The research on interlaboratory comparison test of LED lighting products

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Abstract: The article introduces the Interlaboratory Comparison (IC) test for three different types of light emitting diode (LED) lamps measurement about the key photometric, colorimetric, and electrical parameters. The article analyses the deviations of the test results between the reference values and test results from six participating laboratories. It found that the photometric and colorimetric parameters showed high deviations between the reference values and participating laboratories' test results. The recommended participating laboratory improvement measures in the article are as follows: checking the traceability of standard artefacts, checking data correction, improving test procedures, checking ambient temperature, checking calculation software, and checking the response of the photodetector, etc.

Keywords: LED lighting; interlaboratory comparison (IC); test

1. Introduction

This Inter-laboratory comparison testing project is one of a series of efficient lighting compliance activities. In order to better understand the measurement capacity of six lighting laboratories. The main purpose of this project was to analyze the test results from the participating laboratories, and by comparison with the reference laboratory, to identify potential testing issues in the participating laboratories and help the participating laboratories to identify differences between their own laboratory and the other participating laboratories. The project results and findings will then be beneficial for improving their testing capacity.

GELC, as the reference laboratory, developed the testing protocol and the measurement methodology for the participating laboratories; and organized all the comparison test activities in compliance with ISO/IEC 17043, Conformity assessment - *General requirements for proficiency testing.*

2. Description of Comparison Samples

This project was carried out through a star-type approach, as illustrated in Figure 1. GELC prepared six sets of samples and, as the reference laboratory, conducted tests twice for all six sets of samples. The first series of tests at GELC were carried out before the samples were shipped to the participating laboratories. Once the participating laboratories finished their testing, the test results, and the original set of samples, were returned to GELC. After receiving the samples back from the laboratories, GELC conducted the second series of tests.

Each set of samples included three different kinds of LED lamps: omnidirectional, directional and high CCT.

Table.1 gives the detailed rated parameters of each lamp and Table.2 summarizes the details of the individual lamps sent to each laboratory.

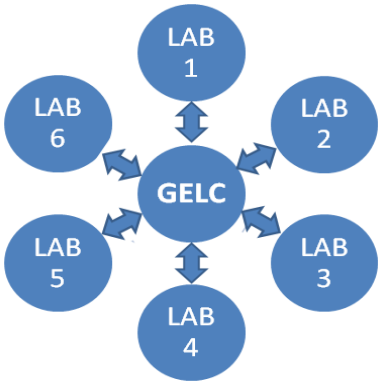

Fig. 1. Star-type comparison

Table 1. Properties of comparison samples

Identifier	Lamp Type	Rated Voltage	Rated Power	Nominal CCT
GELC-OD	Omnidirectional LED lamp	12V	4 W	2,700 K
GELC-D	Directional LED lamp	220 V AC	8 W	3,000 K
GELC-HCCT	High CCT LED lamp	220 V AC	6 W	5,000 K

Note: The information listed above is the rated value of the sample.

Table 2. Samples sent to each participating laboratory.

Laboratory code	Samples sent to each laboratory
GELC-LAB-1	GELC-OD-1; GELC-D-1; GELC-HCCT-1
GELC-LAB-2	GELC-OD-2; GELC-D-2; GELC-HCCT-2
GELC-LAB-3	GELC-OD-8; GELC-D-3; GELC-HCCT-3
GELC-LAB-4	GELC-OD-7; GELC-D-4; GELC-HCCT4
GELC-LAB-5	GELC-OD-5; GELC-D-5; GELC-HCCT-5
GELC-LAB-6	GELC-OD-6; GELC-D-6; GELC-HCCT-6

3. Measurands

The following parameters were measured and recorded by each laboratory:

1. Total luminous flux (lm)*
2. RMS voltage (V) and RMS current (mA)
3. Active power (W)*
4. Luminous efficacy (lm/W)*
5. Chromaticity x*and y*
6. Correlated colour temperature (K)*
7. General colour rendering index[1], referred to in this report as CRI*
8. Power factor*

Note 1: Only the parameters marked with an asterisk (*) were compared and analyzed.

Note 2: Participating laboratories were requested to give all decimal places, providing at least four significant digits.

Note 3: All laboratories were requested to report uncertainty values for analyzing the test results. However, results without uncertainty values were also accepted.

Note 4: GELC-OD samples were tested by Direct Current (DC) and therefore power factor was not tested. GELC-D samples and GELC-HCCT samples were tested by Alternating Current (AC) and the power factor was tested.

4. Reference Values and Analysis Calculations

4.1. Reference Values

In this project, the comparison samples were tested twice by GELC. The first time before delivering to each participating laboratory, and the second time after they were returned from those laboratories. The test results obtained by GELC are presented in Annex A.

The reference value (X) is the average value of X1 and X2, and is calculated by:

$$X = \frac{X_1 + X_2}{2} \tag{1}$$

Where:

X_1 is the value tested by GELC before delivering the comparison samples to participating laboratories;

X_2 is the value tested by GELC after receiving comparison samples returned from the participating.

4.2. Analysis Calculations

The test results from participating laboratories are presented in Annex C. In accordance with ISO 13528, Statistical methods for use in proficiency testing by inter-laboratory comparisons, the relative differences of these test results to the reference values are calculated by Equations (2) and (3).

For the value of active power consumption, total luminous flux and luminous efficacy, the relative difference ($\Delta X_{relative}$) between the results from each laboratory and the reference values is given by:

$$\Delta X_{relative} = \frac{x - X}{X} \tag{2}$$

Where:

x is the average testing result of each participating laboratory;

X is the GELC reference value.

For the value of power factor, chromaticity coordinates (x, y), correlated colour temperature (CCT), colour rendering index (CRI), the relative difference (ΔX) between the results from each laboratory and the assigned values is given by:

$$\Delta X = x - X \tag{3}$$

Where:

x is the average testing result of the participating laboratory;

X is the GELC reference value.

5. Evaluation Calculations

In addition to the uncertainty values associated with their test results, the participating laboratories were requested to report the uncertainty values relating to more general laboratory factors, such as the equipment, standard artefact, and burning position.; Unfortunately, as not all of the participating laboratories provided these additional uncertainty values, it was not possible to use E_n *or* z' criteria to analyze the results [2]. For that reason, in this report, the test results were analyzed by z-score to give an evaluation of their performance. The uncertainties provided were used as additional information to evaluate the testing capacities of the participating laboratories that provided them.

The z-score (z) is calculated and determined by Equation (4):

$$z = \frac{(x - X)}{\sigma} \tag{4}$$

Where:

σ is the SDPA value (standard deviation for proficiency assessment). In this inter-laboratory comparison test, σ = 0.7413 x IQR (interquartile range)[3,4] of test results provided by participating laboratories;

x is the average testing result of the participating laboratory;
X is the reference value calculated by GELC.
If $|z| \leq 2$, it means the results are generally considered to be satisfactory;
If $2 < |z| < 3$, it means the results are considered to be questionable; and
If $|z| \geq 3$, it means the results are considered to be unsatisfactory.

6. Analysis of Relative Differences Between Participating Laboratory Results and GELC Reference Values for Each Laboratory

The relative differences between the measurement values of participating laboratories and the GELC reference values are shown in Tables 3 to 8 Each table refers to an individual laboratory and lists the differences of every parameter tested of each type of sample.

7. Analysis of Relative Differences Between Participating Laboratory Results and GELC Reference Values for Each Measurand

The (relative) differences of results for each measurand between each participating laboratory and GELC are summarized in the following subsections. In each figure:

.....	represents relative expanded uncertainty of the GELC reference value, X (where the coverage factor, $k = 2$);
◆	represents the relative difference between the participating laboratories' measurement values and the GELC reference values, (x - X)/X;
I	represents the error bars which show the uncertainties of measurement (expanded uncertainty with a coverage factor, $k = 2$) of the participating laboratories

7.1. Total Luminous Flux

Figure 2 shows the relative differences in total luminous flux for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 2 shows that the test result deviation of GELC-LAB-5 is within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of the GELC-LAB-3 test result is within the reference laboratory uncertainty. However, the test result uncertainty bars of the other four laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-4 and GELC-LAB-6) are outside the uncertainty of the reference laboratory.

