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**MAINS OPERATED LED BASED TRANSFER SOURCE FOR
LUMINOUS FLUX SCALE REALISATION AND
DISSEMINATION**

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MAIN S OPERATED LED BASED TRANSFER SOURCE FOR LUMINOUS FLUX SCALE REALISATION AND DISSEMINATION

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Abstract

Mains operated lamps have been developed to enable LED based luminous flux scale realisation at NMI level and dissemination to testing laboratories. Stable power consumption and luminous flux, as well as well-defined spectral power distribution (SPD) are key design criteria for the lamps. Five of the lamps were seasoned for 800 hours, after which their SPDs and spectral luminous intensity distributions were measured for the purpose of predictable quantum efficient detector based scale realisation. One of the lamps was seasoned for 200 hours, after which the electronic performance and stability was assessed. After warmup of 30 minutes the lamps have luminous flux stability of 0.1 %, power factor higher than 0.97, and total harmonic distortion of the current (3.80 ± 0.38) %. When powered through an impedance stabilized power network the relative difference in power consumption measured at bandwidths from 1 kHz to 300 kHz was within 0.017 %.

Keywords: luminous flux, scale realisation, scale dissemination, reference lamp, LED

1 Luminous flux traceability (motivation, specific objective)

Global phase out of incandescent light sources has drastically changed the lighting industry over the past years. Consequently, many laboratories are nowadays measuring LED light sources rather than incandescent light sources. This has changed the requirements for traceability chains and calibration lamps used by laboratories. Traditional luminous flux measurements rely heavily on the use of tungsten filament standard lamps operated close to the correlated colour temperature of CIE Standard Illuminant A (2856 K) ("CIE S 014-2," 2006), and integrating spheres or goniophotometers equipped with $V(\lambda)$ -filtered photometers. A new traceability route has been introduced based on LED calibration sources and detectors without optical $V(\lambda)$ -filters, instead utilizing silicon based trap detectors or predictable quantum efficient detectors (PQEDs) together with the SPD of the LED source (Pulli et al., 2015). To enable this traceability route, LED based luminous flux transfer light sources with highly stable luminous flux and commonly agreed spectral power distribution are required. Also, even when using a traditional $V(\lambda)$ -based measurement setup, the use of a LED based reference lamp will generally reduce the spectral mismatch error when other LED sources are measured (Kokka et al., 2018)

In this work, an LED based light source was designed that can not only be used for luminous flux realisation at NMI level, but also for calibration of luminous flux responsivity of integrating sphere photometers and goniophotometers by test laboratories. This introduces additional requirements such as compatibility with European two wire mains voltage (230 VAC), E27 fitting and a high power factor to reduce the impact of voltage and current phase measurements error on power measurements. The lamps are designed to have a luminous flux output of approximately 800 lm, stability better than 0.1 %, and active power consumption that is stable within 0.5 %.

In this paper, seasoning, characterization and calibration of the developed luminous flux transfer sources are reported.

2 Methods

2.1 Source design

The designed lamps (Figure 1), contain five high-power LEDs on a printed circuit board (PCB) with spectral properties selected close to correlated colour temperature of 4000 K, based on a new proposal of an LED reference spectrum. The LED circuit board is covered with a diffuse dome to improve the uniformity of the angular intensity distribution. The LEDs were selected to yield high luminous flux and colour stability. To ensure both constant power consumption from the mains as well as stable current driving the LEDs, an AC/DC LED driver has been developed. The driver was designed to consume more power than needed to drive the LEDs. The excess power makes it possible to regulate both the consumed power from the mains as well as the power (current) needed for the LEDs. Any excessive power is dissipated as heat. The driver was built by combining a rectifier followed by a power factor correcting DC/DC converter. From the stable intermediate DC voltage, a constant current regulator stabilizes the current flowing through the LED PCB to ensure a stable luminous flux and spectral power distribution. Care has been taken to make the circuit insensitive to temperature changes by both selecting components that are temperature insensitive and placement on the PCB away from heat sources. A circuit board with a specific form factor, not to obscure the light emitted from the LEDs, has been developed which contains the LED driver. Furthermore, the components on the circuit board as well as the LEDs are actively cooled with a built-in DC fan. The driver circuit was tested for power consumption with varying load and stabilisation time of consumed power when switching-on the driver.



Figure 1 – Mains operated led based lamp for luminous flux.

