The Effects of Using Some Common White Pigments on Thermal and Aesthetic Performances of Pigmented Coatings *

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Abstract
A coated surface with high reflectance in the near infrared (NIR) region and low reflectance in the visible (VIS) region can both stay cool in the sun and retain its appearance by reducing the glare of reflected sunlight. To design such coatings, an optimization method that embraces both thermal and aesthetic effects is introduced. White pigments are widely used in designing cool coatings due to their relatively high reflectance of sunlight. However, using white pigments may produce glare, which can cause visual discomfort. It is possible to control these effects by controlling the size of pigment particles, volume concentration of pigments and coating thickness. Among the various white pigments that are available, we chose titanium dioxide, zinc oxide and alumina for this study. Radiative heat transfer in an anisotropic scattering, monodisperse pigmented layer was analyzed using the radiation element method by ray emission model (REM²). Both collimated and diffuse solar irradiations were considered. The CIE (International Commission on Illumination) colorimetric system was used for color analysis. Finally, the optimum values of particle size, volume fraction of pigment, and coating thickness were obtained and compared for the three mentioned pigments.

Key words: Pigmented Coatings, White Pigments, Thermal Performance, Aesthetic Performance

1. Introduction

Dark tones, such as black, are used abundantly on exteriors, either from an aesthetic viewpoint or to make dirt harder to see. However, since the absorption of sunlight by dark surfaces is high, dark rooms get warmer than white rooms in the summer, thus increasing cooling loads. On the other hand, when white paint, which strongly reflects both VIS and NIR radiation, is applied to exterior surfaces such as roofs, those surfaces absorb less sun and relatively reduce the cooling load. For a clean, smooth and solar-opaque white surface which strongly reflects both visible and NIR radiation, solar reflectance can reach about 85% (1). This is the coolest type of roofing surface but it is only ideal for low-slope roofs visible neither from ground level nor from taller buildings (1), because the high reflectance of visible light (VIS) will produce glare that can offend the eye and make the object less visually appealing.

Many studies in designing temperature-moderating coatings have been focused on achieving high reflectance across the NIR or whole solar spectrum without consideration of aesthetic effects. Johnson et al. (2) optimized the grain size distribution of zinc oxide pigment...
in a thermal control coating (TCC) used for spacecraft walls in order to maximize the diffuse solar reflectance at a lower film thickness, and reduce the pigment volume concentration. Moreover, Vargas (3) considered thermal optimization of particle diameter and volume fraction, paying attention to the radiation characteristics of particles group and diffuse reflectance of titanium dioxide pigmented coating. Dombrovsky et al. (4) studied the infrared radiative properties of a polymer containing hollow glass microspheres used for the development of heat-insulating coatings to reduce nighttime heat loss from the walls of buildings. Solar-reflective nonwhite surfaces and their applications to residential roofing materials were studied by Levinson et al. (5).

In this study we address two subjects simultaneously: increasing the NIR reflectance to minimize the heat gain into interiors from walls subject to solar radiation, roofs and car bodies, and decreasing glare to improve aesthetic appeal. To satisfy both conditions, using pigmented coatings with selective spectral reflectance against solar irradiation is required. Approximately 53% of sunlight energy is NIR light (6), and it is possible to sharply reduce sunlight absorption of outer walls by reflecting this light. Although the ultraviolet (UV) rays in sunlight account for about 5% of solar energy (6), they destroy the molecular bonds in organic matter, such as plastic, and this degrades the paint film (7). In addition, when sunlight is strong, air conditioning becomes more efficient by the transmission of long-wavelength infrared (IR) rays with a wavelength of about 10 µm emitted from the body surface of a building, car, etc. Based on these facts, our target coating would reflect UV and NIR radiation well, decrease the reflectance of VIS radiation, and transmit long-wavelength infrared radiation, which is equivalent to high reflectance in this region as shown in Fig. 1.

Fig.1 Schematic diagram of a pigmented coating using nanoparticles to maximize the reflectance of the UV and NIR regions of sunlight, minimize the reflectance of the VIS region, and transmit IR wavelengths.