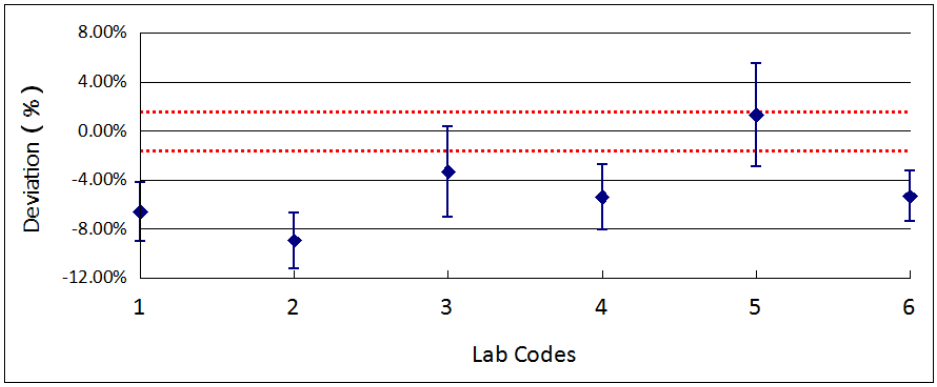

Fig. 2 Relative differences (participant) of total luminous flux for GELC-D samples

Figure 3 shows the relative differences in total luminous flux for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 3 shows that the test result deviations of GELC-LAB-3, GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6 are within the uncertainty of reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-1 is within the reference laboratory uncertainty. However, the test result uncertainty bar of GELC-LAB-2 is outside the uncertainty of the reference laboratory.

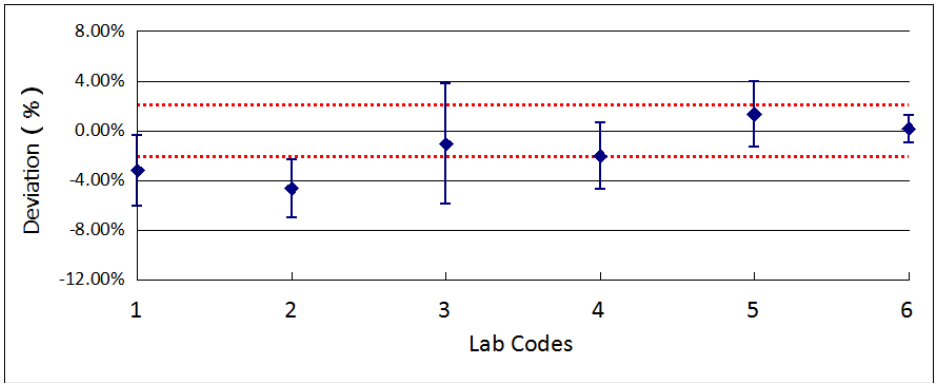

Fig. 3 Relative differences (participant) of total luminous flux for GELC-OD samples

Table 3 Differences between GELC-LAB-1 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-1	-6.61%	-1.01%	0.0016	-5.66%	0.0059	0.0022	-74	-0.0232
GELC-OD-1	-3.20%	0.48%	/	-3.66%	-0.0010	-0.0002	14	-0.0277
GELC-HCCT-1	-5.66%	-0.95%	-0.0122	-4.76%	0.0042	0.0044	-174	0.1915

Table 4 Differences between GELC-LAB-2 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-2	-8.94%	-1.40%	0.0204	-7.65%	-0.0024	-0.0047	1	0.8562
GELC-OD-2	-4.64%	1.47%	/	-4.90%	-0.0011	-0.0029	-6	0.6035
GELC-HCCT-2	-5.24%	-1.66%	-0.0118	-3.64%	-0.0035	-0.0065	209	2.5112

Table 5 Differences between GELC-LAB-3 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-3	-3.32%	0.75%	0.0242	-4.05%	-0.0023	-0.0020	22	0.3649
GELC-OD-8	-1.07%	1.42%	/	-2.45%	-0.0021	-0.0012	22	0.2570
GELC-HCCT-3	-3.46%	0.72%	0.0047	-4.15%	-0.0030	-0.0043	175	0.8433

Table 6 Differences between GELC-LAB-4 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-4	-5.40%	0.25%	0.0044	-5.64%	0.0014	-0.0002	-25	0.0559
GELC-OD-7	-2.02%	0.25%	/	-2.27%	-0.0003	-0.0006	0	0.4331
GELC-HCCT-4	-7.85%	0.40%	-0.0021	-8.22%	-0.0004	-0.0009	37	0.1660

Table 7 Differences between GELC-LAB-5 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-5	1.32%	0.12%	0.0155	1.21%	-0.0024	-0.0058	-16	0.7448
GELC-OD-5	1.34%	-0.01%	/	1.35%	-0.0005	-0.0043	-21	1.1845
GELC-HCCT-5	0.63%	0.25%	-0.0048	0.37%	-0.0029	-0.0079	154	1.4440

Table 8 Differences between GELC-LAB-6 measured values and the GELC reference values

Identifier	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT (K)	CRI
GELC-D-6	-5.33%	-1.22%	0.0254	-4.16%	-0.0002	0.0032	30	-0.7569
GELC-OD-6	0.18%	1.14%	/	-0.95%	-0.0048	0.0007	79	-0.5892
GELC-HCCT-6	-3.05%	-2.26%	0.0007	-0.81%	-0.0024	0.0006	108	-0.5908

Figure 4 shows the relative differences in total luminous flux for the GELC-HCCT samples between the participants' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 4 shows that the test result deviation of GELC-LAB-5 is within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of the GELC-LAB-3 and GELC-LAB-6 are within the reference laboratory uncertainty. However, the test result uncertainty bars of the other three laboratories (GELC-LAB-1, GELC-LAB-2 and GELC-LAB-4) are outside the uncertainty of the reference laboratory.

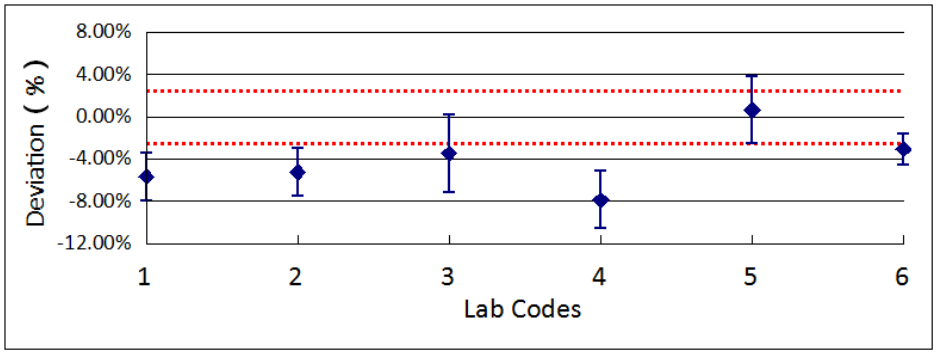

Fig.4. Relative differences (participant) of total luminous flux for GELC-HCCT samples

7.2. Active Power

Figure 5 shows the relative differences in active power consumption for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 5 shows that the test result deviations of three laboratories, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-5, are inside the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of the other three laboratories (GELC-LAB-1, GELC-LAB-2 and GELC-LAB-6) are within the reference laboratory uncertainty.

Figure 6 shows the relative differences in active power consumption for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 6 shows that the test result deviations of three laboratories (GELC-LAB-1, GELC-LAB-4 and GELC-LAB-5) are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-3 is within the reference laboratory uncertainty. However, the test result uncertainty bars of GELC-LAB-2 and GELC-LAB-6 are outside the uncertainty of the reference laboratory. It can also be seen that the reported uncertainty values of GELC-LAB-1, GELC-LAB-2 and GELC-LAB-6 are very small.

Figure 7 shows the relative differences in active power consumption for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 7 shows that the test result deviation of two laboratories (GELC-LAB-4 and GELC-LAB-5) are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-3 is within the reference laboratory uncertainty. However, the test result uncertainty bars of GELC-LAB-1, GELC-LAB-2 and

GELC-LAB-6 are outside the uncertainty of the reference laboratory. It can also be seen that the reported uncertainty values of GELC-LAB-1, GELC-LAB-2 and GELC-LAB-6 are very small.