2.2 Seasoning

After fabrication, five of the lamps have been seasoned for 800 hours to improve their photometric long-term stability. To maximize the amount of burning hours, while still including possible ageing effects due to on/off-switching, the lamps were burned for 23,5 h each day while being switched off twice for 15 minutes to allow the lamps to cool down. During the seasoning, the temperature of each light source was recorded every 5 minutes with temperature sensor attached onto the top screw heads on each lamp. This position was chosen as it corresponds to the maximum lamp temperature when measured with a thermal camera. At approximately 100 hour intervals the relative luminous flux and the spectral distribution of each lamp were measured using a \varnothing 50 cm integrating sphere equipped with a photometric detector and a fibre optic sensor for spectral measurements using spectroradiometer with TE cooled CCD. The sphere was mounted on a hydraulic lift allowing it to be easily moved between the lamps and accurately positioned for the measurements. For stability monitoring of the whole setup, another LED lamp with more than 5000 h burn time and verified stability was always measured together with the lamps. Additionally, basic electrical parameters such as RMS current, active power and power factor were monitored at the same intervals.

2.3 Electronic characterization

One of the built lamps was characterized for electronic performance after 200 hours of ageing. The lamp was mounted in base-up position and powered by a stable 230 V AC-source. During warm-up, the operating voltage, RMS current, active power and power factor were measured. To minimize voltage-drop, the voltage was measured as close as possible to the socket of the lamp ("CIE S 025," 2015). To study the impact of power analyser bandwidth on the measurements, the electrical parameters have been measured additionally by switching the higher corner frequency of the power-analyser from 1 kHz to 2 kHz, 5 kHz, 15 kHz, 30 kHz, 45 kHz, 65 kHz, 75 kHz, 100 kHz, and 300 kHz. The same procedure was repeated using the Impedance Stabilization Network (ISN), developed for the project EMRP Metrology for efficient

and safe innovative lighting, MESaIL (Zhao, 2017). To determine the total harmonic distortion (THD) of the lamp current, a custom-made electrical measurement system for SSL products was used consisting of a stable 230 V AC-source and a digitizer card, developed for the EMRP project MESaIL (Zhao et al., 2016).

2.4 Luminous intensity distribution

To verify that all lamps have similar spectral power distribution and luminous intensity distribution, goniometric measurements were performed using a type C goniometer. These results are needed to achieve the lowest uncertainty when calibrating the total luminous flux of the lamps using an integrated sphere, in order to compensate for sphere non-uniformities and determining the effective spectral distribution when using a PQED in the luminous flux calibration of the sources. For each lamp, the luminous intensity distribution was determined in 1° steps and in six equally distributed c-planes using a photometric detector located 25 m away from the lamp. A similar measurement but in 5° steps was done using a spectrometer with the collecting integrating sphere located about 40 cm from the lamp centre. Due to the lamp design and the used lamp holder, it is estimated that the light emitted backwards (towards the socket) is blocked within $\pm 15^\circ$ which should be considered when interpreting the results.

2.5 Reference lamp calibration

The total luminous flux calibration of the lamps is carried out using an absolute integrating sphere that utilises a stable external LED standard lamp with spectral properties close to the proposed LED reference spectrum. In the luminous flux calibration, the external reference luminous flux is produced by measuring illuminance of the external LED source using an unfiltered PQED (Kokka et al., 2018; Meelis-Mait Sildja, n.d.; Müller et al., 2013; Sildoja et al., 2013) accompanied with a double monochromator spectroradiometer for obtaining the photometric weighting, and passing the emitted light into the sphere through a precision limiting aperture. The relative spectral radiant flux of the lamps is measured using a gonio-spectroradiometer. In the calibration, the lamps are operated with a stable 230 V AC-source.

3 Results

3.1 Seasoning

Apart from an initial drop in luminous flux for four of the lamps during the first 150 h, the stability over the seasoning period was within ± 0.2 % for all lamps. This is about the same as the estimated long-term repeatability of the monitoring method which means that no final conclusions regarding possible small trends can be drawn yet, but the stability for all five lamps are well within what is required for their intended use. A similar drop of luminous flux was observed when seasoning DC-driven LED PCBs with no additional electronics. Also, no significant changes in either electrical parameters nor spectral characteristics have been detected. The seasoned lamps proved to have a short term stability better than 0.07 % for power and 0.1 % for luminous flux after 6 minutes and 30 minutes of stabilisation, respectively. After 45 minutes of warmup the luminous flux stability of the lamps improve even further to better than 0.01%.