The spectral reflectance of a pigmented coating strongly depends on the amount of absorption and/or back-scattering of light by suspended pigment particles (5). The radiative properties of pigment particles such as scattering and absorption efficiencies can be controlled by controlling the particle size. To find the optimum characteristics of a pigmented coating (e.g. particle size, volume fraction of pigment particles and film thickness), we defined our optimization parameter as the ratio of reflected sunlight in the NIR region to that in the VIS region weighted by spectral eye sensitivity. When the optimization parameter is maximized, the resultant coating will have high reflectance of the NIR region and low reflectance of the VIS region. Here, we focused on white pigments, selecting titanium dioxide (TiO₂), aluminum oxide (Al₂O₃), and zinc oxide (ZnO) for this study. Although in reality powders of different-size particles are formed, in this paper we assumed monodisperse particles, to more directly compare the performance of different pigments.

To calculate the radiative properties of particles, Mie scattering theory by the ratio method (8) was used and databases for radiative properties were constructed. In order to find
the reflectance of the coated system against solar direct and diffuse irradiation, we conducted a radiation thermal analysis using the radiation element method by ray emission model (REM2) \(^9\). The CIE colorimetric system was used for color analysis to yield the color coordinates for the chromaticity diagram and the amount of luminance (or brightness). The effects of particle diameter, volume fraction and film thickness on the optimization parameter and color coordinates are discussed and compared for titanium dioxide, zinc oxide and aluminum oxide pigmented coatings.

2. Radiative properties of single particles of TiO\(_2\), ZnO and Al\(_2\)O\(_3\)

The radiative properties of a single homogeneous spherical particle in a nonabsorbing medium can be obtained using Mie theory. These properties depend on the particle diameter \(d_p\), the wavelength of the incident electromagnetic wave \(\lambda\), and the complex refractive index of the particle \(m=n-ik\). To perform the Mie calculation, the ratio method devised by Wang and Hulst \(^8\) is used because it can be applied over a wide range of size parameters with good accuracy. Using this method, Mie computations are feasible up to at least \(x=50000\), where \(x=\pi d_p \lambda\). In the Rayleigh region where \(x\) is very small, this method can be applied down to \(x=10^{-5}\).

Databases for the radiative properties are constructed over wide ranges of particle diameters in the solar spectrum (0.3-2.6 µm) based on rigorous Mie theory. The scattering angle between 0 and \(\pi\) is divided into 3000 logarithmically equal intervals. The complex refractive indexes for titanium dioxide and alumina were taken from Ref. \(^10\) and that for zinc oxide from Refs. \(^11\) and \(^12\). The diameter range is 10 nm-500 µm and is composed of 1000 data points set to equal intervals with a logarithmic scale. The medium is assumed to be non-absorbing acrylic resin with a refractive index equal to 1.5. The radiative properties of particles can be obtained by interpolating the database values \(^13\). As mentioned before, absorption and back-scattering efficiencies of suspended particles are two important parameters that affect the performance of pigmented coating. The peak of absorption of TiO\(_2\) and ZnO in the solar spectrum falls in the UV region. Thus, these two pigments are good absorbers of UV wavelengths but they are nonabsorbing in the VIS and NIR regions. However, alumina is nonabsorbing across the entire solar spectrum. By these explanations it is obvious that the back-scattering efficiency plays the most important role in the performance of these coatings. The back-scattering efficiency is related to the scattering efficiency and the asymmetry parameter as follows

\[
Q_{\text{back,scat}} = \frac{1-g}{2} Q_{\text{scat}}
\]

where \(g\) is the asymmetry parameter, defined as

\[
g = \frac{1}{2} \int_{-1}^{1} \varphi(\mu) \mu d\mu
\]

Figure 3 shows the variation of scattering efficiency \((Q_s)\) and asymmetry parameter \((g)\) with respect to particles size for single TiO\(_2\), ZnO and Al\(_2\)O\(_3\) particles. For small TiO\(_2\) particles, the peak scattering efficiency is in the UV region. However, as can be seen in Fig. 3(a), as the size of particle increases, the scattering efficiency peak moves toward the VIS and NIR wavelength.

