UV LED curing systems: Measuring accurately and eliminating safety hazards

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Abstract

The Ultraviolet (UV) LED technologies are progressing very rapidly in recent years both in performance and cost. Therefore, the measurement equipment and methods for UV LED curing systems are required to be well understood. This paper focuses on the measurement and characterization of the UV LED curing systems, particularly in the UVA range. Moreover, the risks and safety concerns of UV light will be discussed in the paper with a focus on illuminating the inherent advantage of LED.

Introduction

In recent years the demand to incorporate UV LED in curing systems instead of conventional UV lamps has increased significantly. Although applications using UV light sources are still dominated by UV lamps, it was reported by Yole Développement that the forecast of market share of the UV LED has increased from 19.1% in 2014 to 41.4% in 2019 [1]. Furthermore, the total market size of UV LED has increased from US$20.2M in 2008 to US$ 127.0M in 2015 and has been predicted to further increase to reach US$572.5M in 2019 as depicted in Fig.1. Coherent with Yole Développement's report, the study done by Allied Market Research showed that the global UV LED market size is expected to reach $1.2 billion by 2026 from $271.1 million in 2018, growing at a CAGR of 17.3% from 2018 to 2026 [2]. UV curing like inks, coatings and adhesives applications accounts for nearly 60% of UV LED's market size and more than 50% of the users are in Asia. UV curing is a process of utilizing the UV light to initiate the photo-chemical reaction that generates crosslinked network of polymers.

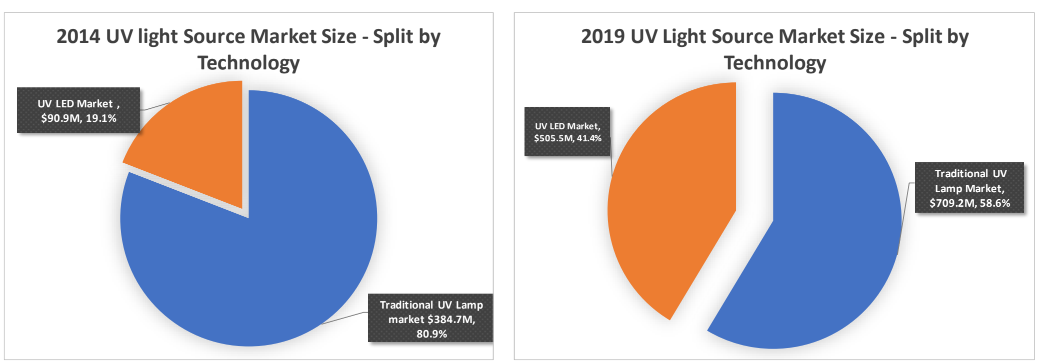


Fig. 1: Report from Yole Développement about the market share of UV LEDs vs traditional UV lamps

The strong growth of UV LEDs is mostly determined by its attractiveness over conventional UV lamps. Some of UV LED's advantages are discussed below:

a. Compactness

UV LED can be utilized in system as SMD package form or in die form factor using COB technology. As a result of its "flexibility", the design of UV LED emitter for curing system becomes compact. Different types of curing system such as flood, spot or modular system can be designed. This flexibility is difficult to realize if the curing system utilizes traditional UV lamps. For example, an end-of wand spot based UV curing system: UV lamp based UV curing system needs long lightguide to divert the light into the spot making the system looks bulky, while the UV LED based curing system can be designed in such a way using only an aspheric lens to converge the light resulting in a simple and compact design with higher efficiency light output.

