**APMP Pilot Study on Transmittance Haze**

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**Abstract.** Five NMIs within APMP, including CMS/ITRI, MSL, NIM, NIMT and KRISS from TCPR applied to the APMP technical committee initiative project for funding to carry out a pilot comparison of transmittance haze in 2012. The project started in 2014 and the final report was completed at the end of 2016. In this pilot comparison, three different haze standards were adopted, and transmittance haze for each standard was measured according to ASTM D1003 or ISO 14782. This paper presents the first results of an APMP pilot study of transmittance haze and the analysis of the variation among different haze measurement systems which are commonly used. The study shows that the variables such as sphere multiplier, transmittance distribution, fluorescence of samples and optical path of the incident beam cause discrepancies among NMIs and highlight deficiencies in current documentary standards.

1. **Introduction**

The definition of transmittance haze ($TH$) is the ratio of the diffuse transmittance ($DT$) to the total transmittance ($TT$). Transmittance haze is usually applied to characterize the light scattering caused by particles in transparent or translucent materials such as plastic, glass, and liquid, or by their rough surfaces. The importance of haze measurement has increased recently due to the development of optoelectronic industries, such as liquid crystal displays, thin film solar cells, touch panels, lampshades, and so on. The intense competition in these developing industries makes quality control for materials more and more important. Haze and luminous transmittance data are especially useful for quality control as they can be used to identify internal defects of the material. Therefore, much attention is being paid to haze measurement accuracy and traceability in recent years. In response to the increasing demands from industries, establishing the standard for transmittance haze and ensuring its global equivalence are the responsibilities of NMIs.

To satisfy the needs of industries, several national metrology institutes (NMIs) within the Asia Pacific Metrology Programme (APMP), including CMS/ITRI, MSL, NIM, NIMT and KRISS from the technical committee for photometry and radiometry (TCPR) applied to the APMP technical committee initiative project for funding to carry out a pilot comparison of transmittance haze in 2012, and CMS/ITRI was the project overseer. These experiments for the comparison were performed between 2014 and 2015, and data analysis and final report were completed in 2016.
Three kinds of haze standard from different manufacturers were adopted, and \(TH\) for each standard was measured according to ASTM D1003 [1] or ISO 14782 [2]. CMS/ITRI measured \(TH\) of all samples by ASTM D1003 and ISO 14782, and then sent them to participant NMIs. All participants measured their artefacts by ASTM D1003, and MSL also measured haze by ISO 14782.

To identify the likely causes of discrepancies in the comparison, some other measurement methods such as Bidirectional Transmittance Distribution Function (BTDF), a newly developed double-compensation method developed by CMS/ITRI [3,4], or double beam method [4], were also used in this study. The combination of methods and NMIs was structured to allow cross-checking of different methods. The results of the pilot comparison are shown in this report, and the causes of the measurement differences between NMIs and CMS/ITRI are also discussed.

2. Method of the Comparison

Five sets of haze plates were used as the artefacts for this comparison; each set has three plates with nominal transmittance haze values of close to 20% from three manufacturers: BYK Gardner, Nippon Denshoku, and Diffusion Systems. The measurement was under illuminants C or D65 according to ASTM D1003 or ISO 14782, the methods of which are shown schematically in Figure 1(a) and 1(b), respectively. Compared to the structure of ASTM D1003, a compensative port is added on the integrating sphere in ISO 14782. Supposing that the light trap could capture the light completely, the ratio \((I_4/I_2)\) would be the main contribution to \(TH\). The components on the sphere in procedure (ii) and (iv) of ISO 14782 in Figure 1(b) are the same, and thus there is no non-equivalence problem of the integrating sphere between the two procedures (in contrast to comparing (ii) and (iv) of Figure 1(a)). The added compensative port makes accurate haze measurement by ISO 14782 possible.

