Effect of polarization to directional surface color measurement

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Abstract

The colorimeter of 45:0 and 0:45 geometry conditions are usually utilized for color measurement of samples such as automotive parts, plastics, paint, raw materials, and packaging. The measurement result of this kind directional colorimeter is easy affected by polarization property of the measured surface. This paper shows the relationship between polarization and color measurement error. First, a preliminary theoretical analysis of the polarization effect is established basing on the Fresnel reflection equation. Then, an error model of the directional colorimeter is proposed, which include the polarization property of samples. After that, an experiment is taken on the reference colorimetry apparatus of NIM China, and the result verifies the error model. The conclusion shows that the effect of polarization should carefully treated for colorimetry, and designer need to minimize the polarization of colorimeter, and the end user should choose a fit colorimeter according to the characteristic of the test surface.

Introduction

The colorimeter of 45:0 and 0:45 geometry conditions are usually utilized for color measurement of samples such as automotive parts, plastics, paint, raw materials, and packaging.

CIE has established a series of standard illuminations, observers and geometry conditions for the color systems, such as CIEXYZ and CIELAB. According to the spectral color measuring method, the tristimulus values or L*a*b* can be obtained by the diffuse reflectance of the sample. And the measurement result of this kind directional colorimeter is easy affected by polarization property of the measured surface and the color instrument[1]:

$$R' = R_{uu} + P_{uj} P_d R_{uu} \qquad R' = R_{uu} + P_{ju} P_i R_{uu} \tag{1}$$

The equations show that the error of the color instrument is the product of P_d and P_i the polarization factor of instrument, P_{uj} and P_{ju} the polarization factor of sample, and R_{uu} the reflectance of sample. The polarization factor is a fix number for a certain instrument, so this paper mainly discusses the polarization factor of sample, and the principle of polarization.

Optic model of color sample

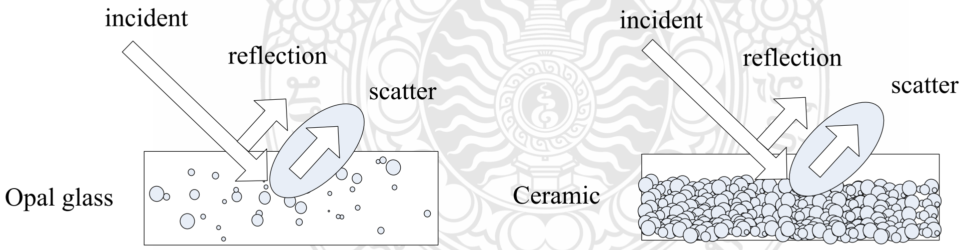
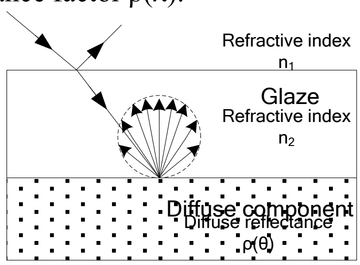


Fig.2 reflection and scatter light of sample

Most of the sample for color calibration is opal glass and ceramic tile. As Fig.2 shows, when the incident light illuminate the sample, the light is reflected and refracted at the front surface of the sample, and then the light into sample is scattered by the material inside. Normally, the first reflection light generates gloss, and the scatter light shows us the color of sample.

So an optic model for discussing the surface color is established. It has two layers, the first layer is the glaze, which has a refractive index n_2, and the second layer is a diffuse component layer, which is assumed as a perfect Lambert diffuser with reflectance factor ρ(λ).



The reflection and refraction at the first surface of glaze layer follow the Fresnel equations:

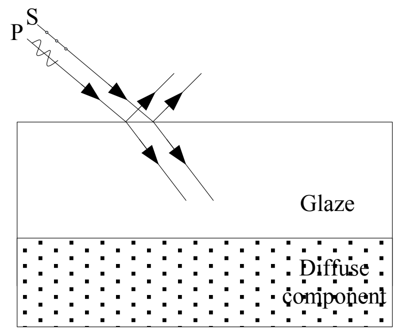


Fig.4 reflection and refraction at the first layer

The reflectance for *s*-polarized light is

$$R_s(\theta_i,n_1,n_2)=\left|\frac{n_1\cos\theta_{\mathrm{i}}-n_2\cos\theta_t}{n_1\cos\theta_{\mathrm{i}}+n_2\cos\theta_t}\right|^2=\left|\frac{n_1\cos\theta_{\mathrm{i}}-n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)}}{n_1\cos\theta_{\mathrm{i}}+n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)}}\right|^2 \tag{2}$$