b. Longer product lifetime
Typical lifetime of conventional UV lamps is about 2000 hours while the UV LED's life is usually reported to be in the range 20000 hours [3]. Typically, UV LED manufactures follow the test standards (LM-80 and TM-21) that are applied to the visible wavelength LEDs to determine the lifetime. The lifetime of the UV LED is defined as the number of operating hours until the degradation of output light reaches the defined level, noted as L_p where p is the percentage of the initial output power. In visible LED, L_{70} is commonly used to determine the lifetime of LED. Higher lifetime of the light source in the system is beneficial for end-user because of its longer replacement cycle, less down-time for the system and it also provides stability overtime. Lifetime can be extended if the UV LED system is operated under intermittent mode Furthermore, the lifetime of the light source depends highly on the driving current and device and environment temperature. Currently, the technology of UV LEDs in UVA region is more advanced and mature compared to UV LEDs operated in the UVB and UVC region. When the UV LED is integrated into the system, for instance emitter and curing system, the lifetime of other parts must also be considered. Therefore, the rated lifetime of the UV LED systems such as UV light curing systems will be shorter at UV LED package level compared to system level. Hence, the actual lifetime should be determined as use-condition in the application. However, the root cause of the system's failure is often due to the environment, the auxiliary system design [4] and the possibility that the end-user does not follow the system's installation requirement.

c. Environment friendly (i.e O-zone and mercury free)
The UV lamp's emission spectrum shows multiple peaks spreading from UVC to the visible spectrum. At the short wavelength which is typically from 160-240nm, the UV light can convert the oxygen into O-zone (O_3). The produced O-zone can be a health issue if it is inhaled for prolonged period. Therefore, it is suggested that the ventilation system surrounding the process should be setup properly to reduce the risk. Furthermore, some conventional UV curing systems use mercury based UV lamp for the emitter. Mercury contamination can occur if the UV lamp is broken. Hence, there will be a safety instruction necessary to handle the breakage of mercury based UV lamps. UV LED's emission only has a single peak with the typical bandwidth of 9-15nm which can be selected, thus entirely avoiding the wavelength ranges that can produce O-zone, especially for curing applications utilizing UV light at UVA and UVB bands. Additionally, the UV LEDs are made of semiconductor material (InGaN type) which is much safer and does not contain harmful materials or complicated procedure for disposal.

On top of the above-mentioned points, there are additional benefits supporting the environmental friendliness: less electrical power consumption, no-warm up time and immediate performance availability and the ease of maintenance with less service intervals are other inherent advantages of UV LEDs.

With the increased demand of the UV LED for curing applications, end-users gradually shift from UV lamp based curing systems to UV LED based curing systems. While there are many advantages using UV LEDs over UV lamps in curing applications [5-8], there are still some technological challenges in performance and remaining safety risks that UV curing system integrators, metrology device providers and end-users will encounter. For instance, the end-user must study and carefully match the adhesive and the UV LED system in terms of adhesive's absorption and LED's wavelength. The end-user needs to characterize the system by evaluating peak irradiance, energy and curing time needed in order to achieve the optimized curing process.

Another key challenge involves proper measurement method of output light from the UV LED system for curing applications. With proper method and right measurement tools such as UV radiometer, the output light of the UV curing system can be measured accurately. This measurement of output light in the manufacturing line is highly recommended for production consistency. The measurement is aimed:

a. To ensure reliable application performance
b. To ensure repeatability and stability of the curing process
c. As preventive measure to monitor the degradation of the curing system

Therefore, this report aims to give an overview and recommendations to the end-users of UV LED curing system such as experienced process engineers, manufacturing engineers and technicians on the performance measurement of UV LED curing system using appropriate radiometer. The report also covers the risks and safety concerns in operating UV LED curing system.

UV radiation and safety concerns

The UV radiation is a radiation in form of electromagnetic waves with wavelength range between x-ray and visible light (10-400nm). Sources of UV radiation can be natural like from the sun or artificial such as mercury-vapor lamps, black lights, metal-halide lamps, UV LEDs and UV lasers. Based on its wavelength range, the UV radiation can be classified into:

a. UVA: 315-400nm
b. UVB: 280-315nm
c. UVC: 180-280nm
d. Vacuum/extreme UV: 10-180nm

Although there are negative effects of UV radiation on human health and environment (O-zone creation), the UV radiation can also be beneficial for our lives [9]. It can be the source of Vitamin D. In industrial and medical applications, UV radiation is widely used in: curing polymers and ink, UV light in medical phototherapy treatment, forensic analysis, water disinfection, sterilization of certain viruses, horticulture lighting for optimal photosynthesis, etc.