![Diagram of measurement methods](image)

**Figure 1.** The method specified in ASTM D 1003 and ISO 14782.

\[ TT = I_2/I_1, \quad DT = [I_4-I_3(I_2/I_1)]/I_1, \quad TH = I_4/I_2 - I_3/I_1 \]

NIMT uses a commercial double-beam spectrophotometer with a diffuse reflectance accessory to measure \(TH\). In such an instrument, the haze artefact is put on the entrance port of the sphere, and a white reference or light trap is placed on the port originally used for the tested reflectance sample. The measurement process is therefore like ASTM D1003 shown in Figure 1(a). However, an additional reference port on the sphere for a reference beam is available to monitor the stability of beam and to correct for the substitution error due to the presence of the sample surface. Thus, its signal \(I_x\) at each step is corrected automatically by the reference beam according to equation (1) where \(I_{s,x}\) is the signal obtained at procedure \(x\) and \(I_{r,x}\) is obtained when the reference beam enters the sphere. Since there is no documentary standard for using double beam system to measure \(TH\), in this pilot study, \(TH\) obtained from such an instrument is still considered as using ASTM D1003.

\[ I_x = I_{s,x}/I_{r,x} \quad \text{(1)} \]

At KRISS, the artefacts were measured under illuminant D65 by ASTM D1003 against the standards traced to NPL in accordance with BS:2782 Part 5[5], shown in Figure 2, while other participants measured haze under illuminant C according to the definition of transmittance haze shown in Figure 1. The pilot calculated the difference between KRISS and the pilot under illuminant D65.
3. Results and Discussion

Five sets of artefacts were prepared and first measured by CMS/ITRI, and then each participant NMI received its own artefacts. After all the measurements were finished, the data was analyzed by CMS/ITRI. The results and discussion of ASTM D1003 and ISO 14782 follow.

3.1 ASTM D1003

The haze results by ASTM D1003 are shown in Table 1, where the $U_{NMI}$ is the expanded $TH$ uncertainty of participant NMIs. As all participants’ results are compared with the pilot, the difference ($\delta$) was calculated by equation (2), where $S_{NMI}$ is the measurement result from the participant, and $S_{CMS}$ is the measurement result from CMS/ITRI.

$$\delta = S_{NMI} - S_{CMS}$$

Table 1 The differences between NMIs and the pilot by ASTM D1003 under illuminant C

| Manufacturer                | NMI | Difference (TH) | Difference (DT) | Difference (TT) | $U_{NMI}$ ($k = 2$) |
|-----------------------------|-----|-----------------|-----------------|-----------------|--------------------|
| BYK Gardner                 | NIM | 1.13 %          | 0.92 %          | -0.61 %         | 0.48 %             |
|                             | NMT | -0.10 %         | -0.04 %         | -0.64 %         | 0.19 %             |
|                             | MSL | -3.40 %         | -3.06 %         | 0.37 %          | 0.26 %             |
|                             | KRISS* | 2.28 %      | 1.91 %          | -0.76 %         | 0.6 %              |
|                             | CMS/ITRI | 0.00 %     | 0.00 %          | 0.00 %          | 0.40 %             |
| Nippon Denshoku             | NIM | 0.69 %          | 0.57 %          | -0.14 %         | 0.42 %             |
|                             | NMT | -0.14 %         | -0.44 %         | -1.86 %         | 0.19 %             |
|                             | MSL | -3.51 %         | -2.97 %         | 0.26 %          | 0.54 %             |
|                             | CMS/ITRI | 0.00 %     | 0.00 %          | 0.00 %          | 0.40 %             |
| Diffusion Systems           | NIM | 0.32 %          | 0.22 %          | -0.31 %         | 0.40 %             |
|                             | NMT | 0.09 %          | -0.17 %         | -1.50 %         | 0.19 %             |
|                             | MSL | -2.80 %         | -2.22 %         | 1.40 %          | 0.38 %             |
|                             | KRISS* | 2.26 %      | 1.92 %          | -0.25 %         | 0.5 %              |
|                             | CMS/ITRI | 0.00 %     | 0.00 %          | 0.00 %          | 0.40 %             |

*KRISS measured haze under illuminant D65, and its $DT$ was calculated according to the definition ($DT = TT \times TH$).

The trends in all kinds of artefacts are very similar. The largest $TH$ and $DT$ were measured at KRISS, the smallest were at MSL, and the closest were between NMT and CMS/ITRI.

The main reason for the haze variation among the NMIs is the non-equivalent sphere reflectance in procedure (ii) and (iv) of ASTM D1003 in Figure 1(a) as the final estimate of $TH$ uncertainty of participant NMIs. As all participants’ results are compared with the pilot, the difference ($\delta$) was calculated by equation (2), where $S_{NMI}$ is the measurement result from the participant, and $S_{CMS}$ is the measurement result from CMS/ITRI.