The maximum value of the scattering efficiency, as our calculations show, is 5.37 at \(\lambda=0.42\) µm when \(d_p=0.178\) µm. For large particles, the scattering efficiency converges to its
Fig. 2 Real (solid lines) and imaginary (dashed lines) parts of the complex refractive index of TiO$_2$, ZnO and Al$_2$O$_3$.

Asymptotic value of 2 in the VIS and NIR regions. Fig. 3(a) also shows the asymmetry parameter of titanium dioxide. As this figure indicates, $g$ does not become negative in the solar wavelength range (0.3–2.6 $\mu$m), which means that titanium dioxide is a forward-scattering medium against solar irradiation. As can be clearly understood from this figure, forward scattering is strong for large size parameters and the scattering approaches isotropism ($a_1 \to 0$) when the size parameter decreases.

The same behavior is seen in the scattering efficiency and asymmetry factor of ZnO particles as shown in Fig. 3(b). However, due to the difference in refractive index of these two pigments, shown in Fig. 2, the scattering efficiency of ZnO is smaller than that for TiO$_2$ particles. The maximum value of scattering efficiency cannot exceed 4 for ZnO particles. But the asymmetry parameter is larger for ZnO particles than for similar-size TiO$_2$ particles.

As mentioned before, Al$_2$O$_3$ is a nonabsorbing pigment with an almost uniform refractive index (1.72–1.82) across the entire solar spectrum as shown in Fig. 2. Thus, as expected, more regular behaviors can be seen in the radiative properties of Al$_2$O$_3$ as shown in Fig. 3(c). The value of the scattering efficiency is smaller for Al$_2$O$_3$ particles in comparison with TiO$_2$ and ZnO particles except in the UV region with moderate particle diameters. The maximum value of the scattering efficiency for Al$_2$O$_3$ pigment is 3.6.

3. Optimization parameter and color coordinates

The performance parameter of pigmented coating for solar heat rejection in the NIR region is proposed as

$$\rho_{\text{NIR}} = \frac{\int_{0.78}^{2.6} \rho(\lambda) I(\lambda) d\lambda}{\int_{0.78}^{2.6} I(\lambda) d\lambda}$$  \hspace{1cm} (3)$$

where $I(\lambda)$ is the solar irradiation and $\rho(\lambda)$ is the spectral reflection of the pigmented coating. A new parameter which can evaluate the aesthetic performance of a pigmented coating by considering spectral eye sensitivity is defined as follows:

$$\rho_{\text{VIS}} = \frac{\int_{0.38}^{0.78} \rho(\lambda) \eta(\lambda) I(\lambda) d\lambda}{\int_{0.38}^{0.78} I(\lambda) d\lambda}$$  \hspace{1cm} (4)$$
Here, $\eta(\lambda)$ is the normalized standard luminous efficiency. As mentioned in the introduction, we are looking for an optimum coating design which reflects NIR wavelengths as much as possible and simultaneously decreases the energy received by the human eye. To satisfy these requirements, the optimization parameter is proposed as

$$R = \frac{\rho_{NIR}}{\rho_{VIS}}$$  \hspace{1cm} (5)

In order to optimize the coating, the parameter $R$ should be maximized.

The CIE (International Commission on Illumination) colorimetric system is used for color analysis to yield the three tristimulus values which become the chromaticity coordinates for normal vision. They are found from the following convolution integrals (14):

$$X = \frac{1}{k} \int_{380}^{780} I(\lambda) \rho(\lambda) \bar{R}(\lambda) d\lambda, \hspace{1cm} (6)$$

$$Y = \frac{1}{k} \int_{380}^{780} I(\lambda) \rho(\lambda) \bar{G}(\lambda) d\lambda, \hspace{1cm} (7)$$

$$Z = \frac{1}{k} \int_{380}^{780} I(\lambda) \rho(\lambda) \bar{B}(\lambda) d\lambda. \hspace{1cm} (8)$$
The normalized color coordinates are calculated as follows:

\[ \begin{align*}
    x &= \frac{X}{X+Y+Z}, \\
    y &= \frac{Y}{X+Y+Z}, \\
    z &= \frac{Z}{X+Y+Z}
\end{align*} \] (9)

Finally, the color of a reflective object is expressed with brightness \( Y \) and a chromaticity coordinate \( (x,y) \). This system allows the representation of a color on a two-dimensional chromaticity diagram.

