\text{Ge} + \text{SiO}$, the reflectance of Al mirrors as metal-dielectric mirrors to be used in prolonged exposure to intense light, reached to about 0.9, the substrates being glass or fused silica, and Mo (Hass, 1982). With Y_2O_3 and HfO_2 as durable protective coatings, Al mirrors reflectance was kept high and their durability increased (Hass, 1982). A reflectance-enhancing double layer of $\text{Al}_2\text{O}_3 + \text{CeO}_2$ was used for Rh mirrors, which increased the reflectance from 0.782 to 0.89 (Hass, 1982). In addition, with $\text{SiO}_2 + \text{TiO}_2$ reflectance-enhancing film, Rh mirrors reflectance was about 0.931 or higher in some cases (Hass, 1982).

As mentioned above, aluminum mirrors have some advantages including lower cost, higher durability, and better material adherence in comparison to silver mirrors. However, silver mirrors have higher reflectance. Therefore, in all of the above researches done into aluminum mirrors, the researchers have always been endeavoring to trade off the aluminum mirrors favorable factors against their unfavorable ones, regarding the demands made in solar industry. Table 2 presents the specific mirror materials and configurations already applied in aluminum mirrors in various researches.

2. Results and discussion

Regarding the paper concentration on the radiative heat transfer within the absorber tube of a parabolic trough solar collector, Eq. (1) states how mirror reflectance in parabolic trough solar collectors directly influence the thermal efficiency of them (Jamali, 2016).

$$\eta_{\text{Thermal,g}} = \frac{q_{\text{SolAbs-a}} - q_{\text{ThermalLoss,g}}}{AG_s} \quad (1)$$

where $q_{\text{ThermalLoss,g}}$ can be calculated using the following correlation, regarding Fig. 1 (Jamali, 2016):

$$q_{\text{ThermalLoss,g}} = q_{\text{rad-g-sky}} + q_{\text{conv-g-air}} + q_{\text{cond-sup}} \quad (2)$$

As $q_{\text{SolAbs-a}}$ is the radiative heat transfer from the mirror to the absorber tube of a parabolic trough solar collector, the higher the mirror reflectance, the higher the radiative heat transfer q_{SolAbs} and consequently the thermal efficiency $\eta_{\text{Thermal,g}}$. Regarding the data presented in Tables 1 and 2, there are, inter alia, silver mirrors of nearly ideal reflectance achieved in some researches; for instance, Silvered Mirror/Reflectance-enhancing Double Layers configuration represents a reflectance about 0.993 yielding a nearly ideal q_{SolAbs} and best favoring $\eta_{\text{Thermal,g}}$; however, silver mirrors have lower durability than aluminum mirrors, in spite of the fact that aluminum mirrors, on the other hand, in their ideal state represent a reflectance of about 0.9, as dielectric aluminum mirrors do for instance, which is lower than what silver mirrors generally do.

Table 2
Brief data collection on configuration and reflectance of various silver-focused mirrors.