$$\delta = S_{NMI} - S_{CMS}$$

The ratio of procedure (iv) to (ii), $R = M_{(iv)}/M_{(ii)}$, for MSL, NIM and CMS/ITRI is 0.75, 0.98 and 0.95, respectively. At KRISS, the reference standards were calibrated by BS:2782 Part 5 whose structures of the sphere are the same in procedures (iii) and (iv), and also the same in procedures (i)
and (ii), so $R_{KRIS}$ is 1. At NIMT, the non-equivalence of sphere structures was corrected by reference beam shown in equation (1), so $R_{NIMT}$ is also 1. The difference of participants’ measurements from CMS/ITRI measurements are shown in Figure 3 for the original measurements made according to ASTM, and for measurements corrected by the ratios indicated above according to equation (4).

$$\delta = S_{NMI}/R_{NMI} - S_{CMS}/R_{CMS}$$  \hspace{1cm} (4)

**Figure 3** The difference between NMIs and the pilot before and after correction. Uncertainties are shown at a $k = 2$ level. (BG = BYK Gardner, DS = Diffusion Systems, ND = Nippon Denshoku)

Through the results in Figure 3, it can be noticed that except for the data from NIMT, all differences became close to zero after being corrected by the multiplier factor. At MSL, the three differences with the expanded uncertainties cover zero after corrections, and at NIM, it is only a little over zero for the BYK Gardner sample. The sphere multiplier is the key factor for the deviation for these two NMIs. The largest variation from the BYK Gardner sample at NIM might be due to fluorescence. The BYK Gardner sample was fluorescent when it was illuminated by a UV lamp, but the other two kinds of the haze samples had no such characteristics.

**Figure 4(a)** BTDF at 540 nm for the three samples at 0° angle of incidence (and at 400nm for BYK sample)

Measurements of the BTDF for the three samples were made on the MSL goniospectrophotometer at a 0° angle of incidence. The BTDF for the samples is shown in Figure 4(a) at 540 nm. These curves are representative of the BTDF at all other wavelengths for each sample, except for the shortest wavelengths for the BYK Gardner sample (also shown at 400 nm in Figure 4(a)). In fact, it also appears that the light scattered to large angles is greater for the BYK sample at 400 nm, than for either of the other samples. This is likely to be the isotropic fluorescence. To confirm if the BYK Gardner artefact is fluorescent, its fluorescence emission spectrum was measured in a commercial fluorometer.
shown in Figure 4(b). At MSL, monochromatic light is incident on the haze sample, and thus the fluorescence was observed at short wavelengths, even though the fluorescence is emitted at visible wavelengths. In such the measurement system, the fluorescence has minimal effect on $TH$ because $V(\lambda)$ is very small at short wavelengths. At NIM, a halogen lamp and a suitable filter were used to form a light source close to illuminant C, and the transmitted light and induced fluorescence were detected together by a $V(\lambda)$ detector. At CMS/ITRI, broadband light beam from a halogen lamp is incident on the sample and then the signals were measured by a spectrometer. Thus the fluorescence at the two NMIs was measured at correct wavelengths. Compared to the light source at CMS/ITRI close to illuminant A, the one at NIM to simulate illuminant C is stronger at short wavelengths, so the fluorescence was more pronounced at NIM.

The persistent differences of KRISS can be attributed to a non-normal incident angle in procedure (iii) of BS:2782 Part 5. The effective illuminance on the surface should be multiplied by a cosine factor since the incident angle is not 0°. Thus, $I_2$ is larger than $I_3$ compared to the relative intensity in ASTM and BS methods. In addition, a light trap on the integrating sphere may capture some light, and that would also lower $I_3$. Therefore, the $TH$ mainly contributed to by the ratio ($I'_4/I_3$) is larger.

At NIMT, the non-equivalence of sphere structures was corrected by a reference beam so its data should be close to those of ISO 14782. The original data at NIMT agreeing with CMS/ITRI can be attributed to a non-normal incident angle of 8°, not zero. To check the effect of the incident angle, CMS/ITRI measured $TH$ of its own three samples by using 0/d (actual incident angle: 3°20’) and 8/d integrating sphere accessories installed in the commercial spectrophotometer and by ISO 14782, and the results are shown in Table 2. The data from the 0/d accessory is near the data obtained by ISO 14782 as expected. From the ratio of $TH$ using each accessory, the effect of the incident angle is largest for the BYK Gardner sample, and is similar for the other two samples. It is inferred that the light beam after passing through BYK Gardner sample has a higher portion of diffuse transmittance influenced by the incident angle. Compared to the other two samples, a greater fraction of the light scattered by the BYK Gardner sample is within ~ 20° of normal (shown in Figure 4(a)), and thus BYK Gardner sample is more severely affected when the flux is weakened due to a non-perpendicular light beam on the surface of the sample.