4. Numerical Simulation by REM²

We consider the participating medium in a plane parallel system. The spectral radiation intensity \( I_{\lambda} \) at \( \vec{r} \) in the direction of \( \hat{s} \) can be expressed as follows (9):

\[
\frac{dI_{\lambda}(\vec{r},\hat{s})}{ds} = \beta_{\lambda} \left[ -I_{\lambda}(\vec{r},\hat{s}) + (1 - \omega_{\lambda}) I_{\lambda}(\vec{r}) + \frac{\omega_{\lambda}}{4\pi} \int_{4\pi} I_{\lambda}(\vec{r},\hat{s}') \Phi_{\lambda}(\hat{s}' \rightarrow \hat{s}) d\Omega' \right]
\] (10)

where \( \beta_{\lambda} \) and \( \omega_{\lambda} \) are the spectral extinction coefficient and single scattering albedo, respectively. Here, \( s \) is the path length in the direction \( \hat{s} \), and \( \Phi(\hat{s}' \rightarrow \hat{s}) \) is the phase function from \( \hat{s}' \) to \( \hat{s} \). Assuming the independent scattering, for a group of monodisperse particles the scattering and absorption coefficients can be calculated using the following equations:

\[
\sigma_{\lambda} = N \frac{n d^2}{4} Q_{\text{ sca},\lambda}
\] (11)

\[
\kappa_{\lambda} = N \frac{n d^2}{4} Q_{\text{ abs},\lambda}
\] (12)

where \( Q_{\text{ sca}} \) and \( Q_{\text{ abs}} \) are scattering efficiency and absorption efficiency obtained from Mie calculation in Sec. 2 and \( N \) is number density of particles.

To solve this equation Maruyama et al. proposed the radiation element method by ray emission model (9). They introduced the effective radiation area for both the surface and volume elements in the same manner. They also defined the extinction view factor \( F_{\text{E},i,j} \) as the fraction of energy radiated from radiation element \( i \) that is absorbed, isotropically scattered or diffusely reflected by radiation element \( j \). Once the extinction view factors have been obtained, the absorption view factors \( F_{\text{A},i,j} \) and diffuse scattering view factor \( F_{\text{D},i,j} \) can be written as:

\[
\begin{align*}
    F_{\text{E},i,j,\lambda} &= \frac{E_{j,\lambda}}{1 - \omega_{j,\lambda}^{\text{S}}} F_{\text{E},i,j,\lambda} \\
    F_{\text{D},i,j,\lambda} &= \frac{\omega_{j,\lambda}^{\text{D}}}{1 - \omega_{j,\lambda}^{\text{S}}} F_{\text{E},i,j,\lambda}
\end{align*}
\] (13)

where \( E_{j,\lambda} = 1 - \omega_{j,\lambda}^{\text{D}} - \omega_{j,\lambda}^{\text{S}} \) is the emissivity, \( \omega_{j,\lambda}^{\text{D}} \) is the diffuse reflectance of the surface elements or the albedo of participating media elements and \( \omega_{j,\lambda}^{\text{S}} \) is the specular reflectance of the surface elements. By introducing these coefficients, the radiative heat transfer under arbitrary thermal conditions can be determined for each participating radiation element and boundary surface. For a system consisting of \( N \) radiation elements, one can write:
\[ Q_{J,I,\lambda} = Q_{T,I,\lambda} + \sum_{j=1}^{N} F_{D}^{j} Q_{J,j,\lambda} \]  
(14)

\[ Q_{X,I,\lambda} = Q_{T,I,\lambda} - \sum_{j=1}^{N} F_{A}^{j} Q_{J,j,\lambda} \]  
(15)

where \( Q_T \) is emissive power and \( Q_J \) is the radiative energy emitted and isotropically scattered by the radiation element. The unknown \( Q_{X,I} \) can be obtained by solving Eqs. (14) and (15). The relationship between \( q_{X,I} \) and \( Q_{X,I,\lambda} \) is obtained by

\[ Q_{X,j} = \int_{0}^{c} Q_{X,j,\lambda} d\lambda \]  
(16)

\[ q_{X,j} = \frac{Q_{X,j}}{\Delta x} \]  
(17)