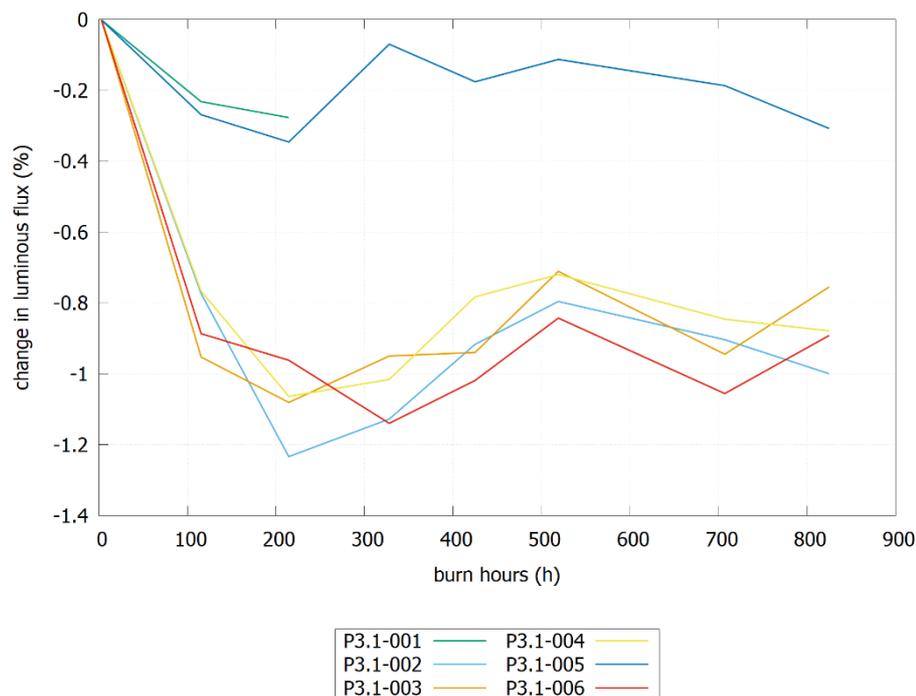


Figure 2 – Change in luminous flux during seasoning. Note that one lamp (ID P3.1-001) was removed after 200 h as it was needed for the electronic evaluations.

3.2 Electronic characterisation

During a stabilization time of 35 min all measured electrical parameters showed a stable read out within the required 0.5 % according to the standard CIE S025 (“CIE S 025,” 2015). Moreover, after 15 min the curves tend to reach a plateau Figure 3. The aim of stabilization time to achieve 0.1 % variation of power is only about 2 minutes, rather shorter than the 45 minutes for typical commercial lamps with consumer grade AC/DC electronics. Furthermore, the demand of a high power factor for the developed luminous flux standard lamp, to potentially improve the stability of AC voltage supply during measurement, could be achieved as a value of 0.971 ± 0.016 for the power factor was calculated from the measured parameters (Table 1)

Table 1 - Optical and electrical parameters of lamp P3.1-001 with expanded uncertainties.

Quantity	Values
RMS Voltage	230.0 V
Frequency	50.0 Hz
RMS Current	(89.44 ± 0.21) mA
Apparent power	(20.57 ± 0.03) VA
Active power	(19.97 ± 0.20) W
Power factor	0.971 ± 0.016
Luminous flux	(809 ± 10) lm
Luminous efficacy	(40.54 ± 0.72) lm/W
Total harmonic distortion of the voltage without ISN	(0.0937 ± 0.0046) %
Total harmonic distortion of the current without ISN	(3.91 ± 0.39) %
Total harmonic distortion of the voltage with ISN	(0.49 ± 0.024) %
Total harmonic distortion of the current with ISN	(3.80 ± 0.38) %

Measuring the electrical parameters with different high corner frequency settings of the power analyser showed that the active power, RMS current and the power factor depend on the bandwidth (Figure 4). This dependency can be reduced by using an ISN in the electrical measurement network (Figure 5). With the ISN, the current readout for lower bandwidths (higher

corner frequency was changed between 1 kHz – 300 kHz) showed improved stability compared to the measurements without ISN. In Table 1, the THD measurement with and without ISN is summarized for a power analyzer with a high corner frequency set to 200 kHz. Both the voltage THD and the current THD were measured. The THD of the voltage supply increases slightly when the ISN is included in the measurement system because the current harmonics of the load create additional voltage drop along the inserted ISN.

