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Silicone-based thickness insensitive spectrally selective (TISS) paints as selective paint coatings for coloured solar absorbers (Part I)

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Abstract

The objective of this study was to make paints having a variety of colours and whose spectral selectivity would be independent of the thickness of the deposited layer of paint (thickness insensitive spectrally selective (TISS) paint coatings). TISS paint coatings combine the advantages of paints (longevity and chemical resistance achieved by a high thickness of the applied layer, variety of colours and simple application) with spectral selectivity. Low emittance is attained by the addition of bare aluminium, coloured aluminium flake pigments or copper flake pigments, while other inorganic pigments impart various colours to the paints. Pigments were dispersed in silicone resin binder imparting the TISS paint coatings high-temperature tolerance, excellent adhesion, uv resistance, flexibility and weather-durability, which make them suitable coatings for coloured glazed or unglazed solar absorbers.

Keywords: Spectral selectivity; Coloured paints; Silicone; Façade solar absorbers

1. Introduction

Black paints represent the oldest coating material [1–3] for making solar absorbers, but in the course of time they have been gradually driven out of use and replaced with coatings prepared by other more sophisticated deposition methods such as reactive sputtering, vacuum evaporation, electrochemical deposition and spraying of colloidal solutions combined with post-treatment. The main reason for abandoning research of paints lies in the fact that the light-to-heat transformation efficiency of solar collectors with black painted absorbers drops profoundly at higher operating temperatures; due to their high (~0.9–0.94) thermal emittance (e_T) the corresponding thermal radiation losses are not suppressed as they are in the case of thin absorbing layers deposited on a metal substrate obtained by one of the techniques mentioned above. The latter coatings—known as thickness sensitive spectrally selective (TSSS) coatings—combine absorption in the solar range with high transmission in the thermal infrared (TIR), while the low-emitting (i.e. metal) substrate ensures low thermal radiation losses. TSSS coatings, mostly based on black inorganic oxide, dominate the market at the moment. They represent the best choice for production of highly efficient glazed and vacuum-type solar collector systems. Typical examples are sputtered evaporated titanium oxi-nitride and electroplated chromium oxi-nitride.

TSSS coatings made of black paint have already been reported in 1976 by Mar et al. [2]. During the following 20 years, black paints suitable for sprayed [4,5] and coil-coated [6,7] TSSS absorbers have been developed. The coil-coated black solar absorber typically exhibits a solar absorptance (a_s) of 0.90 and a thermal emittance (e_T) in the range 0.25–0.30, depending on the paint layer thickness (1–2 μm). Only aluminium was used as substrate.

TSSS sputtered and coil-coated paint coatings have certain disadvantages. They are thin and therefore vulnerable to

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mechanical tearing, can be easily abraded, require careful handling and are not cheap. Their spectral selectivity depends on the thermal emittance of the metal substrate. For this reason, they are not suitable for plastic absorbers, important for future utilization of solar collector systems mainly on behalf of expected decreased production costs. Among metal substrates copper is preferred ($e_T = 0.03$), while stainless steel reach thermal emittance of about 0.14–0.16. This also limits the use of mild steel protected with corrosion resistance alloys (Zn and Al based). In addition, sufficient corrosion resistance of sputtered or coil-coated TSSS paint coatings could not be achieved for unglazed collectors. Particularly, in saline environments sputtered coatings degrade fast and their use in solar collectors without cover glass is not recommended. To a lesser extent this also holds for coil-coated TSSS paint absorbers. However, the most limiting property of all kinds of TSSS coatings lies in the fact that they are usually black or exhibit some dark shade of blue. As such they are not appropriate for façade absorbers. Accordingly, new solutions are needed before building façades will be widely used for photo-thermal conversion of solar radiation.

It is generally accepted [8–13], that colours other than black are desired, even if a lower efficiency would have to be accepted. Various approaches, other than coloured paint coatings have already been attempted. Recently, Schüeler et al. [9] suggested cover glass, coated with a thin multi-layered coating (i.e. TiO_2, SiO_2), also combination with an additional antireflective layer. The results are promising because the overall solar transmittance is above 70% and the reflectivity peaks are well-distinct in the visible range. The colour of the interference coatings is angularly dependent, which might be attractive for certain applications.