This chapter discusses the safety of using UV light in curing application. For application in adhesive curing, it typically utilizes radiation at UVA region because majority of the polymers and ink can only be cured by UVA light due to their specific properties of the photo-initiator used in the formulations. The biggest hazard of the conventional UV lamp based system is the UV radiation from the emitter. Being exposed to excessive dose of UV radiation can be dangerous for human. UV radiation especially in UVA and UVB spectrum can lead to different types of cataract and other eye diseases, skin cancer, sunburn and accelerated skin ageing. There is also evidence that UV radiation reduces the effectiveness of the immune system [8]. The curing systems available in the market use conventional UV lamp as the light source and this lamp emits not only in UVA but also UVB and some visible spectrum.

However, using UV LED system is inherently safer, the emitter's wavelength is controlled in UVA region with a narrow bandwidth. Thus, from safety perspective, the risks of UV LEDs are more manageable with easy precautions.

When it comes to the maximum value of UV exposure, most authorities follow the UV exposure threshold limit values (TLVs) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH). The recommended TLV value for the UVA wavelength region (315 to 400 nm) should not exceed 1.0 mW/cm^2 for period greater than 1000 seconds (approximately 16.7 minutes) and for exposure time less than 1000 seconds, the total energy should not exceed 1.0 J/cm^2. To put it into perspective, 1 mW/cm^2 is the typical intensity level in a cloudless spring day in New England measured using a radiometer that is pointed directly at the sun [10].

Effects on the eye

UV light exposure to eyes has been associated with cataract and retinal degeneration. The cornea and intraocular lens are the most important tissues of the eye to absorb UV radiation. As reported by Walsh [11], cornea absorbs the most UVB light (below 300nm) and the intraocular lens absorbs UVA light (below 370nm) as illustrated in Fig 2. It is therefore recommended to wear UV grade eye protection when operating an UV light source or in close proximity to the UV curing system. The safety eye protection must be qualified under the OSHA and ANZI Z87.1 standard. For UV radiation protection, the safety eye wear code is indicated in letter "U" followed by a number on the scale 2-6, with 6 being the lowest transmission of UV radiation through the eye wear. It is advisable to consider the following factors in choosing the appropriate safety eye protection: (1) the ability of the safety eye wear to protect against specific workplace hazards other than UV radiation, (2) provision of unrestricted vision and movement and (3) it should not interfere with or restrict the function of any other PPE the employee wears.

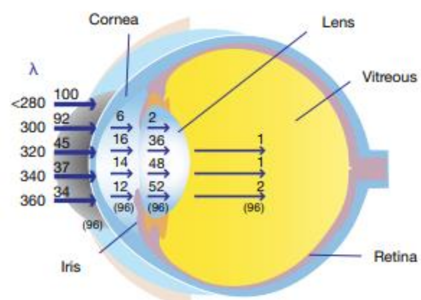


Fig.2: Intraocular filtering by UV radiation by ocular tissue [10].

Besides safety eye wear, a protective shield can also be used as additional protection to minimize the exposure of UV light to the end-user since UV emitter in the curing machine might emit stray light even away from the application surface. The possibility that stray light can leak is high because it can arise from the light reflection on various surface materials and improper installation or design of the system. The UV protective shield can be made of black anodized or black coated metal sheets, rigid plastic films typically acrylic and polycarbonate, or flexible films such as UV blocking flexible urethane film [12]. Plastic materials are melted at very low temperature compared to metals. Therefore, the shields which are made from acrylic or polycarbonate must be placed in sufficient distance from the light source to overcome the heat generating by UV light sources especially conventional UV lamps to avoid any form of softening,

Effect on the skin

The effects of UV radiation on skin can be classified into two categories namely acute which its effects appear within a few hours of exposure, and chronic effects, which are long-lasting and cumulative and may not appear for years. An acute effect of UV radiation can appear as redness of the skin called erythema or sunburn. Chronic effects include accelerated skin aging and skin cancer. Furthermore, the UVB radiation's effect in the skin tissue is associated with the skin burning which increase the likelihood of developing skin cancer [13]. The effect of UVA radiation which penetrates deeper into the skin tissue as depicted in Fig. 3 is associated with premature skin ageing and can also lead to skin cancer.