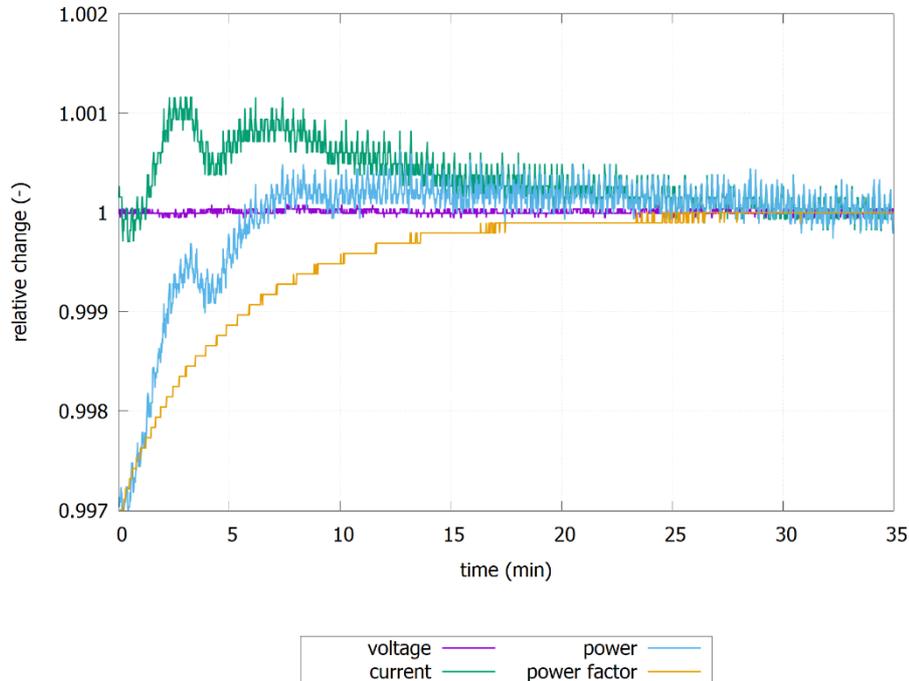


Figure 3 – Stabilisation of voltage, current, power and power factor of lamp P3.1-001 after power on.

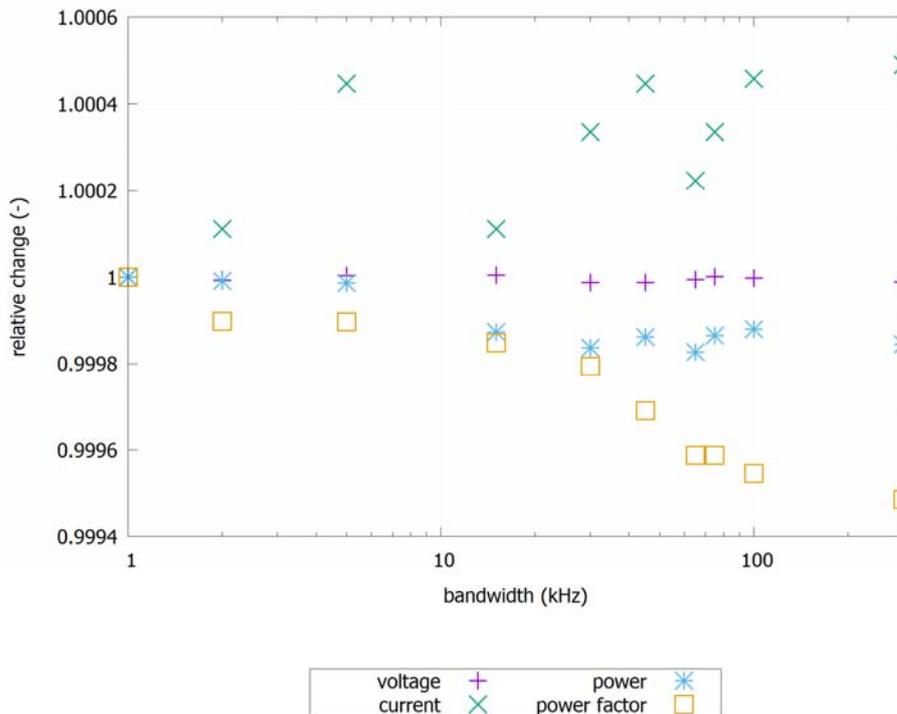


Figure 4 – Relative changes of the electrical parameters of lamp P3.1-001 measured with varying bandwidths from 1 kHz to 300 kHz without ISN.

