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A comparison of polymer film and glass collectors for concentrating solar power

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Abstract

This paper describes work to compare the optical properties and surface texture of glass and polymer film collectors. We also present the results of experiments designed to simulate collector cleaning processes (both contact and non-contact), and the degradation of glass and polymer reflecting surfaces owing to sand and dust abrasion. Finally we present initial results on the applicability of anti-soiling and self-cleaning coatings on glass and polymer film collector surfaces. Measurements, which include specular and hemispherical reflectance, surface roughness, and electron microscopy, indicate the excellent performance of currently available polymer film in terms of its optical performance and robustness in comparison with traditional glass collectors in CSP applications.

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Keywords: T Solar Collector; Polymer film; CSP

1. Introduction

Varieties of reflective materials are available for solar collectors; including silvered glass, metallised polymer film, polished and anodised aluminium, with or without anti-reflective coating (DiGrazia and Jorgensen, 2010). Each material brings its own distinctive features. For high efficiency it is desirable to use material that has high

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reflectance across the solar spectrum as well as demanding that it reflects with a high level of specularity, (DiGrazia et al, 2011 and Gee et al, 2010). Moreover the mirror material needs to be durable in harsh environments, for example in the presence of high ambient temperatures and sand or dust storms.

A silvered glass mirror has several advantages when it comes to optical properties. However, the high manufacturing cost, fragility during transport, and damage due to harsh environmental effects offer engineers an opportunity to investigate alternative solutions. These aforementioned problems were the reasons for developing highly reflective polymer film. Overall it is one of the most promising developments in term of cost reduction in concentrated solar power systems. Its advantages of cheaper transportation, lightweight, flexibility, good optical properties, and the fact that it is unbreakable are some of the reasons why this material is considered as a reflector material for solar thermal applications.

It is therefore important to assess the performance of polymer film material in comparison with conventional silvered glass. The aim of this research was to examine and analyze silvered polymer film reflectors and compare their properties and performance with traditional glass mirrors.

2. Polymer thin film collectors

This section of the paper describes research undertaken to characterize the spectral properties of silvered polymer film and compare the total (specular plus diffuse) reflectance with traditional glass mirrors. Having first established the surface optical properties of silvered polymer film reflectors and glass mirrors, we designed experiments to simulate the degradation of the reflecting surfaces under both contact and non-contact cleaning regimes. In addition, coatings for both anti-soiling and self-cleaning behavious have also been investigated. The polymer film used throughout is ReflecTech®PLUS and was supplied by SkyFuel.

Several standards are applicable for reflective materials for concentrated solar power systems. ASTM G173 is important for characterization of the optical properties of spectrally sensitive products such as the reflectors (mirrors) of solar collectors. ASTM D2486 describes scrubbing resistance of wall paints, but is still appropriate for reflectors when our aim is to analyse the resistance of surfaces to cleaning processes, especially contact cleaning. Standard ASTM D3359 is especially important for coating since it describes the method of measuring the adhesion of coatings by the tape test.

2.1 Surface structure of glass and polymer film collector pieces

The surface roughness of the two different reflector types was examined. These comprised a 1mm thick silvered glass mirror laminated on 3mm thick ceramic substrate from Ronda, and a 0.1mm thick silvered polymer film mirror (ReflecTech®PLUS from Skyfuel) laminated on a 1.3mm thick aluminium substrate. Figure 1a shows the surface roughness of the glass (arithmetic average), Ra=967nm whereas for the polymer film a value of Ra=957nm was measured. Figure1b shows an example of a polymer film sample poorly mounted on its aluminium substrate with a tilt of approximately 1.3µm.