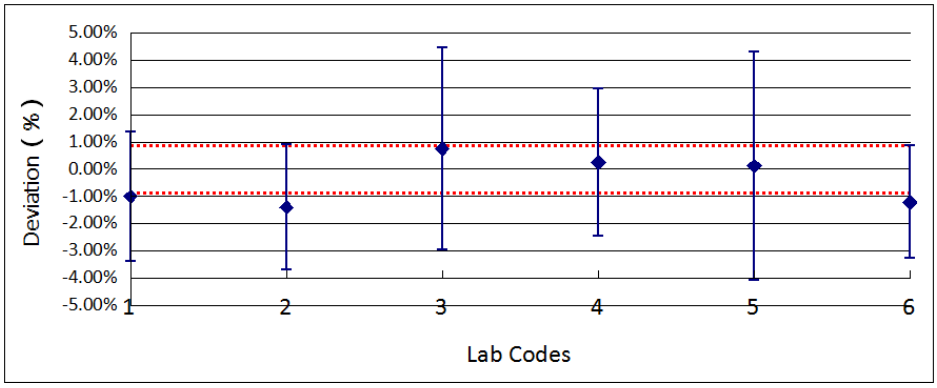

Fig.5. Relative differences (participant) of active power for GELC-D samples

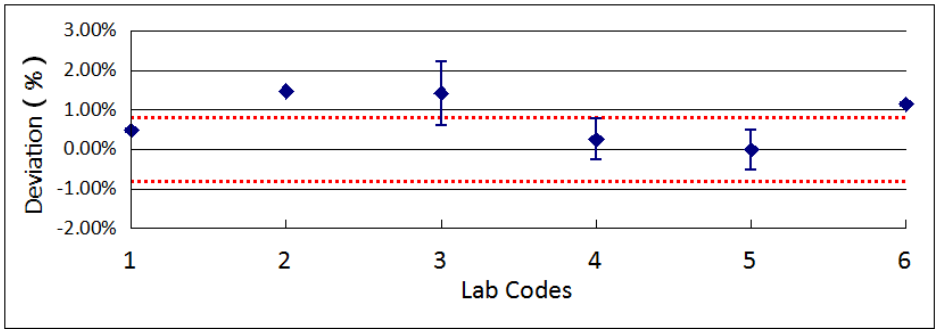

Fig.6. Relative differences (participant) of active power for GELC-OD samples

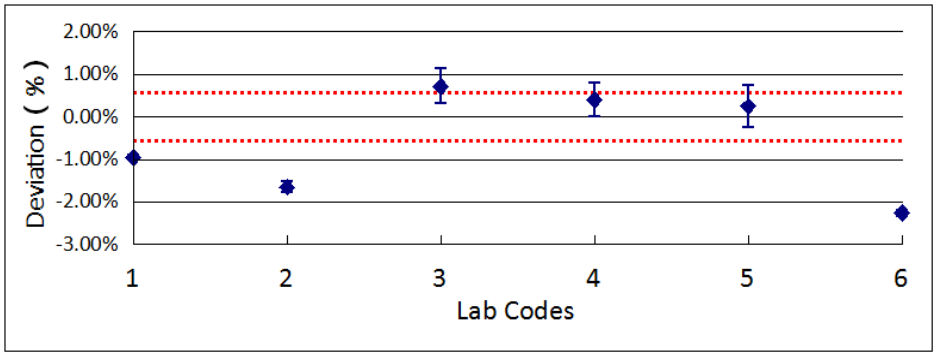

Fig.7. Relative differences (participant) of active power for GELC-HCCT samples

7.3. Luminous Efficacy

Figure 8 shows the relative differences in luminous efficacy for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 8 shows that the test result deviation of GELC-LAB-5 was within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-3 is within the reference laboratory uncertainty. However, the test result uncertainty bars of the other four laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-4 and GELC-LAB-6) are outside the uncertainty of the reference laboratory.

Figure 9 shows the relative differences in luminous efficacy for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 9 shows that the test result deviations of GELC-LAB-5 and GELC-LAB-

6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-1, GELC-LAB-3 and GELC-LAB-4 are within the reference laboratory uncertainty. However, the test result uncertainty bar of GELC-LAB-2 is outside the uncertainty of the reference laboratory.

Figure 10 shows the relative differences in luminous efficacy for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The relative differences are calculated by Equation (2). Figure 10 shows that the test result deviations of GELC-LAB-5 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-1, GELC-LAB-2 and GELC-LAB-3 are within the reference laboratory uncertainty. However, the test result uncertainty bar of GELC-LAB-4 is outside the uncertainty of the reference laboratory.

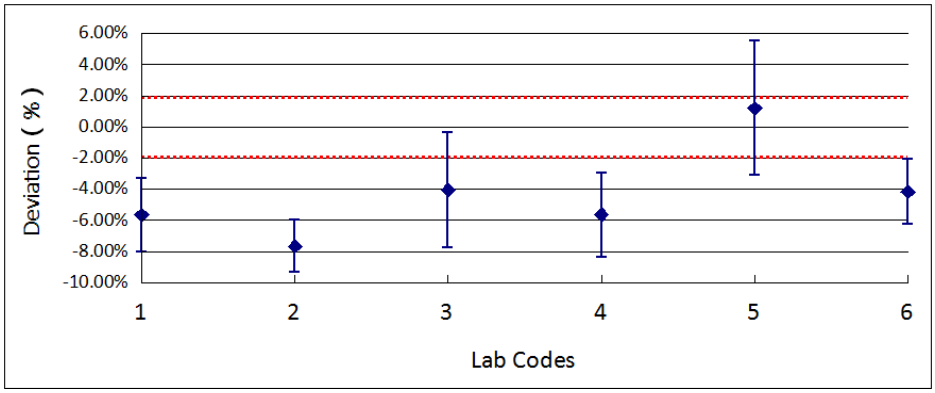

Fig.8. Relative differences (participant) of luminous efficacy for GELC-D samples

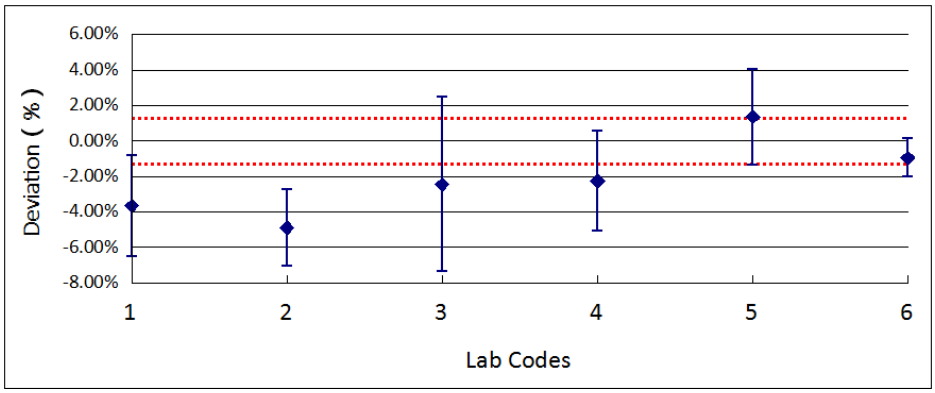

Fig.9. Relative differences (participant) of luminous efficacy for GELC-OD samples

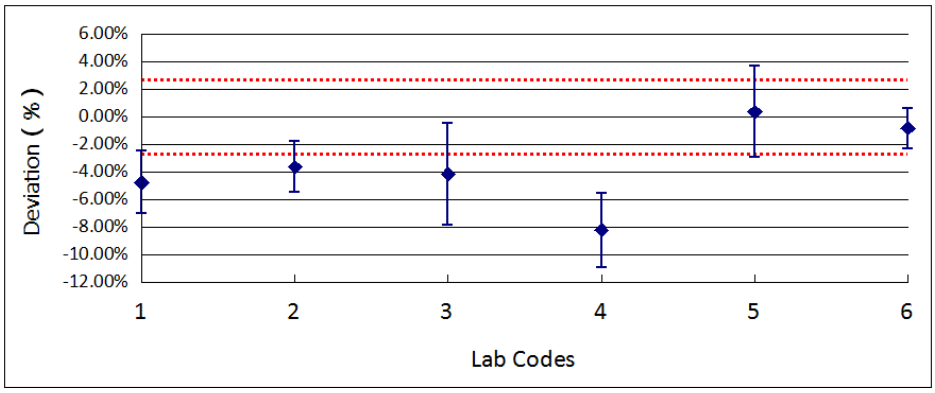

Fig.10. Relative differences (participant) of luminous efficacy for GELC-HCCT samples

7.4. Chromaticity x

Figure 11 shows the deviation in chromaticity x for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 11 shows the test result deviations of GELC-LAB-2, GELC-LAB-3, GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-1 is within the reference laboratory uncertainty.