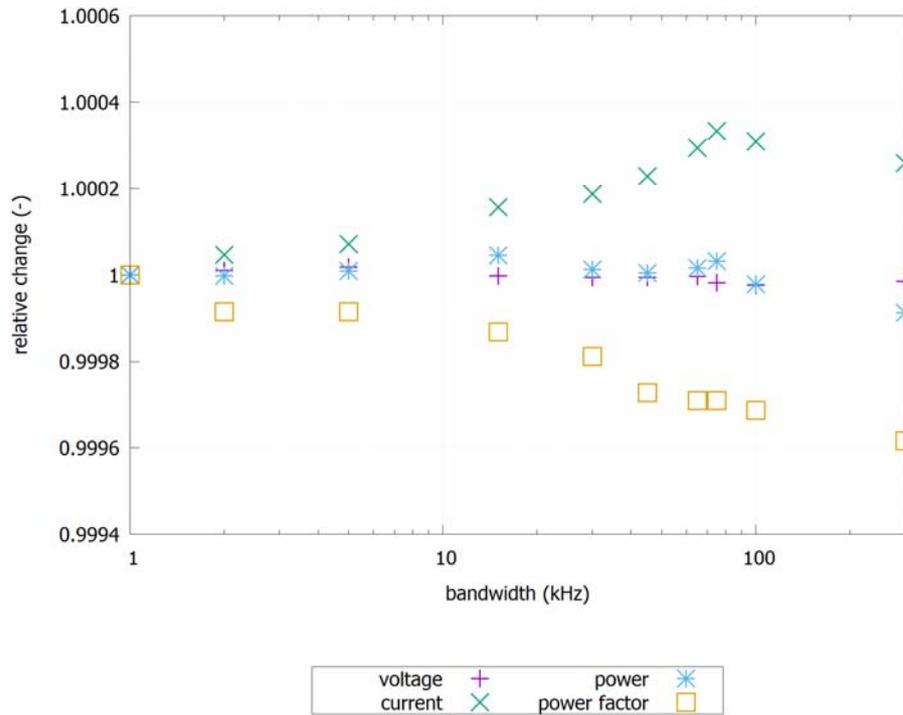


Figure 5 – Relative changes of the electrical parameters of lamp(ID P3.1-001) measured with varying bandwidths from 1 kHz to 300 kHz with ISN.

3.3 Optical characterisation

In terms of luminous intensity distribution, as well as the spectral angular distribution, all five evaluated lamps are very similar. As shown in Figure 7, the symmetry around the lamp axes and the c-planes are generally good although with some individual variations and one of the lamps exhibiting an asymmetry of about 10% for the luminous intensity. However, the influence of this should be negligible in most applications and could also be corrected for if needed. In terms of the spectral distribution, all lamps have the highest CCT in the 0° direction (~4100 K). The CCT then slowly decreases towards the sides to about 3900 K at ±160°. The effective colour temperature when integrating the flux over 4π decreases about 100 K compared to the 0° value.