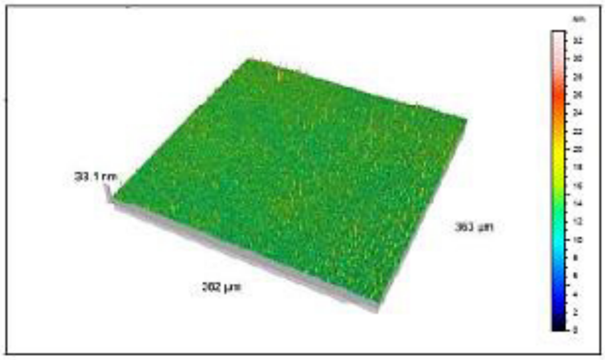

Figure 1a. Surface profiles of glass

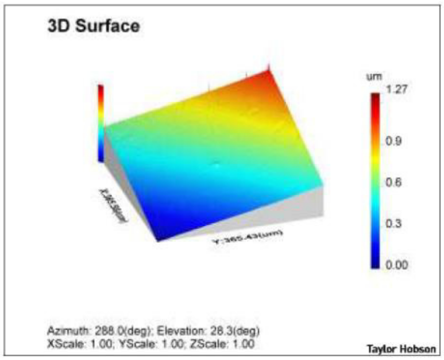

Figure 1b. Polymer film on aluminium

2.2 Spectral characteristics

The same source of material was used for spectral characterization as described in section 3.1 above (1mm thick silvered glass mirrors laminated on 3mm thick ceramic substrates, and 0.1mm thick silvered polymer film, ReflecTech®PLUS, laminated on 1.3mm thick aluminium substrates). Similar tests on glass and polymer solar collectors have been reported previously in the literature. See for example DiGrazia et al, 2011; Gee et al, 2010; and Heimsath et al, 2010. The equipment used was a Jasco V-670 UV-VIS-NIR spectrophotometer. To measure total reflectance an integrating sphere was used as an accessory, with a diameter of 60 mm and incidence angle of 8°. Calibration was performed with Spectralon TM which is a diffuse reflectance standard polymer material. Specular reflectance was measured with a PIKE UV-Vee MAX-II Variable Angle Specular Reflectance Accessory. The advantage of this accessory was its wide range of incidence angles; from 30° - 75°. Three different masks were available which then determine the size of the measured area; (7 x 4) mm, (13x4) mm, and (25x4) mm. Calibration was done with a first surface aluminium mirror for every change of angle. The roughness of reflector surfaces was measured with a Talysurf CCI 600. Total reflectance and specular reflectance with incident angles of 35° to 75° were measured, with emphasis on lower angles. Specular reflectance plots for glass and polymer film for a number of incidence angles, prior to any cleaning experiments, are presented in Figure 2 and Figure 3 below. These show that 45 degrees is the best incidence angle for the glass specimen, while 75 degrees is best for the polymer film.

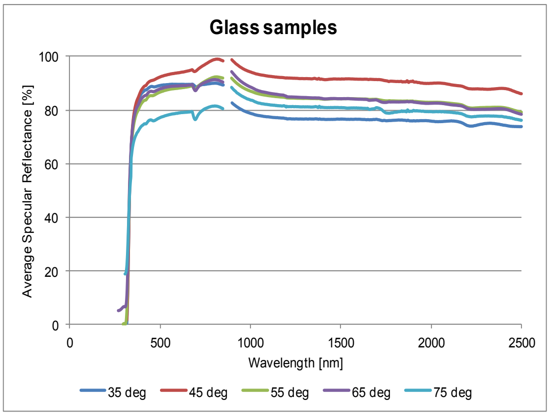

Figure 2. Specular reflectance of glass

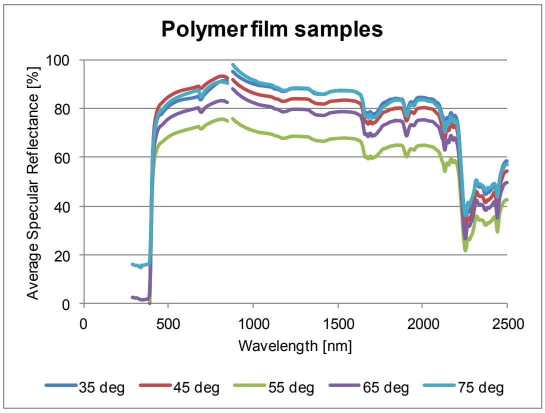

Figure 3. Specular Reflectance of polymer film

2.3 Contact cleaning experiments

Contact cleaning of glass collectors usually requires equipment of the type where there is contact between the reflecting surface and the cleaning brush. There is therefore the potential for particles of various shapes, sizes, and hardness to abrade the collector surface under the action of the cleaning brush. Our simulation of contact cleaning involved the controlled soiling of both glass and polymer film samples, followed by abrasion of the surface to represent the action of a contact brush process. The experimental design is shown in Figure 4.