Figure 12 shows the deviation in chromaticity x for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 12 shows the test result deviation of GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-5 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-6 is within the reference laboratory uncertainty.

Figure 13 shows the deviation in chromaticity x for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 13 shows that the test result deviations of GELC-LAB-4 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of other four laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-3 and GELC-LAB-5) are within the reference laboratory uncertainty.

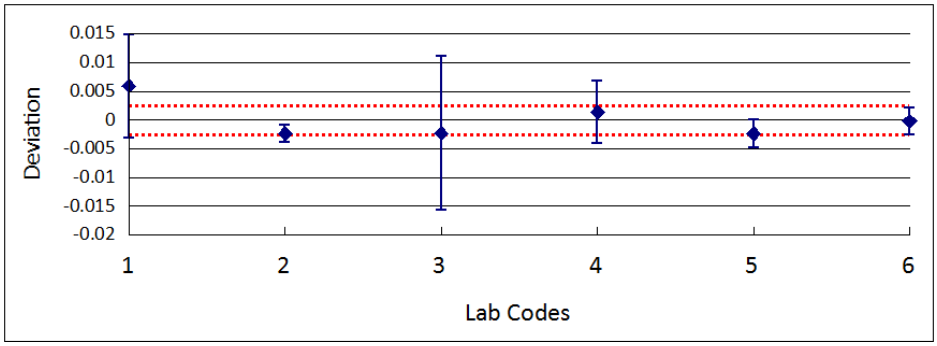

Fig.11. Differences (participant) of chromaticity x for GELC-D samples

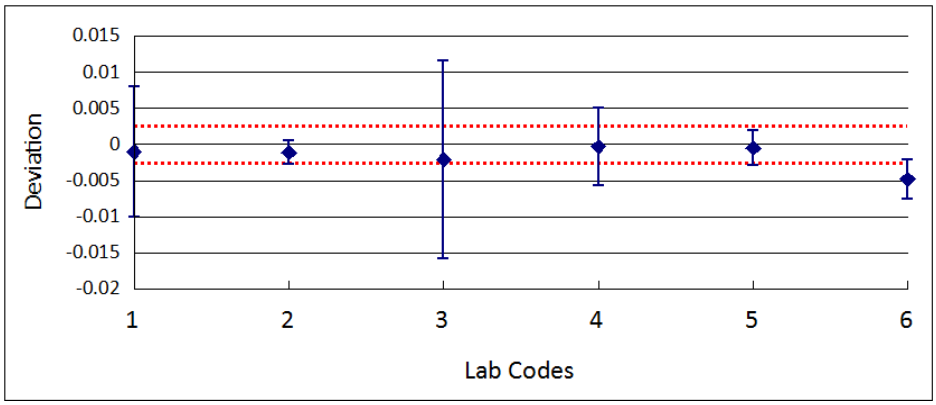

Fig.12. Differences (participant) of chromaticity x for GELC-OD samples

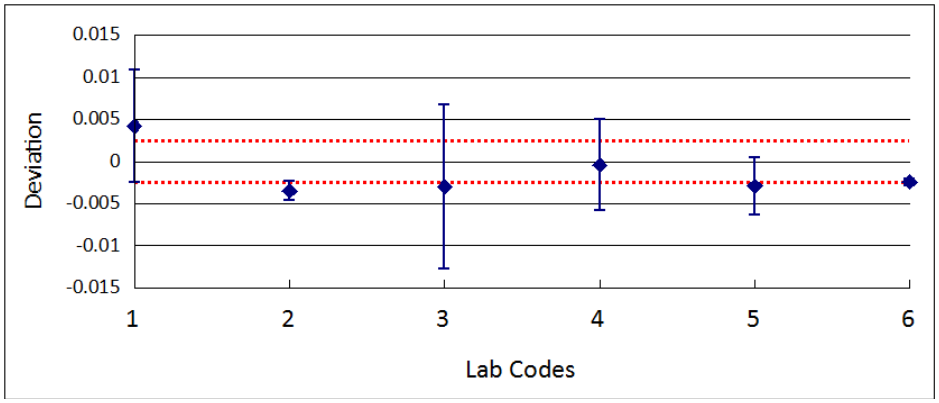

Fig.13. Differences (participant) of chromaticity x for GELC-HCCT samples

7.5. Chromaticity y

Figure 14 shows the deviation in chromaticity y for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 14 shows that the test result deviation of GELC-LAB-1, GELC-LAB-3 and GELC-LAB-4 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-5 and GELC-LAB-6 are within the reference laboratory uncertainty. However, the test result uncertainty bar of GELC-LAB-2 is outside the uncertainty of the reference laboratory.

Figure 15 shows the deviation in chromaticity y for the GELC-OD samples between the participant's measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 15 shows that the test result deviation of GELC-LAB-1, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of the other two laboratories (GELC-LAB-2 and GELC-LAB-5) are within the reference laboratory uncertainty.

Figure 16 shows the deviation in chromaticity y for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 16 shows that the test result deviations of GELC-LAB-4 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-1, GELC-LAB-3 and GELC-LAB-5 are within the reference laboratory uncertainty. However, the test result uncertainty bar of GELC-LAB-2 is outside the uncertainty of the reference laboratory.