θ_i is the incident angle. While the reflectance for *p*-polarized light is

$$R_p(\theta_i,n_1,n_2)=\left|\frac{n_1\cos\theta_t-n_2\cos\theta_i}{n_1\cos\theta_t+n_2\cos\theta_i}\right|^2=\left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)}-n_2\cos\theta_{\mathrm{i}}}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)}+n_2\cos\theta_{\mathrm{i}}}\right|^2 \tag{3}$$

So the transmission factor satisfies:

$$\begin{aligned}T_{si}&=T_s(\theta_i,n_1,n_2)=1-R_s(\theta_i,n_1,n_2)\\T_{pi}&=T_p(\theta_i,n_1,n_2)=1-R_p(\theta_i,n_1,n_2)\end{aligned} \tag{4}$$

If flux of the incident light: $\Phi_p=\Phi_s=\Phi/2$, and the absorption of glaze is α, the irradiance of the diffuse component is:

$$E_s=\frac{\Phi_s T_s(\theta_i,n_1,n_2)\alpha}{dS}$$

$$E_p=\frac{\Phi_p T_p(\theta_i,n_1,n_2)\alpha}{dS}$$

Where dS is the illuminated area on the diffuse component

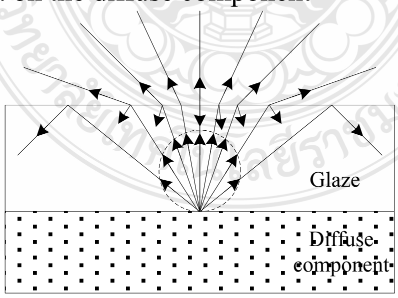


Fig.5 diffuse reflection of the diffuse component and refraction at the glaze layer

As Fig.5 shows, the light is reflected by the diffuse component, and refracted by the out surface of glaze. For the assumption of the diffuse component is a Lambertian surface and a perfect depolarizer, the radiance of the exitance light satisfies:

$$L_{ss}=\frac{\rho E_s}{\pi}T_s(\theta_e,n_1,n_2)=\frac{\rho\alpha\Phi_s T_s(\theta_i,n_1,n_2)}{2\pi dS}T_s(\theta_e,n_1,n_2)=\frac{\rho\alpha\Phi}{4\pi dS}T_{si}T_{se}$$

$$L_{sp}=\frac{\rho\alpha\Phi}{4\pi dS}T_{si}T_{pe},\quad L_{ps}=\frac{\rho\alpha\Phi}{4\pi dS}T_{pi}T_{se},\quad L_{pp}=\frac{\rho\alpha\Phi}{4\pi dS}T_{pi}T_{pe}$$

Where, the subscript of L_{ss} means the input and output polarization state, subscript *i* and *e* indicate the incident beam and exitance beam.

The diffuse reflectance factor of the directional geometry condition can be obtained by measure the ratio of the sample's radiance and the radiance of the reference plate multiplies its calibrated reflectance value, so:

$$R_{ss}=\frac{L_{ss}}{L_{ref}}R_{ref},R_{sp}=\frac{L_{sp}}{L_{ref}}R_{ref},R_{ps}=\frac{L_{ps}}{L_{ref}}R_{ref},R_{pp}=\frac{L_{pp}}{L_{ref}}R_{ref}$$

Hence, the reflectance for the uniform illumination and detection is:

$$R_{us}=\frac{L_{ss}+L_{ps}}{2L_{ref}}R_{ref},R_{su}=\frac{L_{ss}+L_{sp}}{2L_{ref}}R_{ref},R_{up}=\frac{L_{sp}+L_{pp}}{2L_{ref}}R_{ref},R_{pu}=\frac{L_{ps}+L_{pp}}{2L_{ref}}R_{ref} \tag{5}$$

Where, subscript u indicates the uniform polarization illumination or detector.

And the reflectance factor of the sample satisfies:

$$R_{uu}=\frac{L_{ss}+L_{ps}+L_{sp}+L_{pp}}{4L_{ref}}R_{ref}=\frac{\rho\alpha\Phi R_{ref}}{16\pi dSL_{ref}}\left(T_{si}+T_{pi}\right)\left(T_{se}+T_{pe}\right) \tag{6}$$

Eq.4 and 5 shows that the illumination and viewing angle θ have an effect to the reflectance property of the sample by changing the transmission factor, thereby the color result is influenced.