Mirror material or configuration	Reflectance	Comment
Aluminum/float glass	0.883	Silane coupling agents as a way of chemical passivation of metal surfaces were used (Dennis, 1980).
Aluminum/float glass	0.82	SiO film was used as the front-surface (Almanza, 1992b).
Aluminum/float glass	0.86	Si ₂ O ₃ film was used as the front-surface (Almanza, 1992b).
Aluminum/float glass	0.89	SiO ₂ film was used as the front-surface (Correa, 1998).
Aluminum/float glass	0.85	The protective film Al ₂ O ₃ was made through sputtering (Correa, 1998).
Si _y O _x -protected Mirror	0.86	Si ₂ O ₃ film was used as front-surface by evaporation of SiO in an atmosphere of oxygen using one electron gun (Almanza, 1988).
Si _y O _x -protected Mirror	0.89	By using two electron guns, the better adherence between Si _x O _y and aluminum surface was achieved, compared to the state with one electron gun (ref. Ho (2013)) (Almanza, 1995).
First- and second-surface mirror	0.85 to 0.86	The reflectance was 0.73 for second-surface film, after degradation of the first mirror (Almanza, 1999).
Glass/Al/SiO ₂ /Al/SiO ₂	0.81 to 0.82	Double first-surface mirror was produced using magnetron sputtering method (Hernandez, 2007).
Epoxic paint/Al/glass/Al/SiO ₂	0.8 order	The reflectance of the first- and second-surface mirror was measured regarding the corrosion with big holes (Almanza, 2009).
Glass/Al/SiO ₂ /Al/SiO ₂	0.8 order	The first-surface compound mirror had a longer life than a simple first-surface mirror (Almanza, 2009).
Miro	0.886	Miro was produced by applying a three layer coating deposited on standard aluminized coils as substrate (Fend, 2000).
Miro2+	0.893	Miro2+ was produced by applying a protective lacquer to Miro (Fend, 2000).
Miro/4270kk	0.89 to 0.9	Miro/4270kk was demonstrated using a fluoropolymer overcoat (Fend, 2003).
Aluminum polymer mirror	0.82	The mirror was produced through lamination process (Brogren, 2004).
ReflecTech mirror	> 0.9	An abrasion resistant coating was used to produce the mirror through lamination (Jorgensen, 2010).
SMF1100	0.86	The mirror was produced through lamination process under controlled conditions (Ho, 2013).
Aluminized polyester mirror	0.895	The reflectance was measured at near normal incidence and an acceptance half-angle of 17.5 mrad (Good, 2016).
Aluminized aluminum mirror	0.86	The reflectance was measured at near normal incidence and an acceptance half-angle of 17.5 mrad (Good, 2016).
CGW-7809 mirror	0.91	CGW-7809 represented satisfactory quality by minimizing the total iron content (Coyle, 1980).
Dielectric aluminum mirror	> 0.9	Dielectric overcoats were deposited by RLVIP method (Guenther, 1992).
Sol-gel aluminum mirror	0.895	The mirror was protected with alternating layers of TiO ₂ and SiO ₂ (Morales, 1999).
Al film/reflectance-enhancing double layers	0.99	Different reflectance values up to 0.99 were achieved using various reflectance-enhancing double layers (Hass, 1982).

Fig. 1 renders schematic mechanisms of heat transfer directions within the absorber tube of a parabolic trough solar collector. As Fig. 1 presents, $q_{SolAbs-a}$ constitutes a percentage of the solar irradiance G_s onto collector mirrors, which is reflected onto the collector absorber tube. Accordingly, an ideal mirror is a mirror which reflects %100 of the solar irradiance onto a collector absorber tube, and also has other ideal characteristics such as a possibly highest durability. In other words, such an ideal mirror represents a reflectance of 1. Hence, regarding the fact that the maximum normal solar irradiance reaching every 1 m² surface of the earth is approximately 1000 W (Coddington, 2016), an ideal mirror reflects %100 of the solar irradiance onto collector absorber tube; therefore, assuming that $IAM = 1$, and the transmittance of glass cover and the absorbance of receiver absorber tube are 100%, $q_{SolAbs-g} = r_m \times \tau_g \times G_s = 1 \times 1 \times 1000 = 1000$ W, and then $q_{SolAbs-a} = q_{SolAbs-g} \times \alpha_a = 1000 \times 1 = 1000$ W. The formulas apply to all other mirrors, such as the aforementioned instances where the former with a reflectance of 0.993 yields $q_{SolAbs-a} = 993$ W, and the latter with a reflectance of 0.9 yields $q_{SolAbs-a} = 900$ W.

Here is a comparison made between the thermal efficiencies of two parabolic trough solar collectors with the above-mentioned mirror types as instances, in order to further elucidate how mirror reflectance can influence thermal efficiency in parabolic trough solar collectors. For this comparison, the absorber tubes of parabolic trough solar collectors of a solar power plant situated in Shiraz, Iran

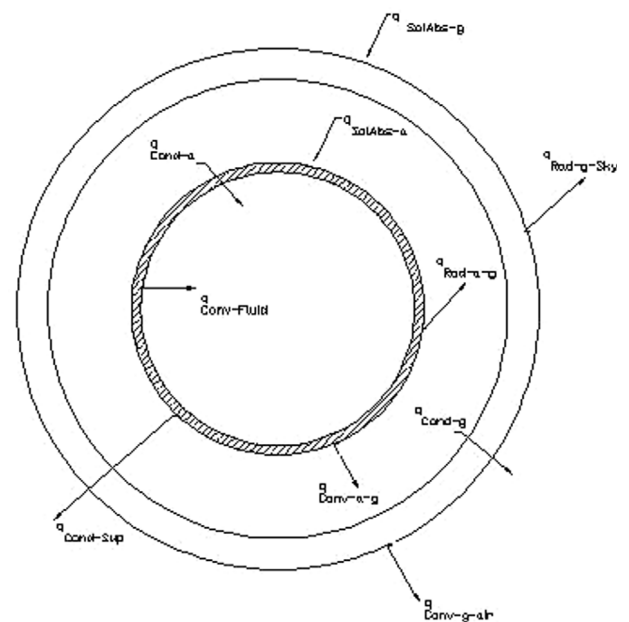


Fig. 1. Control surface of PTSC absorber tube with glass cover.