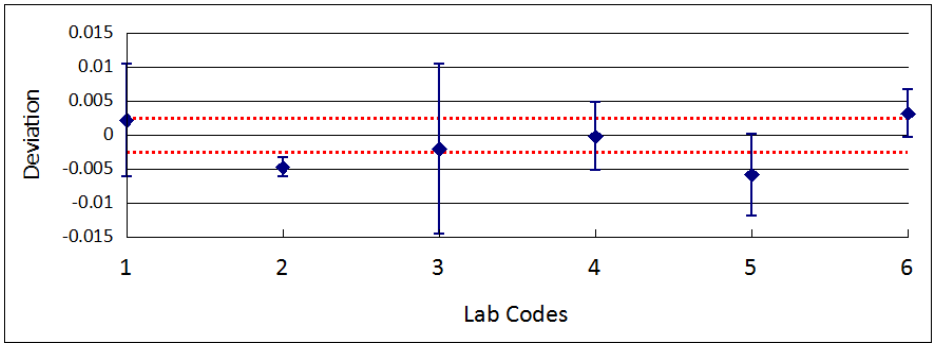

Fig.14. Differences (participant) of chromaticity y for GELC-D samples

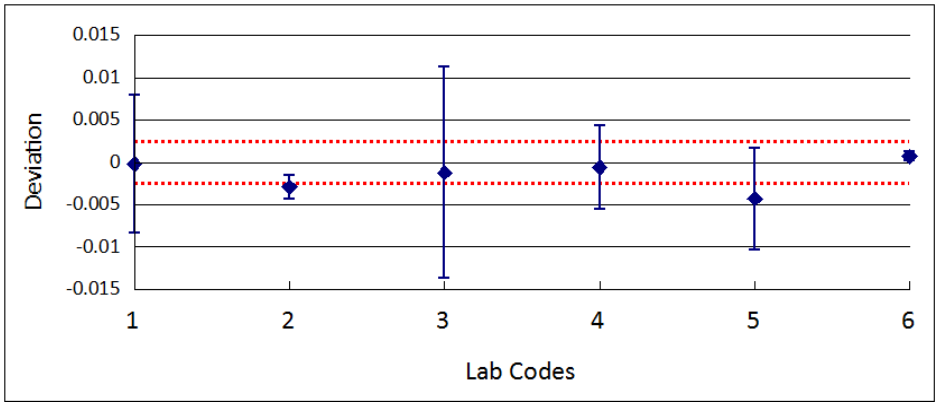

Fig.15. Differences (participant) of chromaticity y for GELC-OD samples

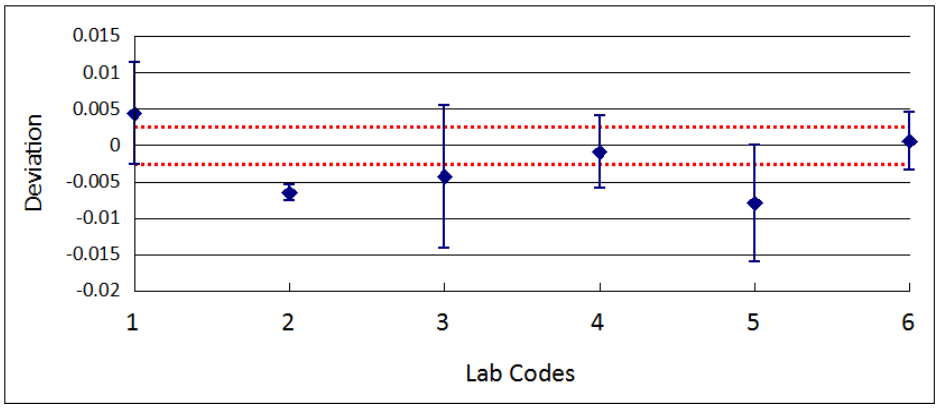

Fig.16. Differences (participant) of chromaticity y for GELC-HCCT samples

7.6. Correlated Colour Temperature (CCT)

Figure 17 shows the deviation in CCT for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 17 shows that the test result deviations of GELC-LAB-2, GELC-LAB-3, GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the test result uncertainty bar of GELC-LAB-1 is within the reference laboratory uncertainty.

Figure 18 shows the deviation in CCT for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 18shows that the test result deviations of GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-5 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the test result uncertainty bar of GELC-LAB-6 is within the reference laboratory uncertainty.

Figure 19 shows the deviation in CCT for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 19 shows the test result deviation of GELC-LAB-4 is within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-3 and GELC-LAB-5 are within the reference laboratory uncertainty. However, uncertainty bars of GELC-LAB-2 and GELC-LAB-6 are outside the uncertainty of the reference laboratory. It can also be seen that the reported uncertainty values of GELC-LAB-2 and GELC-LAB-6 were very small.

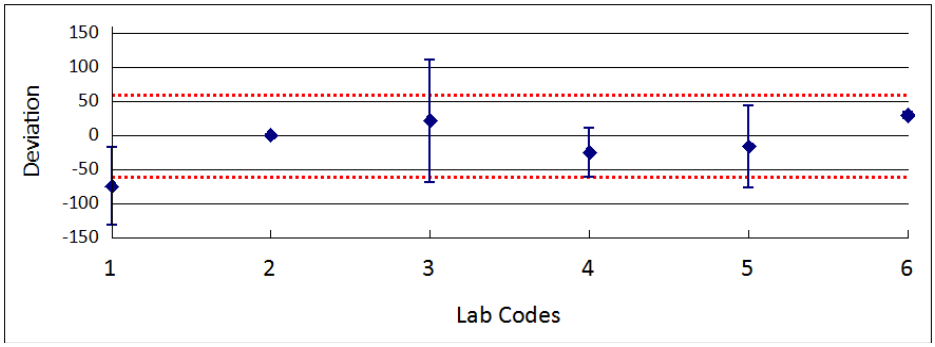

Fig.17. Differences (participant) of CCT for GELC-D samples

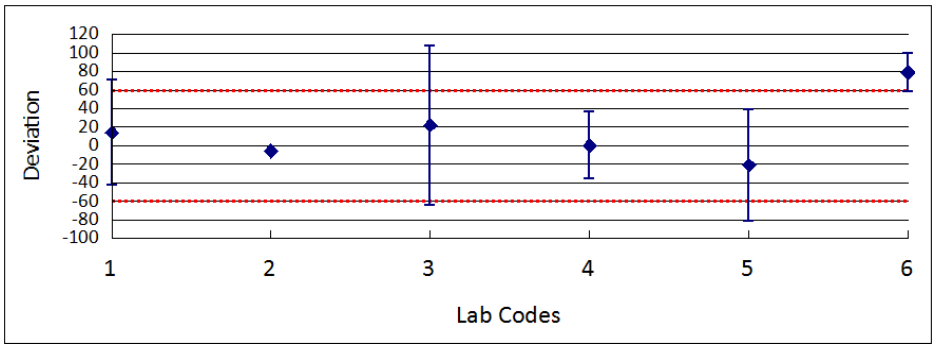

Fig.18. Differences (participant) of CCT for GELC-OD samples

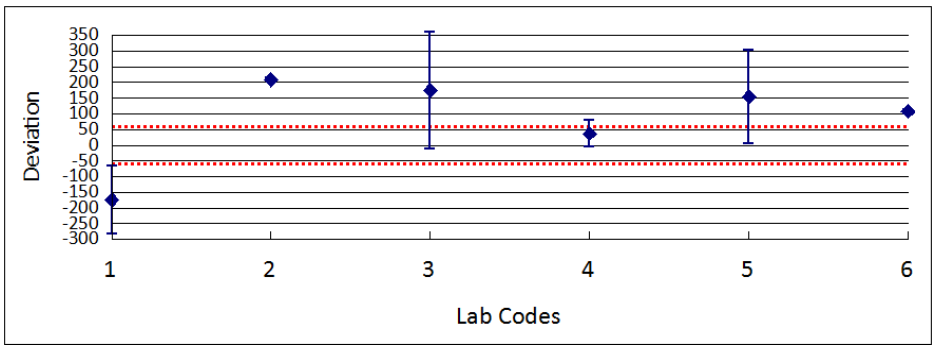

Fig.19. Differences (participant) of CCT for GELC-HCCT samples

7.7. Colour Rendering Index (CRI)

Figure 20 shows the differences of CRI results for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 20 shows the test result deviations of GELC-LAB-1, GELC-LAB-3 and GELC-LAB-4 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bar of GELC-LAB-5 is within the reference laboratory uncertainty. However, the uncertainty bars of GELC-LAB-2 and GELC-LAB-6 are outside the uncertainty of the reference laboratory. It can also be seen that the reported uncertainty values of GELC-LAB-2 and GELC-LAB-6 were very small.

Figure 21 shows the deviation in CRI for the GELC-OD samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 21 shows that the test result deviations of GELC-LAB-1 and GELC-LAB-3 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-4 and GELC-LAB-5 are within the reference laboratory uncertainty. However, the

uncertainty bars of GELC-LAB-2 and GELC-LAB-6 are outside the uncertainty of the reference laboratory. It can also be seen that the reported uncertainty values of GELC-LAB-2 and GELC-LAB-6 were very small.

Figure 22 shows the deviation in CRI for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 22 shows that the test result deviations of GELC-LAB-1 and GELC-LAB-4 are within the uncertainty of the reference laboratory. Considering the uncertainty of the participating laboratories, the uncertainty bars of GELC-LAB-3 and GELC-LAB-5 are within the reference laboratory uncertainty. However, the uncertainty bars of GELC-LAB-2 and GELC-LAB-6 are outside the uncertainty of the reference laboratory. It also can be seen that the reported uncertainty values of GELC-LAB-2 and GELC-LAB-6 were very small.