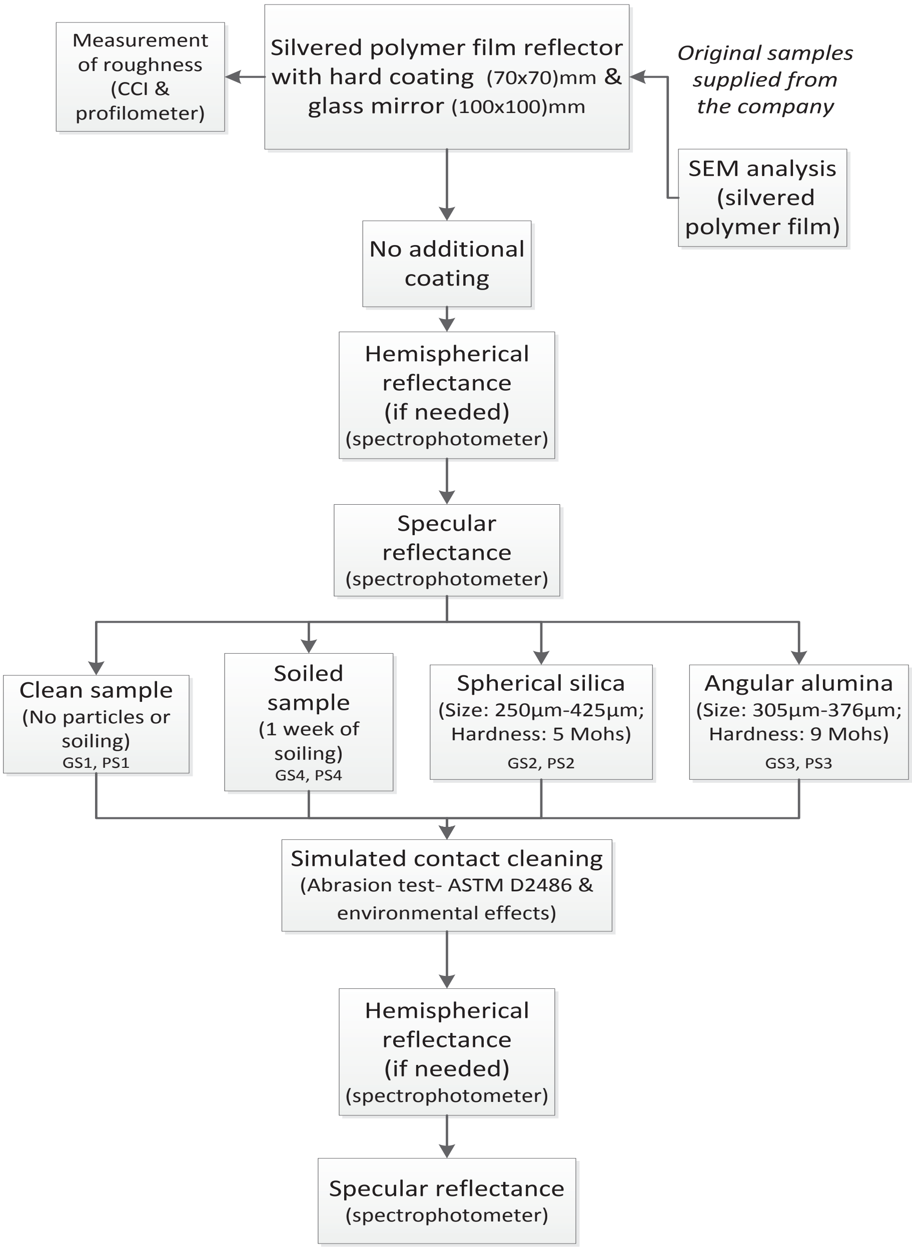

Figure 4. Experimental design for contact cleaning

The soiling agents were jagged (sharp cornered) alumina with very high hardness, spherical silica with medium hardness, plus "soiled samples" which were simply left exposed to the laboratory environment for one week, realistically to gather a layer of dust particles. For our simulation of the contact cleaning process we used a FANUC Robot M-710i, as shown in Figure 5. It has a six-axis, modular construction and is electric servo-driven with repeatability of ±0.15mm. The robot was programmed to complete 400 cycles with a linear speed of 285mm/min in accordance with the standard ASTM D2486. Apart from linear motion we also considered rotation with a speed of 300 rpm. The cleaning tool used was an in- house produced brush.