The polarization factor of sample can be defined by [1]:

$$\begin{aligned}P_{ju}&=\frac{R_{su}-R_{pu}}{R_{su}+R_{pu}}=\frac{L_{ss}+L_{sp}-L_{ps}-L_{pp}}{L_{ss}+L_{sp}+L_{ps}+L_{pp}}=\frac{T_{si}(T_{se}+T_{pe})-T_{pi}(T_{se}+T_{pe})}{T_{si}(T_{se}+T_{pe})+T_{pi}(T_{se}+T_{pe})}=\frac{T_{si}-T_{pi}}{T_{si}+T_{pi}}\\P_{uj}&=\frac{R_{us}-R_{up}}{R_{us}+R_{up}}=\frac{L_{ss}+L_{ps}-L_{sp}-L_{pp}}{L_{ss}+L_{ps}+L_{sp}+L_{pp}}=\frac{T_{se}-T_{pe}}{T_{se}+T_{pe}}\end{aligned} \tag{7}$$

where P_{uj} indicate the factor of uniform illumination, and P_{ju} indicates the uniform detection. And they are only affected by the transmit factor of the glaze layer, which is discussed in Eq.4. Hence the polarization factor can be calculated by Fresnel equation, when the light angle and refractive index of the glaze layer is obtained.

Fig.6 shows the data curves of Eq.7.

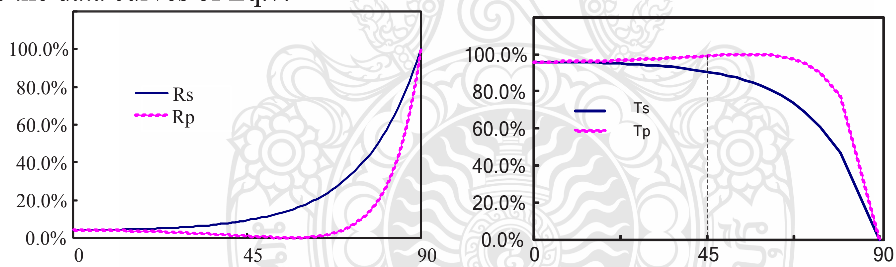


Fig.6 reflection and transmit factor of glaze layer

Experiment

A reflectance colorimetry measurement system of NIM is constructed using scanning spectrometer with array detector, and the color measurement can be achieved under 45:0 and 0:45 geometry conditions[2].

Fig.7 reflectance colorimetry measurement system and No.1 opal glass (left), No.2 high gloss ceramic (mid) and No.3 diffuse ceramic (right)

A polarizer is inserted into the illumination light path, so as to change the polarization state of the sample. And three samples is selected, No.1 opal glass, No.2 high gloss ceramic and No.3 diffuse gloss ceramic.

With opal glass in air, for example, the refractive index is about 1.55 with no anti-reflection coating. Set n_1=1, n_2=1.55, the polarization factor can be obtained for 45:0 (θ_i=45) geometry conditions by Eq.7 :

$$P_{ju-450} = \frac{T_{si45} - T_{pi45}}{T_{si45} + T_{pi45}} = \frac{89.6 - 98.9}{89.6 + 98.9} = -4.9\% \tag{8}$$

And in 0:45 (θ_i=0) geometry conditions, the polarization factor is:

$$P_{ju-045} = \frac{T_{si0} - T_{pi0}}{T_{si0} + T_{pi0}} = \frac{95.3 - 95.3}{95.3 + 95.3} = 0 \tag{9}$$

The comparison between the calculated data from Eq.7 and the measured result is shown in the table below. The result of high gloss plate consist with the theoretical result well, the deviation is below 1%, but the polarization factor result of diffuse sample No.3 is 3% less than the theoretical result. It shows the rough surface of No.3 has a depolarizing ability, the random microstructure of the glaze surface reduces the polarization effect, and the optic model is not fit for this kind of samples.

Table 1 Comparison between Theoretical and Measured

		bl3	7000A	bl6
45/0	Theoretical	-4.9%	-4.9%	-4.9%
$P_{ju\text{-}450}$	Measured	-5.2%	-5.1%	-1.8%
0/45	Theoretical	0%	0%	0%
$P_{ju\text{-}045}$	Measured	-0.7%	-0.9%	0.3%

Also the data shows the polarization factor is changing with the angle of the light in and out. When the incident angle is decreased from 45 to zero degree, the polarization factor is decreased too. According to Eq.1, the measurement error is the product of polarization factor of the sample and instrument. So the factor of sample is 5%, and limits the color error to 0.5%, the polarization factor of instrument should be less than 10%.

Conclusion

The theoretical analysis of the polarization effect is established basing on the optic model and Fresnel reflection equation. An experiment of the sample is taken on the reference colorimetry apparatus of NIM China, and the result verifies the error model. The analysis and experiment shows the relationship between polarization and color measurement result: the illumination and viewing angle have an effect to the polarization property and the color result. The effect of polarization should carefully treated for colorimetry, and designer need to minimize the polarization of colorimeter, and the end user should choose a fit colorimeter according to the characteristic of the test surface.

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