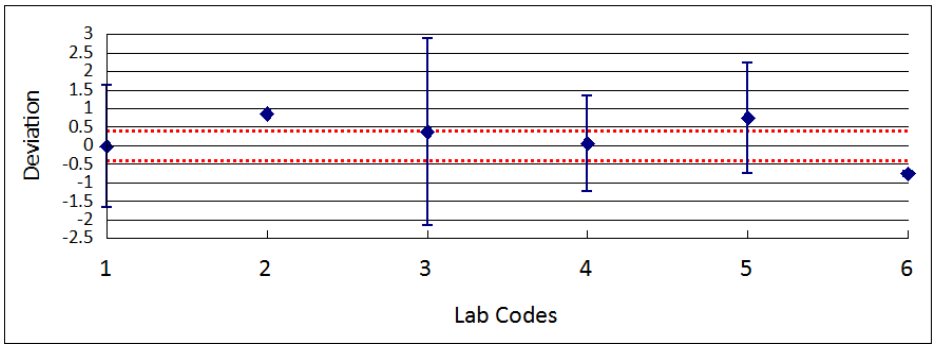

Fig.20. Differences (participant) of CRI for GELC-D samples

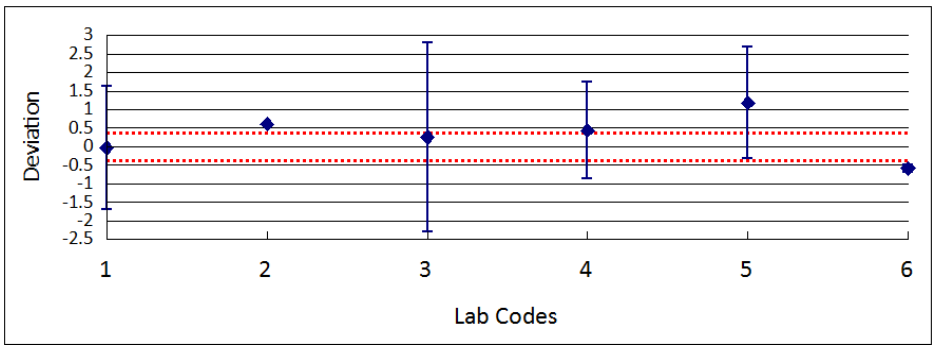

Fig.21. Differences (participant) of CRI for GELC-OD

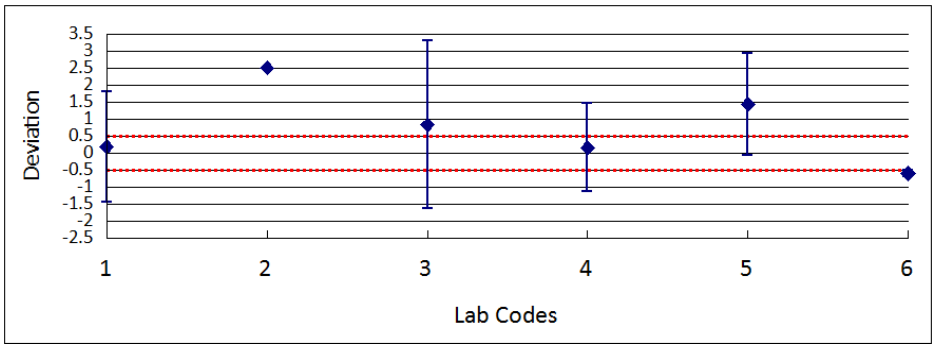

Fig.22. Differences (participant) of CRI for GELC-HCCT samples

7.8. Power Factor

Figure 23 shows the deviation in power factor for the GELC-D samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 23 shows that the test result deviations of GELC-LAB-1 and GELC-LAB-4 are within

the uncertainty scope of reference laboratory. The participating laboratories were not required to submit uncertainty values for power factor measurements to the reference laboratory.

Figure 24 shows the deviation in power factor for the GELC-HCCT samples between the participating laboratories' measurement values and the GELC reference values. The differences are calculated by Equation (3). Figure 24 shows that the test result deviations of GELC-LAB-4 and GELC-LAB-6 are within the uncertainty scope of reference laboratory. The participating laboratories were not required to submit uncertainty values for power factor measurements to the reference laboratory.

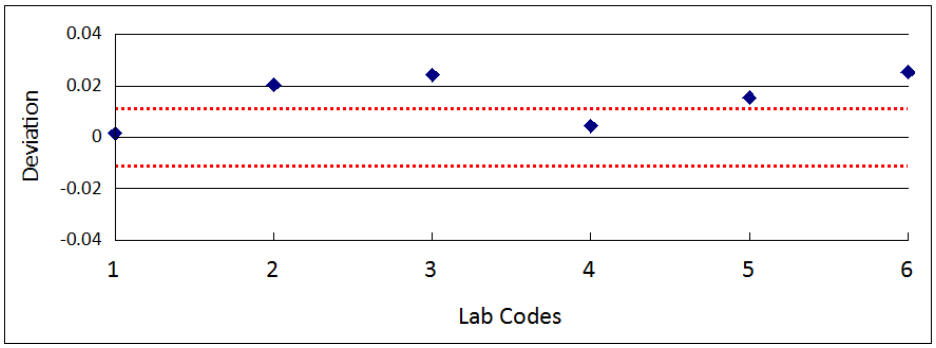

Fig.23. Differences (participant) of power factor for GELC-D samples

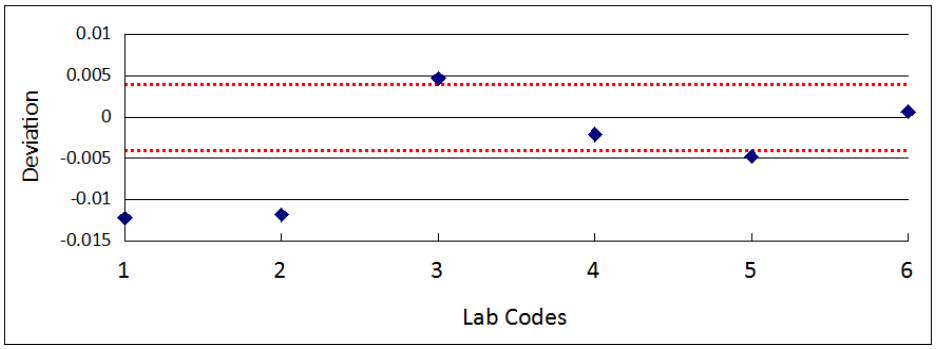

Fig 24. Differences (participant) of power factor for GELC-HCCT samples

8. Evaluation of Performance

As discussed in Section 5, some laboratories provided the uncertainty values along with the test results, but other laboratories did not calculate their uncertainties. Therefore, in this report the z-score is used to analyze the test results and provide an evaluation of the performance of the participating laboratories. The z-score is calculated by Equation (4), as described in Section 5, and:

$|Z| \leq 2$ is generally considered to be satisfactory.

$2 < |Z| < 3$ is considered to be questionable.

$|Z| \geq 3$ is considered to be unsatisfactory.

This section discusses the z-score analysis for the results from the participating laboratories and possible reasons for the deviations in the photometric, electrical and colour parameters.

8.1. Laboratory z-score Analysis by Type of Sample Lamp

Table 9 shows the z-score of each participating laboratory for sample GELC-D (directional LED lamps). For the total luminous flux measurement, the test results of GELC-LAB-3 and GELC-LAB-5 are satisfactory; the test results of GELC-LAB-4 and GELC-LAB-6 are questionable; and the test results of GELC-LAB-1 and GELC-LAB-2 are unsatisfactory. For the active power, chromaticity y and CRI measurements, all of the test results are satisfactory. For power factor, the test results of GELC-LAB-3 and

GELC-LAB-6 are questionable and the other four laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-4 and GELC-LAB-5) are satisfactory. For the luminous efficacy measurement, the test results of GELC-LAB-5 are satisfactory, but the test results of the other five laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-6) are unsatisfactory. For chromaticity x and CCT, the test result of GELC-LAB-1 is questionable and other five laboratories are satisfactory.