is considered as the case study (Jamali, 2016). The absorber tubes equipped with vacuum glass covers are assumed in the case study (Jamali, 2016). The data needed for calculations are collected from a research done by Jamali (2016). Thus, according to Eqs. (1) and (2) and the data available, the following calculations are made for the above-mentioned instances:

The case study data (Jamali, 2016):

$$\begin{cases} q_{\text{rad-a-glass}} = 397.52 \text{ W/m}^2 \\ q_{\text{conv-fluid}} = 201.2 \text{ W/m}^2 \\ q_{\text{rad-g-sky}} = 162.52 \text{ W/m}^2 \\ q_{\text{conv-g-air}} = 28.63 \text{ W/m}^2 \end{cases}$$

Therefore, for the former, with a reflectance of 0.993, and a maximum normal solar irradiance of 1000 W/m^2 :

$$q_{\text{SolAbs-a}} = 993 \text{ W/m}^2$$

Then, assuming that $q_{\text{cond-sup}}$ is negligible:

$$q_{\text{ThermalLoss,g}} = 162.52 + 28.63 = 191.15 \text{ W/m}^2$$

Finally, the absorber tube thermal efficiency will be:

$$\eta_{\text{Thermal,g}} = \frac{993 - 191.15}{1000} \approx 0.8$$

The same procedure can be followed for the latter, with the reflectance of 0.9:

$$\begin{aligned} q_{\text{SolAbs-a}} &= 900 \text{ W/m}^2 \\ \eta_{\text{Thermal,g}} &= \frac{900 - 191.15}{1000} \approx 0.7 \end{aligned}$$

As it is obvious from above calculations, the silver mirror with a reflectance of 0.993 yields a thermal efficiency of 0.8, and the aluminum mirror with a reflectance of 0.9 yields a thermal efficiency of 0.7. Therefore, the results clearly show how mirror reflectance considerably influences thermal efficiency in parabolic trough solar collectors. Likewise, an increase in solar irradiance raises the thermal efficiency of a parabolic trough solar collector as well; to more tangibly understand this trend, a work by W. Zheng et al. on a new type of compound parabolic concentrator solar collector can be referred to Wandong Zheng (2016).

Silvered mirrors and aluminum mirrors, either first-surface or second-surface, present different performances regarding their reflectance, lifetime, and material and manufacturing cost. Aluminum mirrors are more corrosion-resistant than silvered mirrors although they have lower reflectance than silvered mirrors. Since no absolutely perfect reflective material has already been presented, and on the other hand, the industrial needs for reflector materials differ in terms of material cost, material durability, reflectance, and other factors, a lot of researches have already been done in order to make a trade-off between the advantages and disadvantages of each type of mirror. For this, scientists have investigated various substrates, and protective and adherent materials alongside reflective materials through various configurations of the materials layers. Therefore, much progress has already been made by scientists through the following measures, in order to improve solar concentrating mirrors reflectance and quality:

- Metal alloys like aluminum-silver were used as reflective materials in order to overcome or reduce corrosion problems.
- Low-iron glasses were made as high-transmittance glass substrates, to improve reflectance.
- Backing laminates were used in very thin silvered mirrors to prevent glass failure when curved as solar concentrating troughs.