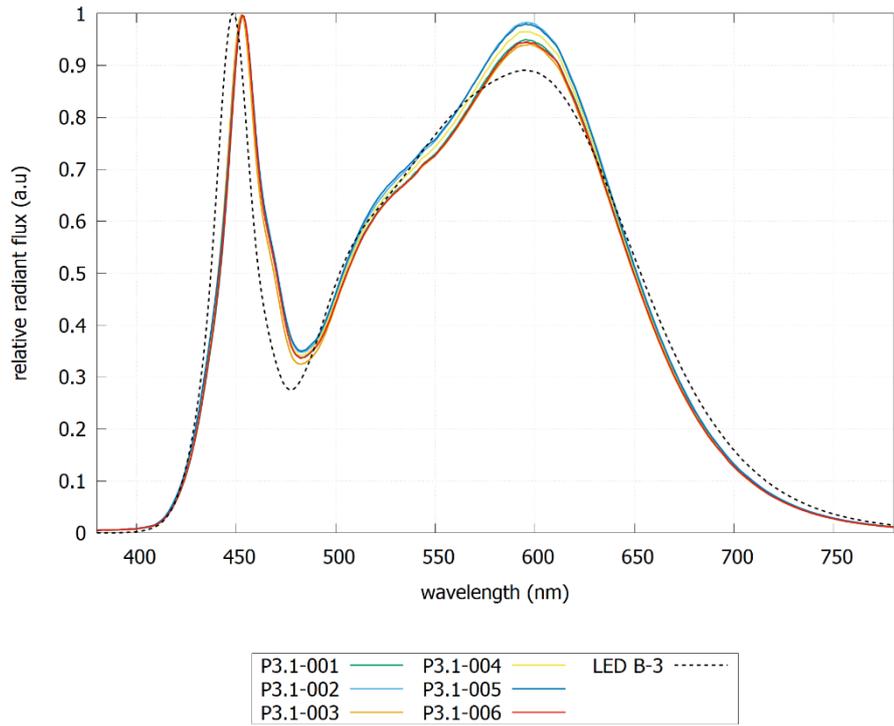


Figure 6 – Relative spectral power distributions of the lamps and the reference spectrum (LED B-3).

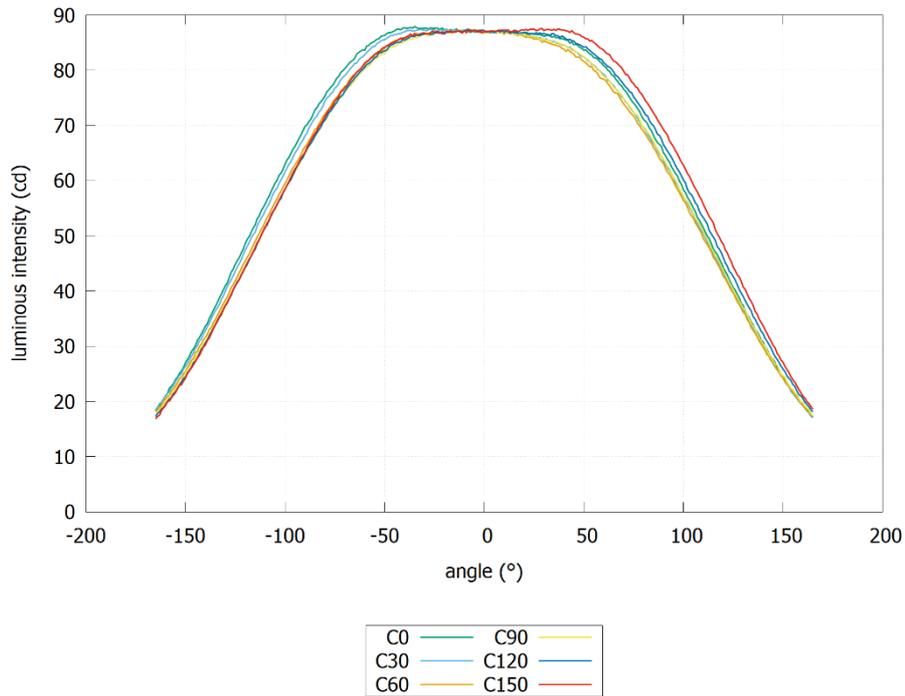


Figure 7 – Luminous intensity distribution for lamp P3.1-002.