Table 9 z-score for GELC-D samples

	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT	CRI
GELC-LAB-1	-3.59	-0.99	0.13	-4.84	2.36	0.53	-2.53	-0.05
GELC-LAB-2	-4.85	-1.37	1.70	-6.54	-0.96	-1.13	0.03	1.77
GELC-LAB-3	-1.80	0.73	2.03	-3.46	-0.92	-0.48	0.75	0.75
GELC-LAB-4	-2.93	0.24	0.37	-4.82	0.56	-0.05	-0.85	0.12
GELC-LAB-5	0.72	0.12	1.30	1.03	-0.96	-1.39	-0.55	1.54
GELC-LAB-6	-2.89	-1.19	2.12	-3.56	-0.08	0.77	1.02	-1.56

Table 10 shows the z-score of each participating laboratory for sample GELC-OD (omnidirectional LED lamps). For the total luminous flux measurement, the test result of GELC-LAB-2 is questionable; the test results of other five laboratories are satisfactory. For active power, the test results of all the participating laboratories are satisfactory. For luminous efficacy, the test results of four laboratories (GELC-LAB-3, GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6) are satisfactory; the test result of GELC-LAB-1 is questionable; and the test results of GELC-LAB-2 is unsatisfactory. For chromaticity x, the test results of four laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-4 and GELC-LAB-5) are satisfactory; the test results of GELC-LAB-3 is questionable; and the test results of GELC-LAB-6 is unsatisfactory. For chromaticity y, the test result of GELC-LAB-5 is questionable and those of the other five laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-6) are satisfactory. For CCT, the test result of GELC-LAB-6 is unsatisfactory and results of the other five laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-5) are satisfactory. For CRI, the test results of GELC-LAB-5 is unsatisfactory and the results of the other five laboratories (GELC-LAB-1, GELC-LAB-2, GELC-LAB-3, GELC-LAB-4 and GELC-LAB-6) are satisfactory.

Table 10 z-score for GELC-OD samples

	Total luminous flux	Active power	Luminous efficacy	Chromaticity x	Chromaticity y	CCT	CRI
GELC-LAB-1	-1.56	0.62	-2.38	-1.10	-0.12	0.77	-0.07
GELC-LAB-2	-2.26	1.91	-3.18	-1.21	-1.80	-0.33	1.57
GELC-LAB-3	-0.52	1.84	-1.59	-2.31	-0.74	1.21	0.67
GELC-LAB-4	-0.98	0.33	-1.47	-0.33	-0.37	0.00	1.13
GELC-LAB-5	0.65	-0.02	0.88	-0.55	-2.67	-1.16	3.09
GELC-LAB-6	0.09	1.48	-0.62	-5.29	0.43	4.35	-1.54

Table 11 shows the z-score of each participating laboratory for sample GELC-HCCT (high CCT LED lamps). For the total luminous flux measurement, the test results of GELC-LAB-3, GELC-LAB-5 and GELC-LAB-6 are satisfactory; the test results of GELC-LAB-2 is questionable; and the test results of GELC-LAB-1 and GELC-LAB-4 are unsatisfactory. For active power, power factor and chromaticity y, the test results of all participating laboratories are satisfactory. For luminous efficacy, the test results of four laboratories (GELC-LAB-2, GELC-LAB-3, GELC-LAB-5 and GELC-LAB-6) are satisfactory; the test result of GELC-LAB-1 is questionable; and the test results of GELC-LAB-4 are unsatisfactory. For chromaticity x, the test results of GELC-LAB-1 and GELC-LAB-2 are questionable; the test results of other four laboratories (GELC-LAB-1, GELC-LAB-3, GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6) are satisfactory. For CCT, the test results of three laboratories (GELC-LAB-4, GELC-LAB-5 and GELC-LAB-6) are satisfactory; the test results of other three laboratories (GELC-LAB-1, GELC-LAB-2 and GELC-LAB-3) are questionable. For CRI, the test result of GELC-LAB-2 is unsatisfactory and the results for the

other five laboratories (GELC-LAB-1, GELC-LAB-3, GELC-LAB-4 GELC-LAB-5 and GELC-LAB-6) are satisfactory.

Table 11 z-score for GELC-HCCT samples

	Total luminous flux	Active power	Power factor	Luminous efficacy	Chromaticity x	Chromaticity y	CCT	CRI
GELC-LAB-1	-3.18	-0.70	-1.64	-2.08	2.73	0.96	-2.04	0.23
GELC-LAB-2	-2.94	-1.21	-1.59	-1.59	-2.28	-1.42	2.45	3.02
GELC-LAB-3	-1.94	0.52	0.63	-1.81	-1.95	-0.94	2.05	1.01
GELC-LAB-4	-4.40	0.29	-0.28	-3.59	-0.26	-0.20	0.43	0.20
GELC-LAB-5	0.35	0.18	-0.64	0.16	-1.89	-1.73	1.81	1.74
GELC-LAB-6	-1.71	-1.65	0.09	-0.35	-1.56	0.13	1.27	-0.71

8.2. Photometric Quantities Measurements

Table 12 z-score for total luminous flux

	z-score of GELC-D	z-score of GELC-OD	z-score of GELC-HCCT
GELC-LAB-1	-3.59	-1.56	-3.18
GELC-LAB-2	-4.85	-2.26	-2.94
GELC-LAB-3	-1.80	-0.52	-1.94
GELC-LAB-4	-2.93	-0.98	-4.40
GELC-LAB-5	0.72	0.65	0.35
GELC-LAB-6	-2.89	0.09	-1.71

Table 12 shows the z-scores for total luminous flux. For sample GELC-D, the z-score calculated from the test results reported by GELC-LAB-1 and GELC-LAB-2, are greater than 3, which is considered to be unsatisfactory; the z-score calculated from test results reported by GELC-LAB-4 and GELC-LAB-6 are between 2 and 3, which means they are questionable. For samples GELC-HCCT, the z-score calculated from test results reported by GELC-LAB-1 and GELC-LAB-4, are greater than 3, which is considered to be unsatisfactory; the z-score calculated from test results reported by GELC-LAB-2 is between 2 and 3, which means they are questionable. For samples GELC-OD, there is no z-score above 3, and only the calculation from the test results reported by GELC-LAB-2 is between 2 and 3, which means it is questionable.

The possible reasons for the deviations found in the test results are:

8.2.1. raceability of the standard artefact

Laboratories should ensure that traceability of the standard artefact is reliable. This includes two aspects:

1) The calibration laboratory can provide highly reliable data.

2) Laboratories calibrate the integrating sphere system using the standard artefacts at the state at which the artefact was calibrated.

In this inter-laboratory comparison testing, the main purpose of testing GELC-OD sample is to inspect the traceability of the standard artefact. From the above analysis, GELC-LAB-2 showed a questionable test results on GELC-OD lamps. It is likely that GELC-LAB-2 needs to check their traceability process.

8.2.2. Sphere spatial non-uniformity correction

The integrating sphere system does not always stay at an ideal condition. For example, if there is too much dirt inside the sphere or there is an irregular stained or blemished area on the sphere, the reflectance of the sphere will be non-uniform. When there is a different light distribution between the standard artefacts and tested artefacts, the non-uniform reflection will lead to test errors. If a laboratory does not consider this element, and makes no data correction, it will cause a large numerical deviation. In general, as the light

distribution difference increases, the luminous flux deviation will increase, especially for samples which have a narrow beam angle (such as the GELC-D tested in this project). So when using a sphere system to test the samples with narrow beam angle, more attention must be paid to the spatial non-uniformity correction.

In this project, the total luminous flux test results of GELC-D-1# and GELC-D-2# reported by GELC-LAB-1 and GELC-LAB-2 are much smaller than the reference values. While the other two samples, GELC-OD and GELC HCCT, tested by these two laboratories also have smaller results than the reference values. For the GELC-D samples, the relative deviations are both over than 6%. We would suggest GELC-LAB-1 and GELC-LAB-2 check their integrating spheres, especially at the bottom.

8.2.3. Self-absorption correction

Normally, the standard artefacts and the tested artefacts have differences in shapes, size, colour, etc. If a laboratory does not make a self-absorption correction, test results will deviate. In this project, it is not clear if GELC-LAB-2 and GELC-LAB-3 have made a self-absorption correction on their test data, as it wasn't mentioned in their final test report. However, we would suggest that the laboratories conduct a self-absorption correction for all samples.

8.2.4. Near-Field absorption

If the lamp holder is very big, or there are other objects hanging near the sample, it will cause some light to be absorbed by those objects and lead to luminous flux data errors.