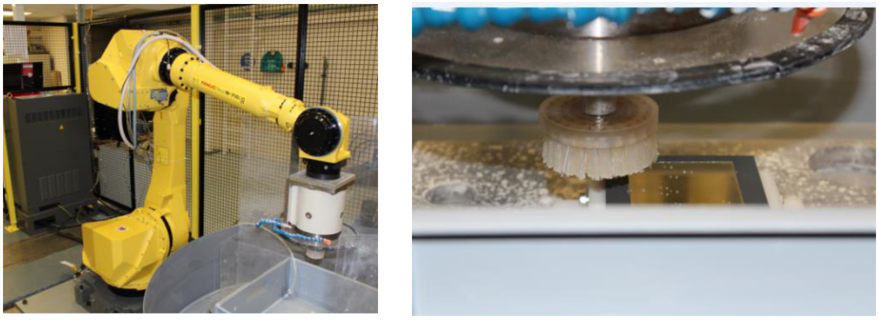

Figure 5. FANUC Robot performing contact cleaning (Standard ASTM D2486)

2.4 Non-contact cleaning, with additional coatings

2.4.1 Non-contact cleaning

Non-contact cleaning of glass collectors usually requires equipment of the type where there is no brush to sweep the collector surfaces and the cleaning action is achieved by the application of a high-pressure water jet. This method has the potential to damage the reflecting surface owing to the combination of a high pressure jet and surface particles of various shapes, sizes, and hardness. To simulate the non-contact washing of collectors a Kärcher K2.36 pressure wash machine was used with an input power of 1400W and a constant water flow of 360L/hr. The distance between sample and washer nozzle was 200mm.

Three different surfaces were used for the non-contact washing experiments; samples with no coating for reference, samples with self- cleaning coating (TiO_2) and samples with an anti-soiling coating (a polymer solution). The experimental design is shown in Figure 6 on the next page.

2.4.2 Coatings

For self-cleaning coatings two approaches were considered. For a hydrophobic surface any particles do not attach to the collector surface and are removed as the cleaning water traverses the surface. For a hydrophilic surface cleaning is based on the photodegradation of an organic pollutant. In this case the water forms a sheet rather than discrete droplets and removes the contaminants as it flows across the surface of the collector (San Vicente et al, 2011). In this work anatase phase Titanium dioxide (TiO_2) was selected as a self-cleaning coating.