TSSS paint coatings have already been considered as an alternative way of achieving different colours of glazed absorbers. First attempts date back to 1996 [10,11]. More recent studies done on the same TSSS paint coatings revealed [12,13] that to achieve relatively high colour strengths, expressed by metric chroma values (C^*) higher than 12, the coating thickness must be at least in the range 2–4 μm. But paint coatings having such a thickness are poorly selective, showing e_T between 0.45 and 0.55 and rather low solar absorptance values (0.55–0.70). Lower e_T value can be obtained with a thinner layer of paint but then the coating becomes a pale colour and the a_s values decrease as well. The addition of black pigment might be a solution, but its addition simultaneously decreases the colour of the coating and the chroma values falls to $C^* = 5$–7. Obviously, the spectral selectivity of coloured TSSS paints is unsatisfactory for unglazed solar absorbers. In this regard coloured absorbers painted with thick layers of spectrally non-selective blue (typical of Cycladic Island) and red paints represent a better but also not satisfactory option [14].

The objective of this study was to make paints having a variety of colours and spectral selectivity independent of the thickness of the deposited layer (TISS paint coatings). Such coatings would combine the advantages of paints (longevity, chemical resistance achieved by a high thickness of the applied layer, variety of colours, simple application) with spectral selectivity. TISS paint coatings attained low emittance by the addition of metallic particles (aluminium or copper flakes), while other inorganic pigments impart them various colours. This idea was reported first in 1979 by McKinley and Zimmer [15] and Telkes [16] the former reporting e_T as low as 0.3. Hoeflaak and Gerrit [17] investigated the paint consisted of a black pigment, a resin binder and low-emitting aluminium (LE_T) flakes, which take over the role of the low-emitting metal substrate in TSSS coatings. The spectral selectivity of the black coloured paint was moderate with $a_s = 0.84$–0.90 and $e_T = 0.41$–0.47.

The idea of achieving spectrally selective paints of various colours by adding low-emitting metal flakes to ordinary paints has been extensively tested during the last few years in our laboratory in the framework of EU projects [18–20]. Expectedly, the added aluminium flakes lightened the initial colour of the pigmented paints, decreasing their a_s values to ~0.80, but at the same time the e_T did not decrease below 0.55 [21]. A certain improvement was attained by using effect pigments (BASF, Paliogen, etc.) [22] characterized by intense interference colours achieved by a thin layer of iron and other metal oxides on the surface of the aluminium flakes. Even the addition of black pigment, although it increased both a_s and e_T, did not improve the spectral selectivity and it remained in the range a_s~0.83 and e_T~0.55.

This paper collates recent information concerning the preparation and optical properties (e_T, a_s, colour coordinates, lightness and metric chroma values) of TISS paints that exhibit spectral selectivity and colour at the same time. We focused here on paints made of silicone resin binder while analogous TISS paints made of polyurethane binder are reported in Part II. The selection of blue, green and red colours with regard to their spectral selectivity was made by means of performance criteria, an efficiency formula ((Eqs. (1) and (2))—see Experimental section), in which the loss of a_s and the increase of e_T due to the colour were appropriately taken into account [18–20].

We avoided any mathematical modelling of our pigment/resin binder dispersions because TISS paints are too complex system and their complete theoretical treatment in the middle (2.5–25 μmm, MIR) infrared spectral region has not yet been performed. Regarding this point, we would like to call attention to the fact that TISS paint coatings are in many aspects similar to effect coatings exhibiting special optical effects, such as colour and lightness (L^* in CIELAB system [23]) that are angularly dependent. The exact treatment of the optical properties of effect coatings has been reported by Germer and Nadal [24] and was applied by Sung et al. [25] to calculate the angle resolved reflectance and the orientation distribution of metal flakes. Another approach reported by Klanjšek Gunde and Kunaver [26]