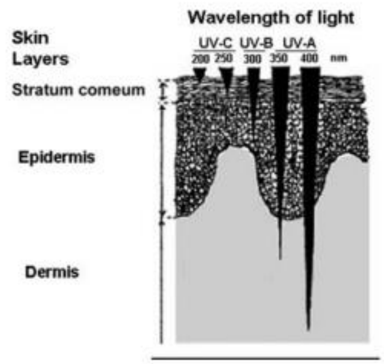


Fig. 3: Penetration depth of UV radiation into skin tissue [14]

To protect the skin from UV radiation, end-users are recommended to use appropriate gloves and coats. Gloves' materials such as nitrile, latex, or tightly woven fabric are suitable to protect the skin against large amount of UVA and UVB. Dark and shiny color can also prevent UV radiation from penetrating the skin by absorption and reflection respectively. These types of gloves have low UV transmission compared to vinyl based gloves. During the operation of UV light, wearing a long sleeve coat is recommended to ensure that the skin is not exposed to UV radiation.

To mitigate the risks of UV radiation exposure, control measures must be designed carefully to minimize exposure to eyes and skin and to prevent the (cumulative) exposure. The precautions needed depend on the risk assessment. If end-users are unsure about the quality of the safety equipment of the UV curing system, they should use a UV light meter/radiometer to measure the stray light at the location of interest. The measurement of UV light using a radiometer is discussed in next chapter.

As discussed, LED UV sources are inherently safer to operate then conventional UV light sources. However, an important element in achieving the goal of eliminating the risk of UV radiation exposure is training and awareness for end-users.

Guideline for measuring UV LED curing system

The quality and consistency of the end-result in the polymerization process of an adhesive depends on many factors. One of the factors is stability and consistency of the UV light output including the radiant power and irradiance. It is therefore very important that the output light of the curing system is checked and monitored regularly to ensure its power or irradiance value is maintained at desired level over time. In this chapter, the guideline for measuring the UV curing system especially for UV LED based curing system shall be elaborated.

Optical parameters of UV LED curing system

Generally, basic optical parameters of UV LED curing systems consist of:

a. Peak wavelength

The wavelength emitted from UV LED is controlled by the selected/engineered semiconductor and doping materials [15, 16]. Unlike conventional UV lamps, the emission of UV LEDs has a "reasonably monochromatic" spectrum (or rather one peak) with specific peak wavelength and relatively narrow bandwidth, typically between 9-15nm, compared to visible LEDs bandwidth. A Spectrometer is required to characterize the wavelength parameters of the UV LED curing system.

b. Peak irradiance

Irradiance is a measure for indicating the intensity of the light on a specific application surface, emitting from a UV LED. It is expressed in unit W/cm^2 or mW/cm^2. Irradiance decreases exponentially with increasing distance. In the specification of UV LED curing system, peak irradiance value is used as a key parameter. Per definition, peak irradiance is the highest irradiance at a point of reference measured by a light meter or a radiometer. Datasheets of UV LED curing systems often indicate the measurement location of peak irradiance at the emitting window or at a specific distance from the emitting window. However, some datasheets do not indicate the exact measurement location in terms of distance and lateral position, for example at the center, edge or corner of the referenced area. This is resulting in confusion for the end-user and might void effective datasheet performance comparisons.

c. Energy density

Energy density measurement is the collection of the irradiance over a specific time and is expressed in Joules per square centimeter (J/cm^2). In a conveyor system, the measurement of energy density is often used as a parameter to determine the UV cure ability. The end-user can adjust the speed of the conveyor in order to set the correct energy density while light source emits the constant intensity.

d. Uniformity

Another important parameter is the uniformity of the UV light distributed over specified locations. Not all UV curing systems emit consistent energy across the entire curing area. Uneven light distribution can lead to poor adhesive curing quality or even non-curing and shall be well understood. Uniformity is the variation of light distribution on specified distance and area. It is measured as ratio between highest and lowest irradiance value in area of interest and expressed in percentage. To establish process uniformity end-users can adjust the measurement location during measurement and tune the UV curing system accordingly to obtain the best end-results.