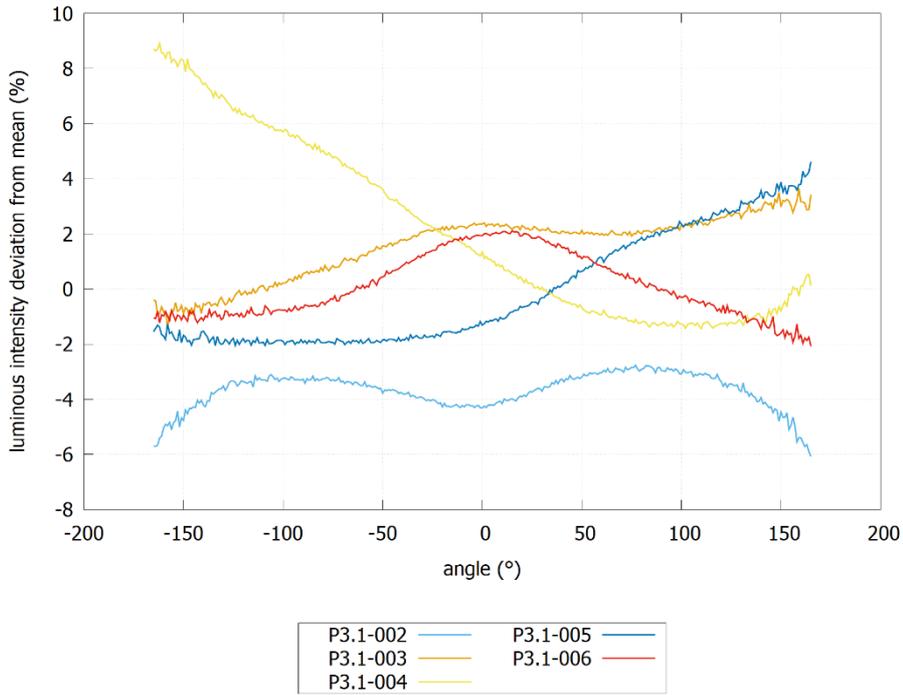


Figure 8 – Deviation of luminous intensity distribution for each lamp relative to the mean.

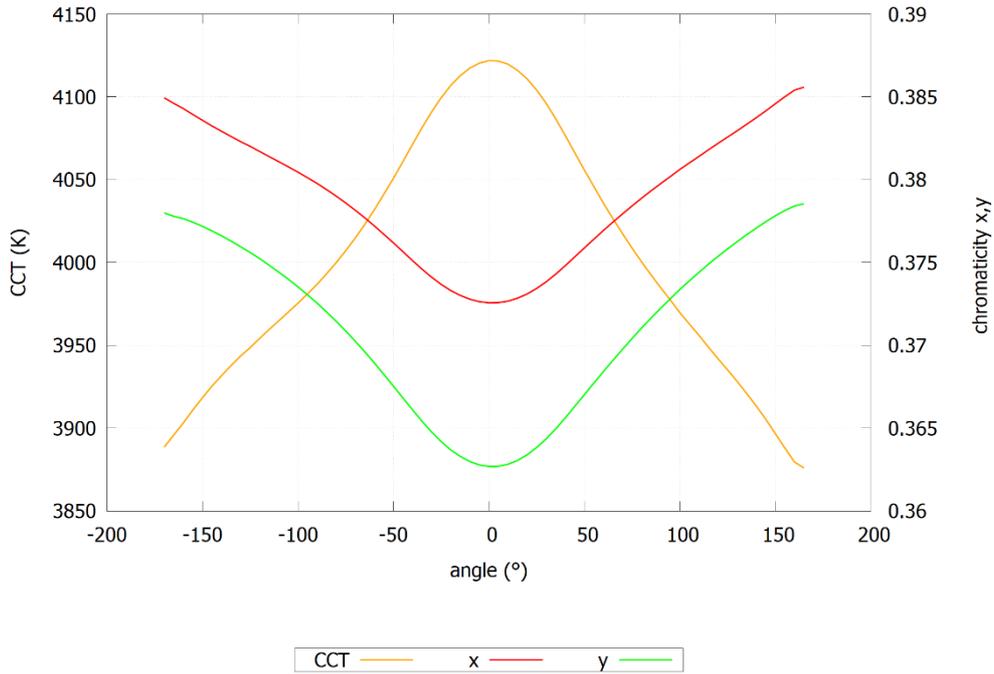


Figure 9 – Correlated colour temperature, chromaticity coordinate x and y for lamp P3.1-002.

4 Conclusion

Mains operated, highly stable E27-base luminous flux transfer sources based on white LEDs have been developed. Seasoning the lamps for about 800 hours proved to be sufficient to achieve a long term luminous flux stability of better than the repeatability of the measurements

facility, namely 0.2 %. After a warmup period of 30 minutes the short term luminous flux stability of the lamps is better than 0.1 %. An even better luminous flux stability of 0.01% can be obtained by extending the warmup period to about 45 minutes. Electronic evaluation of the lamps show that the input power variation can be restricted to 0.1 % (the goal was 0.5 %) after 2 minutes of stabilization time and the RMS current fluctuation can be limited to 0.1 % instantly (the goal was 2 %). Thus, the achieved performances are satisfactory and significantly better than the initial goals. Also, the lamps have power factors higher than 0.97 and THD of current lower than 4 % which facilitates good lamp stability and comparable operation conditions even when different types of AC voltage sources are used.

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