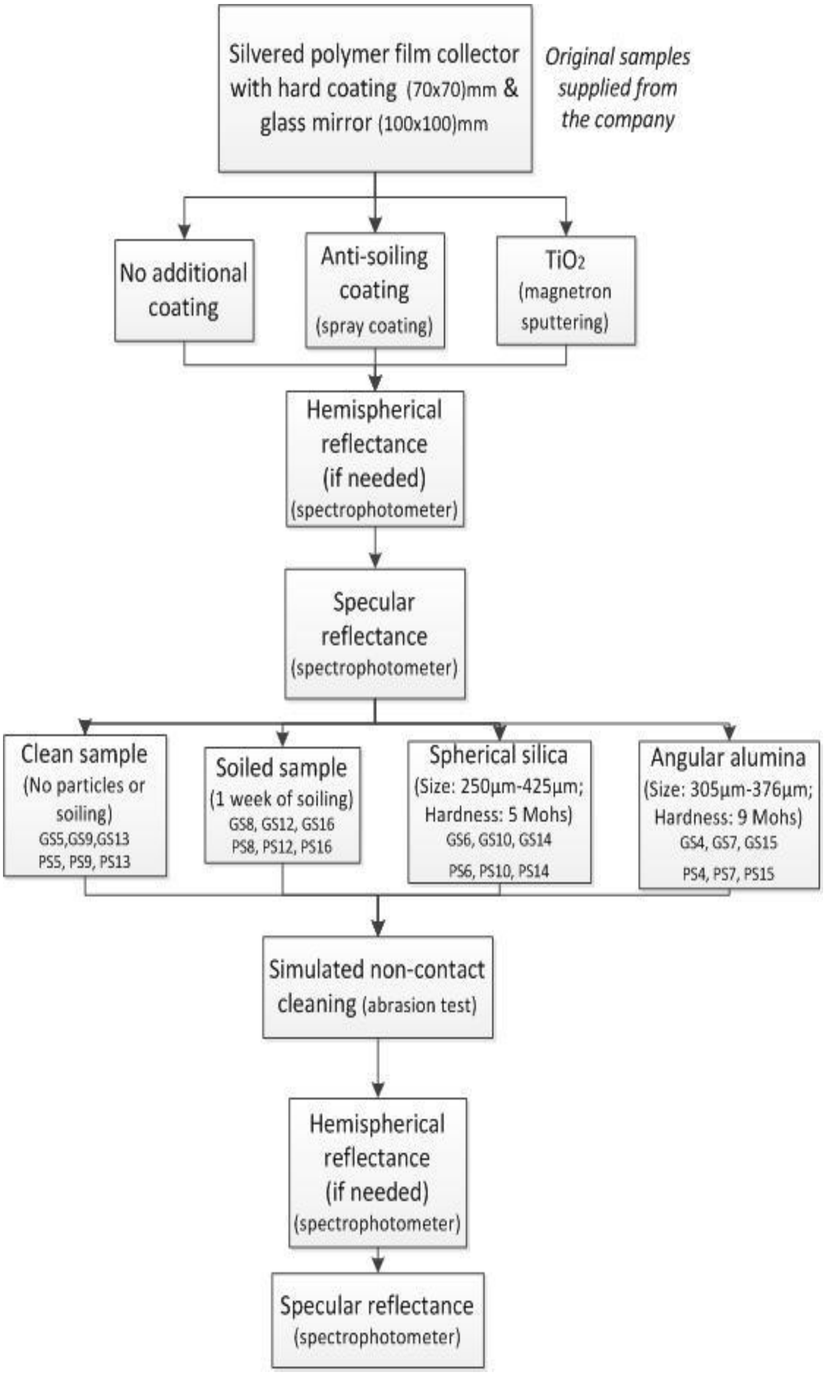

Figure 6. Experimental design for non-contact cleaning

Self-cleaning is achieved by the UV induced photocatalytic decomposition of organic pollutants, which are then removed from the photo-induced hydrophilic surface with a water wash (Glöß et al, 2005; Glöß et al, 2008). TiO_2 nano-layers were deposited using a Balzers PVD-sputtering machine. Ti Layers were RF sputtered at 250W for 92 minutes in an 80% Ar / 20% O_2 environment with no substrate heating. Coatings were analysed using scanning electron microscopy techniques, specifically a Philips, XL 30 SFEG with ultra-high resolution. Back scattered electrons and through lens detectors were used for analysis.

For anti-soiling coatings we seek to reduce the van der Walls force, the electrical double layer force, the electrostatic image force, and the capillary force that form the main components of the adhesive force. Since dust particles normally carry a negative charge it is essential to create a negatively charged surface in order to repel small particles of dust and sand. This is achieved using an appropriate surface coating, and removing any remaining adhered particles with a minimal quantity of surfactant and water. For the anti-soiling coating experiments outlined in Figure 6 we used a commercially available product from Chamelic Ltd, UK.

3. Results and discussion

3.1 Results of Contact Cleaning simulations

Figure 7 shows the total reflectance of samples following the contact cleaning schedule shown in Figure 4. Measurements were taken at four wavelengths across the solar spectrum, at 400, 500, 600, and 700nm. The corresponding specular reflectance at 45° is shown for comparison in Figure 8.

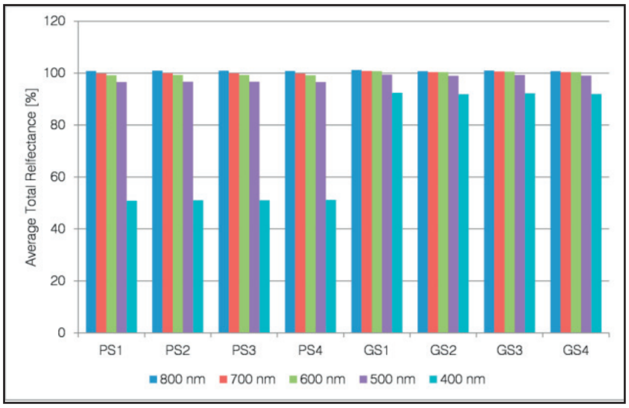

Figure 7. Total Reflectance (contact cleaned)