### Table 2 Haze results by ISO 14782 and the 0/d and 8/d accessories

| Manufacturer     | $TH$  | ISO 14782 | 0/d Accessory | 8/d Accessory | Ratio ($I'_4/I_3$) |
|------------------|-------|-----------|---------------|---------------|-------------------|
| Diffusion Systems| 16.82 % | 16.76 % | 16.19 % | 1.04 |
| Nippon Denshoku  | 18.59 % | 18.52 % | 17.69 % | 1.05 |
| BYK Gardner      | 18.01 % | 18.22 % | 16.51 % | 1.10 |

#### 3.2 ISO 14782

Except for the pilot, only MSL also measured the artefacts by ISO 14782. The results are shown in Table 3, and “Reference” means the data of CMS/ITRI and its uncertainty. Compared to the difference of $TH$ and $DT$ between MSL and CMS in ASTM D1003, the difference by ISO 14782 became significantly smaller, and the $TH$ from all kinds of sample agree within the uncertainties. The $TH$ can be measured accurately by ISO 14782 as the sphere effect is corrected in this method.

### Table 3 Results by ISO 14782 under illuminant C

| Manufacturer     | Difference ($TH$) | Difference ($DT$) | Difference ($TT$) | $U_{rot}$ ($k=2$) |
|------------------|------------------|------------------|------------------|-------------------|
| BYK Gardner      | 0.23 %           | 0.32 %           | 0.36 %           | 0.34 %           |
| Nippon Denshoku  | -0.73 %          | -0.59 %          | 0.92 %           | 0.70 %           |
| Diffusion Systems | -0.32 %         | -0.12 %          | 0.21 %           | 0.48 %           |
| Reference        | 0.00 %           | 0.00 %           | 0.00 %           | 0.40 %           |

In the results of ASTM D1003 and ISO 14782, the largest deviation occurred in the sample of Nippon Denshoku. Among the three kinds of artefacts, only Diffusion Systems sample has no frame. Neither the BYK Gardner sample nor the Nippon Denshoku sample could be presented directly to the sphere port, but the larger deviation was in the Nippon Denshoku sample. To examine the recess effect on the haze, some tests on all three samples were carried out at MSL. Figure 5 shows that the haze changes little when BYK Gardner sample was recessed from the port. The difference between the BYK Gardner sample and the other two samples is consistent with the difference seen in their
transmittance distribution (shown in Figure 4(a)). Light scattered to very wide angles ‘should’ be included in the haze estimate. In the two samples, the effect of recess on Nippon Denshoku sample is severe, and that makes the largest deviation in the Nippon Denshoku sample.

![Figure 5](image_url)

**Figure 5** Effect of recess of the sample from the port on the measured value of TH

4. **Conclusion**

The haze measured by ASTM D1003 was highly dependent on the sphere multiplier because of the different configuration of the integrating sphere ports in each procedure of the measurement process. Most of the variation between participants can be accounted for by the sphere multiplier.

Among the three different artefacts, two of them had a frame that may prevent the sample from touching the port of the sphere directly and influences the fraction of light scattered into the sphere. The recess of the sample from the port makes TH decrease more seriously when samples are more highly scattering at moderate angles from normal. The transmittance distribution of the sample also influences the measurement results at different incident angles. When the incident angle is not 0°, TH of the sample decreases more if most of its scattering is within a smaller angle.

One of the samples exhibited inducement in the UV region, so the UV portion of the incident light might determine the relative intensity of fluorescence in the measurement process. The fluorescence is isotropic, and thus DT and TH could be affected if a certain amount of fluorescence was induced.

5. **Future Work**

The 1st pilot study was finished in the end of 2016. Several reasons for non-equivalent TH in different measurement systems were investigated. There are currently many products labelled ‘high haze’ but no standard specifying the measurement method for this high range. The 2nd pilot study to investigate high haze samples has been approved by APMP with financial support, and will begin soon.

The research results of the first and second haze APMP TC initiative projects will be disseminated via a CIE reportership and potentially lead to a new CIE technical committee (TC). CMS/ITRI proposed the reportership (DR 2-79) of measurement of total transmittance, diffuse transmittance, and transmittance haze to CIE Division 2 in 2016, and it was passed with no objection. All participants will present the results of the pilot study to apply for a new TC in 2018.

6. **References**

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