REM² has been used in several fields, e.g. in analyses of radiative heat transfer in clouds (15), solar collectors (16)-(19), fog layers (20), industrial equipment (21) and polydisperse water particles (13). One of the important characteristics of REM² is that both diffuse and collimated irradiations can be applied at the boundaries, enabling us to analyze coating problems illuminated by both collimated and diffuse light from the sun. In addition, this method lacks the difficulties of approximation methods like two-flux (1)-(4), three-flux and four-flux methods (22)-(23).

5. Analysis model and boundary conditions

To model a pigmented coating system, a one-dimensional parallel plane system was considered. Figure 4 shows the analysis model and boundary conditions. The thin film is divided into 100 elements. Elements 1 and \( N \) are taken as boundary elements. Sij2 approximation of Fiveland is used for direction division (24). The temperature of each element is assumed to be the laboratory temperature and presupposed to be fixed at 293.15 K. Moreover, collimated solar irradiation enters from element \( N+1 \) with an incident angle of \( \theta_0 = 21.54^\circ \), which means that the air mass is equal to 1.0. Diffuse solar irradiation enters from element 1. Bird’s model (25) is utilized for spectral solar irradiation. The refractive indices of air (1) and 1.5 of acrylics resin (1.5) are assumed for the boundary element 1 and volume elements. Here, in element 1, specular reflection is produced by the difference between the refractive indices. The specular reflectance is calculated with Fresnel’s equation (24) using the value of the refractive indices mentioned above. The substrate is assumed to be a black body.

Since the matrix is nonabsorbing, instead of considering the effects of film thickness and volume fraction separately, we defined a new parameter, ‘\( b \)’, as the product of these two parameters

\[ b = f_v \times t \]  
(18)

where \( t \) is the film thickness and \( f_v \) is the volume fraction of pigment particles. As discussed in (24), independent scattering is a good assumption for nearly all heat transfer application including paints and pigments and dependent scattering effects can be ignored when \( f_v < 0.006 \) or \( c/\lambda > 0.5 \), where \( c \) is the clearance. Next we investigated the effect of the new parameter on the performance of a pigmented coating. Parameter ‘\( b \)’ was set to change between 0.01-10 \( \mu \)m. The radiation characteristic of particles could be obtained at high speed by using the databases.
6. Results and discussion

One of the objects of this article is to compare the effects of different pigment particle types and size on spectral reflectance in the solar spectrum. Figure 5 shows the hemispherical spectral reflectance of different sizes of TiO$_2$, ZnO and Al$_2$O$_3$ pigment particles when parameter $b$ is set to 1.25 µm. First, the sudden change observed in the spectral reflectance of TiO$_2$ and ZnO is due to the sudden change in the radiative properties of these pigments near the bluish wavelengths of the VIS region. While the UV reflectance can’t exceed 10% for these two pigments, Al$_2$O$_3$ pigment particles can reflect about 59% of UV light when $d_p=0.515$ µm. As the comparisons show, TiO$_2$ pigment reflects more sunlight than ZnO and Al$_2$O$_3$ pigments with the same volume fraction and film thickness. For example, while the maximum solar reflectance is about 64.7% for a TiO$_2$ pigmented coating with $d_p=0.345$ µm, this value is 42.1% for ZnO and only 31.2% for an Al$_2$O$_3$ pigmented coating with particle diameters of about $d_p=0.752$ µm and $d_p=0.876$ µm, respectively. However in this paper, according to our objectives, we do not focus on the total solar reflectance.

![Fig.4 Analysis of a pigmented coating using REM with related boundary conditions]
Fig. 5 Spectral hemispherical reflectance of (a) TiO$_2$, (b) ZnO and (c) Al$_2$O$_3$ pigmented coatings for different particles sizes when $b=1$ µm. (U, UV reflectance; V, VIS reflectance; N, NIR reflectance; S, solar reflectance)

A comparison between the VIS and NIR reflectance in Fig. 5 shows that for small pigment particles the reflectance of the VIS part is much higher than that for the NIR region. However, when the size of particles increases, the difference between the reflectances of these regions decreases; even for largish particles, the reflectance in the NIR region exceeds the reflectance in the VIS part. As Eqs. (3)-(5) show, the optimum particle diameter will be in this domain.