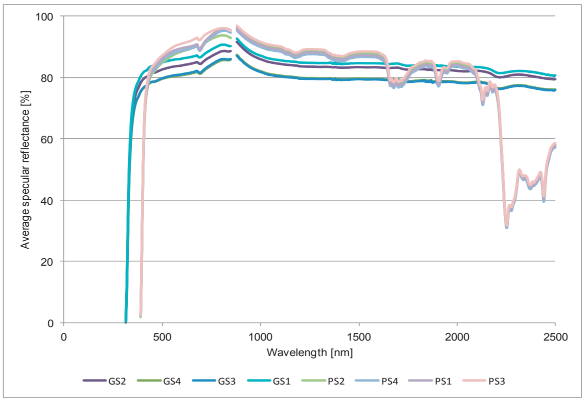

Figure 8. Corresponding Specular Reflectance

As can be seen from the bar chart in Figure 7, the total reflectance at a specific wavelength of 800 nm remained almost 100% for all samples after contact cleaning. The analysis had shown similar spectral behavior at other chosen wavelengths in polymer film implying no significant change in spectral response across the visible and NIR bands following treatments by silica particles (PS2), jagged alumina having hardness on the order of 9 Mohs (PS3) and soiling (dust particles, PS4) respectively. Note: see Figure 9 for sample designations. The specular reflectance plots in Figure 8 had shown similar trend of the spectral characteristics obtained from all samples across the wavelength range of 400-800 nm, which is the solar spectrum of interest.

Glass Samples	**Regime**	**Polymer film samples**	**Regime**
GS1	No additional coating	**PS1**	No additional coating
	No contamination particles		No contamination particles
	Contact cleaning		Contact cleaning
GS2	No additional coating	**PS2**	No additional coating
	Contamination particles: spherical silica		Contamination particles: spherical silica
	Contact cleaning		Contact cleaning
GS3	No additional coating	**PS3**	No additional coating
	Contamination particles: jagged alumina		Contamination particles: jagged alumina
	Contact cleaning		Contact cleaning
GS4	No additional coating	**PS4**	No additional coating
	Contamination particles: dust particles (soiling)		Contamination particles: dust particles (soiling)
	Contact cleaning		Contact cleaning
GS5	No additional coating	**PS5**	No additional coating
	No contamination particles		No contamination particles
	Non-contact cleaning		Non-contact cleaning
GS6	No additional coating	**PS6**	No additional coating
	Contamination particles: spherical silica		Contamination particles: spherical silica
	Non-contact cleaning		Non- contact cleaning
GS7	No additional coating	**PS7**	No additional coating
	Contamination particles: jagged alumina		Contamination particles: jagged alumina
	Non-contact cleaning		Non-contact cleaning
GS8	No additional coating	**PS8**	No additional coating
	Contamination particles: dust particles (soiling)		Contamination particles: dust particles (soiling)
	Non-contact cleaning		Non-contact cleaning
GS9	TiO_2 coating	**PS9**	TiO_2 coating
	No contamination particles		No contamination particles
	Contact cleaning		Contact cleaning
GS10	TiO_2 coating	**PS10**	TiO_2 coating
	Contamination particles: spherical silica		Contamination particles: spherical silica
	Non-contact cleaning		Non-contact cleaning
GS11	TiO_2 coating	**PS11**	TiO_2 coating
	Contamination particles: jagged alumina		Contamination particles: jagged alumina
	Non-contact cleaning		Non-contact cleaning
GS12	TiO_2 coating	**PS12**	TiO_2 coating
	Contamination particles: dust particles (soiling)		Contamination particles: dust particles (soiling)
	Non-contact cleaning		Non-contact cleaning
GS13	Anti-soiling coating	**PS13**	Anti-soiling coating
	No contamination particles		No contamination particles
	Contact cleaning		Contact cleaning
GS14	Anti-soiling coating	**PS14**	Anti-soiling coating
	Contamination particles: spherical silica		Contamination particles: spherical silica
	Non-contact cleaning		Non-contact cleaning
GS15	Anti-soiling coating	**PS15**	Anti-soiling coating
	Contamination particles: jagged alumina		Contamination particles: jagged alumina
	Non-contact cleaning		Non-contact cleaning
GS16	Anti-soiling coating	**PS16**	Anti-soiling coating
	Contamination particles: dust particles (soiling)		Contamination particles: dust particles (soiling)
	Non-contact cleaning		Non-contact cleaning