Further important parameters which are not highlighted in this paper are the operating and ambient temperature. As mentioned in the earlier section, UV LEDs are temperature sensitive devices [17, 18]. The output power is decreased as the function of the temperature hence the lifetime of the emitter will be reduced. The UV LED curing system needs to be placed and operated based on the manufacturers instruction for the cooling mechanism in the system to operate at maximum capacity.

In the following sections, the guidelines on measuring the irradiance of UV LED curing system using radiometer are explained.

Radiometer as measuring device

As already mentioned in the previous chapters, a radiometer is used to measure irradiance values at a given location and distance. It is a very useful device to monitor and ensure a stable UV light curing process. Furthermore, a radiometer can also be used for:

a. Maintaining a reliable light-curing process
   Ensure that a UV curing system is providing good irradiance and dosage levels required for successful curing.
b. Acting as a safety measurement tool during light-curing process
   Radiometers are sufficiently sensitive to measure the intensity of stray or reflected energy
c. Measuring transmission rates through substrates
   Measure the transmission rates of various wavelength ranges through substrates that sometimes absorb various frequencies of energy. To ensure an effective curing process, it is critical to measure the light intensity reaching the cure site below any intervening substrate.

Based on the form factor and application, the radiometers which are available in the market can be classified into hand-held/ end-of wand and disc/ puck type. For manufacturing lines, it is necessary for the design of both types to be compact and easy to operate. Hand-held types of radiometers are suitable for spot and end-of wand curing system configuration. Often, they come with adaptor kits to fit into the light guide or connector of the UV curing system. The puck based radiometer is more suitable for measuring irradiance or energy density in conveyor and flood chamber UV curing system. Fig.4 shows the example of Dymax's UV radiometers.

(a) (b)

Fig.4: Radiometer configuration available (a) hand-held type and (b) puck type.

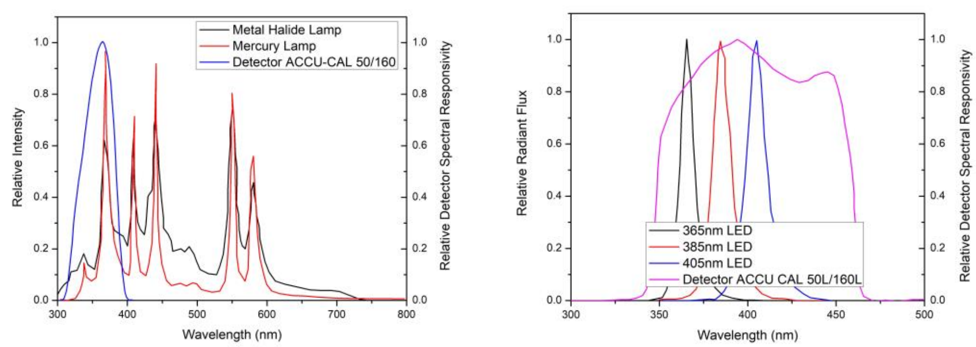
In selecting a suitable radiometer for curing application, several factors need to be considered in order to get accurate and repeatable measurements:

The emitter of the UV curing system

The emitter is the UV light source part in a curing system. It can be designed using conventional UV lamp or UV LED. Typically, the UV emitter consists of light source, additional optics in form of reflector, lens or UV grade optical window, and a thermal system in form of air or liquid cooling mechanism. All light sources emit UV light but in different spectral ranges. The conventional UV lamps have a wide spectral range across UV spectrum and small portion in the visible spectrum, while UV LEDs emit light in the narrow UV spectral range. The end-user should know that different tools might need to be used to measure the irradiance or energy of the conventional UV lamp and UV LED. Radiometer for UV broadband lamp can only measure the conventional UV lamp based curing system and cannot be used to measure UV LEDs curing system because they measure one a particular wavelength range. For measuring UV LED system, a specific measurement tool tuned for this use case is recommended.