The color coordinates and brightness related to those particles whose reflectances are shown in Fig. 5 and discussed above, are tabulated in Table 1. Also, the color coordinates are plotted on the chromaticity diagram of Fig. 6. As seen in this figure, TiO$_2$ and Al$_2$O$_3$ pigments produce a bluish-white to white color while ZnO pigment exhibits a yellowish-white to white color depending on the pigment particle size. A comparison between the brightness of different pigments in Table 1 shows that for the same volume fraction and film thickness, the glare produced by the TiO$_2$ pigment is much higher than those for the ZnO and Al$_2$O$_3$ pigments. For example, when parameter $b$ is 1 µm, the maximum brightness value is about 87% for TiO$_2$ pigmented coating, about 63% for ZnO and only 41% for Al$_2$O$_3$. Typical pigment particles used in designed pigmented coatings have an average size of from 0.05 to 0.25 µm. As our results show, white coatings pigmented with particles in this range of size represent very high brightness or glare, which is unpleasant to the human eye.
Fig. 6 Color coordinates of pigmented coatings whose reflectances are shown in Figure 5

Table 1: Color coordinates \((x, y)\) and brightness \((Y)\) of pigmented coatings whose reflectances are shown in Figure 5.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>(x)-coordinate</th>
<th>(y)-coordinate</th>
<th>Brightness ((Y)) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium dioxide</td>
<td>(a) 0.282134</td>
<td>(b) 0.322193</td>
<td>59.8</td>
</tr>
<tr>
<td></td>
<td>(c) 0.329423</td>
<td>(d) 0.32994</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>(e) 0.324158</td>
<td></td>
<td>54.9</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>(a) 0.319369</td>
<td>(b) 0.342367</td>
<td>56.4</td>
</tr>
<tr>
<td></td>
<td>(c) 0.361506</td>
<td>(d) 0.369167</td>
<td>63.8</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>(a) 0.291744</td>
<td>(b) 0.304168</td>
<td>56.4</td>
</tr>
<tr>
<td></td>
<td>(c) 0.323184</td>
<td>(d) 0.332134</td>
<td>63.8</td>
</tr>
</tbody>
</table>

Figure 7 compares the effect of particle size on the optimization parameter for each of the three pigments when parameter \(b\) is 1 \(\mu\)m. As seen in this figure, the optimization parameter is very sensitive to the size of particles. For very small particles, the optimization parameter has an asymptotic value of about 3, independent of the pigment type. Then, by increasing the particle size, the optimization parameter decreases due to the quick increase in the reflectance of the VIS region as seen in Fig. 5. The minimum values of parameter \(R\) for TiO\(_2\), ZnO and Al\(_2\)O\(_3\) pigments are 0.5, 0.7 and 1.2 at particle diameters of about 0.8, 0.15 and 0.3 \(\mu\)m, respectively. These particles sizes operate exactly in the opposite way that we want. For typical white pigments as shown in Fig. 7, the optimization parameter is very small and near the minimum point. Further increases in the particle diameter increase parameter \(R\) to its maximum level due to the decrease in the VIS reflectance and the increase in NIR reflectance. The optimization parameter again assumes an asymptotic value of 3 for very large particles independent of pigment type. Thus, for each value of parameter \(b\), there is an optimum particle size at which a maximum \(R\) occurs. Figure 8 shows these maximum points versus parameter \(b\) for different pigments. As shown in this figure, the maximum value of parameter \(R\) for Al\(_2\)O\(_3\), TiO\(_2\) and ZnO is 4.403, 4.278 and 4.031 with optimum particle diameters of about 2.5, 1.39 and 0.778 \(\mu\)m, respectively. The related optimum value of parameter ‘\(b\)’ and other properties of the optimized coating with each pigment are shown in Table 2. The spectral reflectances for the optimum design for each pigment are shown in Fig. 9. The observed behavior in the reflectance of the VIS region for Al\(_2\)O\(_3\) is interesting because the reflectance is the least at \(\lambda=0.55\) \(\mu\)m, where the human eye...
sensitivity is the greatest. A comparison between the maximum value of $R$ for $\text{Al}_2\text{O}_3$ pigment and $R$ for a gray surface (i.e., 3.4) shows that using a coating with this pigment at the optimum state can increase the optimization parameter by 30%. For $\text{TiO}_2$ and $\text{ZnO}$ this value becomes 26% and 18%. However, a comparison between the maximum value of the optimization parameter and the related value for typical white pigments shows a 4–8 fold increase in parameter $R$ when particles with optimum size determined according to our design method are used.