Figure 9. Sample designations for contact and non-contact cleaning experiments

The variation of reflectance with wavelength can be explained from Figure 8. The spectral response of the sample was not perfectly flat showing a slight variation of intensity around 2-3% only across the visible and NIR bands. As expected, the reflectance of the polymer film had cut-off wavelengths different from glass due to its intrinsic material response, and had a lower cut-off at 0.40 μm with a large dip at 2.3 μm. However, the polymer film had exhibited comparable reflectance performance as the glass mirror across the visible band and had shown slightly higher intensity of 2% than glass in the NIR band (800-1500 nm). It should be noted that the reflectance of polymer thin film mirrors remained unchanged over the entire visible and NIR bands following contact brushing in the presence of spherical silica and angular alumina particles. The similar response had been obtained for the glass mirror after contact cleaning except for the GS3 sample treated by alumina particles giving lower reflectivity. ReflecTech®PLUS is known to possess a hard surface (Jorgensen et al, 2010). The spectral analysis had clearly demonstrated the robustness of the polymer mirrors designed with little effect on their reflective property following the contact cleaning process under different conditions.

3.2 Results of non-contact cleaning simulations

Figure 10 shows the total reflectance of samples after the non-contact cleaning processes described in Figure 6. As with the contact-cleaned samples, measurements were taken at wavelengths in the visible and NIR range 400-800nm.

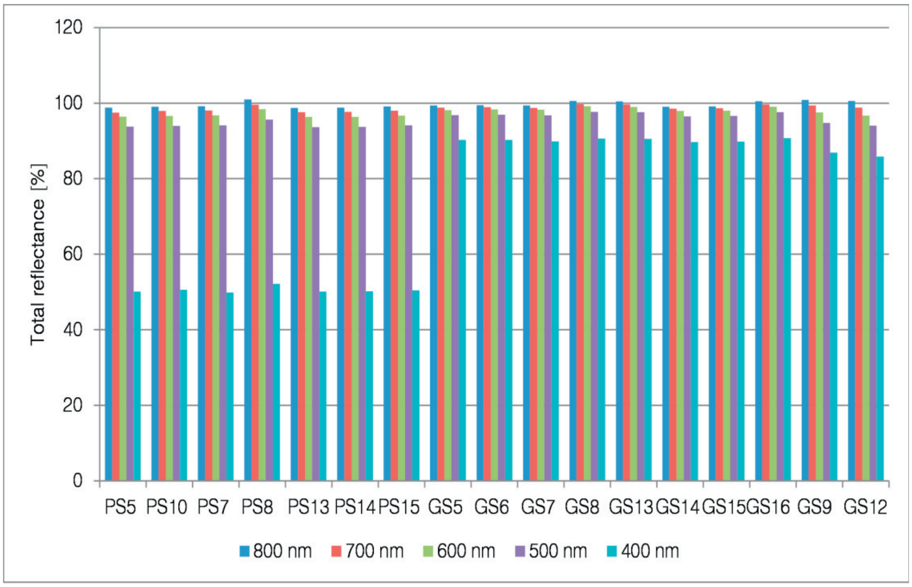

Figure 10. Total Reflectance of Non-contact Cleaned samples

As with the earlier contact cleaning results, Figure 10 demonstrates the low wavelength cut-off of the polymer film reflectance at around 400nm, again not significant in the collection of solar radiation. Otherwise, the reflectance of the glass and polymer film surfaces is again very similar, regardless of their process history. We conclude that both the glass and polymer film samples have not been significantly affected in the presence of surface particles subjected to a high pressure water jet – our non-contact cleaning simulation.

Greater detail is shown in the specular reflectance graphs of Figures 11, 12, 13, and 14 below. Here, we have additional information from samples that possess self-cleaning TiO2 top surface films or the Chamelic anti-soiling treatment (Figure 14) and the specular reflectance of soiled samples (left open to dust collection in the laboratory) prior to any surface cleaning (Figure 13). These latter samples do demonstrate a range of specular reflectance, owing to the uncontrolled particulate deposits during a week’s exposure to laboratory conditions. Measurements of coated samples show that the total reflectance does not change as a result of the non-contact cleaning regime (Figure 11, 12), but the specular reflectance of sample number PS11 is an exception (see Figure 14). This sample, which was damaged by overheating during the TiO2 sputtering process, understandably has a significantly lower reflectance. The TiO2 coated samples generally have a lower reflectivity, which implies that we have some absorption in the coatings within the solar wavelength range. In contrast, the anti-soiling coating is more transparent in the same wavelength band.