8.2.5. Others

All the factors mentioned above are problems that have been found in the test results of this project. However, in general testing there may be other influences on the test result. Although they are not obvious from this project, it is very important they are included in this report for the laboratories. Namely, the laboratories also need to focus on the following factors in their testing:

a) Testing procedures. During the testing, the precise details of the operation steps will directly affect the testing results. The burning position and direction of the sample in the sphere may lead to larger deviations from reference value(s).

b) Ambient temperature has an influence on the sample and solid-state lighting products are sensitive to temperature. Only considering the temperature outside of the sphere during the testing, without paying attention to the temperature inside, will affect the photometric quantities measurements. Small sized integrating spheres in particular may have this problem due to the heat accumulating when burning the lamps inside.

8.3. Colorimetric Quantities Measurements

Table 13 z-score for colour parameters

	Chromaticity x			**Chromaticity y**			**Correlated Colour Temperature (CCT)**			**Colour Rendering Index**		
	GELC-D	**GELC-OD**	**GELC-HCCT**	**GELC-D**	**GELC-OD**	**GELC-HCCT**	**GELC-D**	**GELC-OD**	**GELC-HCCT**	**GELC-D**	**GELC-OD**	**GELC-HCCT**
GELC-LAB-1	2.36	-1.10	2.73	0.53	-0.12	0.96	-2.53	0.77	-2.04	-0.05	-0.07	0.23
GELC-LAB-2	-0.96	-1.21	-2.28	-1.13	-1.80	-1.42	0.03	-0.33	2.45	1.77	1.57	3.02
GELC-LAB-3	-0.92	-2.31	-1.95	-0.48	-0.74	-0.94	0.75	1.21	2.05	0.75	0.67	1.01
GELC-LAB-4	0.56	-0.33	-0.26	-0.05	-0.37	-0.20	-0.85	0.00	0.43	0.12	1.13	0.20
GELC-LAB-5	-0.96	-0.55	-1.89	-1.39	-2.67	-1.73	-0.55	-1.16	1.81	1.54	3.09	1.74
GELC-LAB-6	-0.08	-5.29	-1.56	0.77	0.43	0.13	1.02	4.35	1.27	-1.56	-1.54	-0.71

Table 13 shows the z-score for colour parameters. For GELC-LAB-6, the z-score of chromaticity x and CCT are greater than 3 on sample GELC-OD, which is considered to be unsatisfactory. For GELC-LAB-5,

the z-score of CRI is greater than 3 on sample GELC-OD, which is considered to be unsatisfactory. For GELC-LAB-2, the z-score of CRI is greater than 3 on sample GELC-HCCT, which is considered to be unsatisfactory.

For GELC-LAB-1, the z-score for chromaticity x and CCT on samples GELC-D and GELC-HCCT are between 2 and 3, which means questionable. For GELC-LAB-2, the z-score for chromaticity x and CCT on samples GELC-HCCT is between 2 and 3, which means questionable. For GELC-LAB-3, the z-score for chromaticity x on samples GELC-OD and z-score for CCT on GELC-HCCT are between 2 and 3, which means questionable. For GELC-LAB-5, the z-score for chromaticity y on samples GELC-OD is between 2 and 3, which means questionable.

As shown in Table 13 only the results of GELC-LAB-4 are satisfactory for all colour parameters. The reasons for unsatisfactory and questionable results might be caused by:

8.3.1. Traceability of the standard artefact

As mentioned in 8.2, laboratories should ensure that the traceability of the standard artefact is reliable. It includes two aspects:

a) The calibration laboratory can provide highly reliable data.

b) Laboratories calibrate the sphere system with standard artefacts perfectly.

The traceability of the standard artefact not only affects the photometric test results, but also the colour test results. This project found that GELC-LAB-2 also showed some unsatisfactory or questionable results on the colour parameter tests. Therefore, we would suggest GELC-LAB-2 checks their traceability process.

8.3.2. Software for calculation

The software algorithm has a big effect on the test results. If the test results show a small deviation of chromaticity x and chromaticity y, but a big deviation of CCT and CRI, the reason is probably the software algorithm.

Based on the test results reported by the participating laboratories, GELC-LAB-2, GELC-LAB-3 and GELC-LAB-5 need to check and pay closer attention to the software used to calculate the CCT and CRI.

8.3.3. Response of photodetector

All the factors mentioned above are problems that have been found in the test results of this project. In general testing, there may be other influences on the test result. Although they are not obvious in this project, it is also necessary to present them here for the laboratories, including the response of photodetector.

Laboratories may use different types of detecting devices (photometer/spectroradiometer, etc.). If the device is ideal, then there is no effect on the test results. However sometimes, response problems of devices can be found which will cause a deviation of colorimetric quantities measurements.

8.4. Electrical Quantities Measurements

Table 14 shows the z-score for electrical quantities measurements in this project. It can be seen that electrical parameters have fewer unsatisfactory values than the photometric and colorimetric quantities. For all the participating laboratories, the z-score of active power is no greater than 2, which is generally considered to be satisfactory. For power factor, only the z-scores of GELC-LAB-3 and GELC-LAB-6 are a little greater than 2. Generally the test result could also be considered to be acceptable.

Table 14 z-score for electrical parameters

LAB	Active Power			Power Factor	
	GELC-D	GELC-OD	GELC-HCCT	GELC-D	GELC-HCCT
GELC-LAB-1	-0.99	0.62	-0.70	0.13	-1.64
GELC-LAB-2	-1.37	1.91	-1.21	1.70	-1.59
GELC-LAB-3	0.73	1.84	0.52	2.03	0.63
GELC-LAB-4	0.24	0.33	0.29	0.37	-0.28
GELC-LAB-5	0.12	-0.02	0.18	1.30	-0.64
GELC-LAB-6	-1.19	1.48	-1.65	2.12	0.09

The cause of the active power deviations might be because the four-terminal method was not used to connect the circuit. The four-terminal method is important to enable a high quality measurement for electrical testing on lighting products. The voltage line should be connected directly to the positive and negative electrode of the lamp holder, in order to reduce the effect of the contacting resistance of the voltage measurement. We suggest all the participating laboratories pay closer attention to the four-terminal method.

9. Conclusion

This inter-laboratory comparison testing project was designed in compliance with ISO/IEC 17043, *Conformity Assessment – General Requirements for Proficiency Testing*, for the purpose of identifying the differences in test results among the participating laboratories and analyzing the potential testing issues that exist. Six lighting laboratories from Southeast Asia countries were invited by the UNEP-GEF en.lighten initiative to participate in this inter-laboratory comparison testing activity.

In this comparison test, three different types of LED lamps were selected to measure their photometric, colorimetric, and electrical parameters in each laboratory. This report analyzed each participating laboratory's test results against the reference laboratory (GELC)'s reference values. As mentioned in the Section 9, all the electrical test results from the six participating laboratories are generally considered to be satisfactory. However, the test results also showed that deviations exist between the reference values and the test results of the participating laboratories, especially for the photometric and colorimetric parameters. Based on the result analysis, it suggests the participating laboratories pay closer attention to the factors listed in Table 15, such as the traceability of the standard lamp, sphere spatial non-uniformity correction, self-absorption correction, etc., which may help to make improvements to testing accuracy. It is probable that training will be needed to improve these factors.

Table 15 Summary of Potential Improvements

Photometric Quantities Measurements	**Colorimetric Quantities Measurements**
Traceability of the standard artefact	Traceability of the standard artefact
Sphere spatial non-uniformity correction	Software for calculation
Self-absorption correction	Response of photodetector
Near-Field absorption	/
Testing procedures/working instruction	/
Ambient temperature	/

This inter-laboratory comparison testing project found several issues that some participating laboratories may have. However, these findings are based solely on the test results provided by the laboratories and there are many other factors that could influence the test results during the actual testing. Therefore, further cooperation with the laboratories is recommended to help to identify more solutions and provide specific recommendations to the laboratories for their capacity enhancement.

10. Reference

[1] ISO/IEC , "Conformity Assessment – General Requirements for Proficiency Testing," 1st Edition, 17043: 2010.

[2] ISO, "Statistical Methods for Use in Proficiency Testing by Inter-laboratory Comparisons." 1st Edition, 13528: 2005

[3] ISO, Guide to the Expression of Uncertainty in Measurement, 1st Edition, 1993.

[4] CNAS:, "Guidance on Statistic Treatment of Proficiency Testing Results and Performance Evaluation.", 1st Edition, GL02: 2014