- An adhesion between silver and glass substrates was obtained through a creative manufacturing method, which was ten times as strong as silvered mirrors formed by evaporation.
- Silvered polymer mirrors were prepared as durable, low-cost, and light-weight mirrors.
- Silvered polymer reflector materials were evaluated regarding their cost-per-performance ratio.
- Back protective coatings were used in reflectors configurations to raise their durability.
- Top protective layers of some materials like Teflon™ were used in reflectors configurations to lessen corrosion problems.
- Interlayer materials were used in reflectors configurations to achieve longer optical durability.
- UV absorbers like opaque layers, or dielectric paint layers were added in reflectors configurations in order to avert or slow photon-induced silver corrosion.
- Edge-taping and heat treatment before curving mirrors provided protection against the mechanical stresses.
- Sol-gel derived films were added to give ultra-smooth reflector surfaces, and also as protective coatings.
- Nanoscale films of some materials were used in reflectors configurations in order to improve their reflectance.
- Reflectance-enhancing double-layers were used to increase the reflectance of silvered mirrors.
- Specific binder coatings were used to improve adherence between layers of reflectors configurations.
- Silicone Oxides were applied as protection films in aluminum mirrors.
- Two electron guns were used in manufacturing aluminum mirrors in order to achieve better adherence between the evaporated layers.
- Linear magnetrons were used in sputtering process for aluminum mirrors in order to achieve a good uniformity on deposition thickness, better adherence of layers, fewer corrosion problems, and a higher reflectance.
- Planar magnetron in sputtering technology was used in manufacturing aluminum mirrors to achieve a higher durability.
- Two new concepts, first- and second-surface integrated mirrors and first-surface compound mirrors, were presented in order to produce mirrors of longer life.

3. Conclusion

In the paper, solar mirrors of various reflectance and quality, prepared in various researches to be used in parabolic trough solar collectors, are studied. Among all mirror types, aluminum mirrors and silver mirrors show to have been the most frequently studied and popular ones in the researches. The paper mainly concentrates on the importance of solar mirrors reflectance and the influence it has on the thermal efficiency of parabolic trough solar collectors through the radiative heat transfer between the mirror and the absorber tube of a parabolic trough solar collector. To further elucidate the paper purpose, a case study was investigated considering, inter alia, two types of mirror, one silver mirror with a nearly ideal reflectance of 0.993 and one aluminum mirror with a reflectance of 0.9 as instances. The former and the latter respectively yielded thermal efficiencies of 0.8 and 0.7 for their parabolic trough solar collectors. Thus, it became clear how mirror reflectance can considerably influence the thermal efficiency of parabolic trough solar collectors. On the other hand, silver mirrors showed to be less durable than aluminum mirrors although they showed better reflectance and consequently resulted in higher efficiency. Hence, as there are various types of mirrors with different characteristics such as reflectance, durability, and cost, it can be best concluded that it is reasonable to trade off the mirrors advantages against their disadvantages regarding the requirements on the spot.

4. Prospective study

Regarding the above-mentioned studies, numerous investigations have already been conducted in order to achieve solar concentrating mirrors of higher reflectance than the previous ones. In some cases, the reflectance of some reflectors were improved through creative application of materials and manufacturing techniques although the mirrors lifetime, cost, etc. were affected unfavorably to some extent, and vice versa. For this, scientists have always been trying to make a trade-off between the above-mentioned factors as per their requirements on the spot. Therefore, future works regarding the issue are expected to be focused on application of novel materials and manufacturing methods in order to yield the highest reflectance of mirrors with the most favorable effects on the factors such as mirrors lifetime, manufacturing cost, etc.

Nomenclature

A :	Collector aperture area (m^2)
IAM :	Incidence Angle Modifier
G_s :	Solar irradiance (W/m^2)
$q_{SolAbs-a}$:	Heat gain from sunlight by receiver absorber tube (W/m^2)
$q_{SolAbs-g}$:	Heat gain from sunlight by vacuum glass cover (W/m^2)
$q_{ThermalLoss,g}$:	Thermal loss of absorber tube with vacuum glass cover (W/m^2)
$q_{rad-g-sky}$:	Heat from glass cover to sky by radiation (W/m^2)
$q_{conv-g-air}$:	Heat from glass cover to ambient air by convection (W/m^2)
$q_{cond-sup}$:	Heat from outer surface of absorber tube to support structure by conduction (W/m^2)
$q_{conv-g-air}$:	Heat from glass cover to ambient air by convection (W/m^2)
$q_{rad-a-g}$:	Heat from absorber tube to glass cover (W/m^2)
q_{cond-a} :	Heat from the outer surface of absorber tube to the inner surface of it by conduction (W/m^2)
$q_{conv-fluid}$:	Heat from the inner surface of absorber tube to fluid by convection (W/m^2)
r_m :	Mirror reflectance
α_a :	Absorbance of receiver absorber tube
$\eta_{Thermal,g}$:	Thermal efficiency of parabolic trough solar collector
τ_g :	Transmittance of vacuum glass cover

Acknowledgment

The author would like to express his especial thanks to Dr. H. Eskandari, faculty of engineering – Persian Gulf University – Bushehr–Iran, for his encouraging and helpful guidelines towards doing research into clean and renewable energy.

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