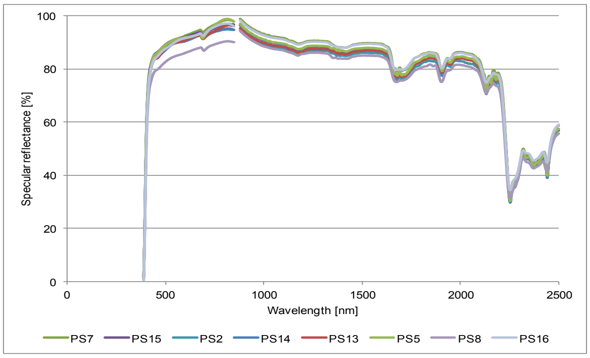

Figure 11. Specular reflectance of polymer film samples after non-contact washing

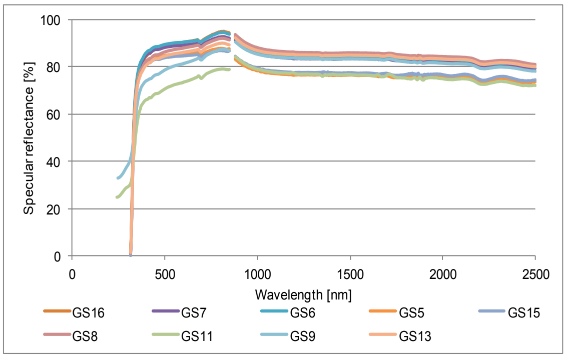

Figure 12. Specular reflectance of glass samples after non-contact washing

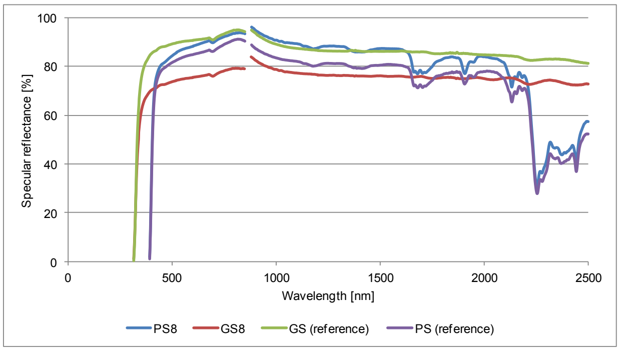

Figure 13. Specular reflectance of soiled samples before non-contact washing

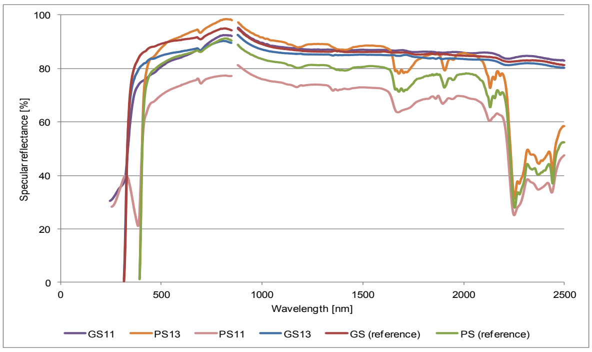

Figure 14. Specular reflectance of samples coated for self-cleaning and anti-soiling

4. Conclusions and further work

The total reflectance of both glass and polymer film mirrors showed no degradation following contact brush cleaning in the presence of spherical silica, angular alumina and dust particle contaminants. The polymer thin film mirror exhibited slightly higher reflectance compared to glass in the visible and NIR bands. The spectral analysis demonstrated the robustness of the polymer mirrors with little impact on their reflective property after the contact cleaning process. The effect of soiling due to dust accumulation on mirror surface has significant effect on reflectivity causing more than 10% reduction in intensity in the visible band for both glass and polymer films. However, the mirrors having self-cleaning and anti-soiling coatings on top showed no significant change in spectral response when subjected to non-contact high pressure water jet cleaning in presence of particle contaminants.

The results shown in the previous section demonstrate the potential for replacing glass with silvered polymer film for use in CSP configurations. From a consideration of the surface topography, the relevant optical properties, the behavior under standard cleaning regimes, and the suitability for enhancement using anti-soiling and self-cleaning coatings, the alternative polymer film solar reflectors performed well in comparison with the standard glass surfaces.

This paper has set out to establish the potential to replace glass reflecting surfaces with polymer film collectors in CSP applications. Whilst clearly there is much further work to verify the detailed performance of polymer film under operating conditions, it is clear that the latest generation of polymer films offer huge potential benefits, and can be further enhanced by the addition of anti-soiling or self-cleaning layers.

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