Table 2: Properties of optimized $\text{TiO}_2$, $\text{ZnO}$ and $\text{Al}_2\text{O}_3$ pigmented coatings.

<table>
<thead>
<tr>
<th></th>
<th>$\text{Al}_2\text{O}_3$</th>
<th>$\text{TiO}_2$</th>
<th>$\text{ZnO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{max}}$</td>
<td>4.479</td>
<td>4.278</td>
<td>4.031</td>
</tr>
<tr>
<td>$d_{\text{opt}}$ (µm)</td>
<td>2.560</td>
<td>0.778</td>
<td>1.395</td>
</tr>
<tr>
<td>$b$ (µm)</td>
<td>1.25</td>
<td>0.27</td>
<td>0.70</td>
</tr>
<tr>
<td>$\rho_{\text{NIR}}$ [%]</td>
<td>26.25</td>
<td>27.89</td>
<td>21.89</td>
</tr>
<tr>
<td>$\rho_{\text{VIS}}$ [%]</td>
<td>5.861</td>
<td>6.53</td>
<td>5.43</td>
</tr>
<tr>
<td>Total Ref. [%]</td>
<td>24.17</td>
<td>23.86</td>
<td>19.25</td>
</tr>
<tr>
<td>Brightness (Y) [%]</td>
<td>16.11</td>
<td>19.86</td>
<td>20.28</td>
</tr>
</tbody>
</table>
Fig. 9 Comparison between the hemispherical spectral reflectance of optimized TiO$_2$, ZnO and Al$_2$O$_3$ pigmented coatings.

The results show that using these optimum coatings on a black surface will increase the brightness only between 16 to 20%. Besides this decrease in brightness in comparison with coatings designed without considering the glare effect, using these pigments at optimum particle size, volume fraction and film thickness obtained according to our design method can reflect 20-25% of NIR light. This means that for these pigments the decrease in VIS reflectance is accompanied with a decrease in NIR reflectance. Thus, one can conclude that Al$_2$O$_3$, TiO$_2$, ZnO and other similar pigments, even at optimum particle size, display a spectral reflectance against solar irradiation which is not in accord with the target behavior.

7. Summary

A new optimization method for use in the design of pigmented coatings considering both thermal and aesthetic requirements by maximizing the ratio of NIR to VIS reflectance was introduced. Radiative heat transfer in an anisotropic-scattering, monodisperse pigmented layer was analyzed using the radiation element method by ray emission model (REM$^3$). The CIE (International Commission on Illumination) colorimetric system was used for color analysis. The effects of three different types of white pigment particles, Al$_2$O$_3$, TiO$_2$ and ZnO, on the performance of the pigmented layer were examined. The findings of this study are:

1- The optimum size of pigment particles is about 0.778, 1.39 and 2.5 µm for TiO$_2$, ZnO and Al$_2$O$_3$, respectively.
2- Using Al$_2$O$_3$, TiO$_2$ or ZnO pigments in the optimum conditions will increase the optimization parameter by about 30%, 26% and 18% relative to a gray surface, respectively.
3- Using pigment particles with optimum size determined according to our design method will increase the optimization parameter 4–8 fold relative to typical size of white pigments.
4- Using these optimized pigmented coatings on a black substrate will increase the luminance only 16–20%.
5- Beside this decrease in brightness compared with typical white coatings designed without considering the glare effects, coatings optimized by our method can reflect 20-25% of NIR light.
References