The responsivity of a radiometer's detector

The key parameter in selecting a radiometer is to identify the wavelength of the emitter's light source. It is extremely important that the spectrum of the emitter's light source is within the spectral responsivity of radiometer's detector. However, radiometer for conventional UV lamps shall be used to measure the UV LED lamps due to the different range of quantifying the light. While it is desirable that the radiometer's detector has flat top responsivity over UV spectrum, such detector would be very costly and would not be handy, hence it is not usually applied in industrial applications. For application in adhesive curing using UVA light such as metal halide and mercury lamp, the detector used has highest responsivity at 360-365nm because the spectrum of UV metal halide and mercury lamp has higher peak at that range as depicted in Fig.5.



(a) (b)

Fig.5: Typical spectral responsivity of Dymax's radiometers and the UV sources spectral intensity: (a). Detector spectrum of ACCU CAL 50 /160 and spectrum of metal halide and mercury lamps. (b). Detector spectrum of ACCU CAL 50L /160L and spectrum of UV LEDs

For UV LED based curing system, it is recommended that the end-users understand at which wavelength the radiometer is calibrated. There are various types of radiometer which can be used to measure irradiance and dosage at single or multiple wavelengths. If the radiometer which its measurement mode is tuned at 385nm is being applied to measure irradiance of the UV LED curing system which has peak wavelength at 365nm, the measurement result will not be reflected as the true value and can only be assumed as relative value. This still can be used for process stability analysis. Simple measurements are performed to find out the difference in irradiance measured between specifically tuned and specifically tuned radiometers. The set-up is constructed in such a way for the measurement to be reliable and repeatable. It is seen from the result in Table 1 at peak wavelength of 365nm that the deviation measured using two radiometers is about 13%.

Peak Wavelength of UV LED module	**PCB Temperature (^{0}C)**	**Irradiance (W/cm^2)**	
		Sensor A tuned at 385 and 405nm	**Sensor B tuned at 365, 385, 405nm**
365nm	27	0.46	0.53
385nm	27	0.95	0.96
405nm	27	0.89	0.88

Table 1: Measurement result of UV LED module using different radiometers. The modules are measured at distance 25mm.

Spot and flood UV curing system

Another important factor to achieve accurate result is the ability of a radiometer to measure spot and flood type UV curing system. The emitter of UV spot curing system is coupled with a light guide or collimated lens resulting in a focused and narrow output beam. The spot type curing system is typically being used to cure small parts with high intensity, thus it provides faster curing time. Unlike the spot curing system, the flood curing system is used to cure a larger part or small parts at the same time. To measure the irradiance of the UV curing system, the end-user should ensure that the emitter and radiometer's detector are in parallel position. Slanted or tilted radiometer sensor will cause inaccurate measurement. To measure the irradiance value of the spot curing system, the radiometer is attached perpendicular onto an adaptor that fits the aperture of the lightguide or connector. The adaptor and connector shall be designed accurately so that the total light is illuminating the entire detector window without loss. It also shall be uniform across such measurement window. Some radiometer's manufacturers provide standard and customized adaptors and connectors or measurement mode specifically designed to measure the light in flood mode or certain spot sizes.

Lateral position and vertical Location during measurement

At a production line, the radiometer is used to monitor the output light of the UV curing system with the aim of ensuring the UV curing system operates within the curing specification. For that reason, consistent irradiance value is desired. Because the irradiance measured is distance dependent, to achieve repeatable and consistent measurements, the location and the orientation must be equal at each measurement. Furthermore, not all flood systems emit consistent energy laterally, which is resulting in

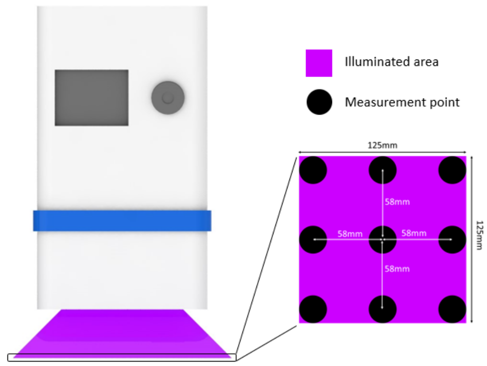


Fig.6: Example of measurement location of the radiometer at a fixed working distance to determine the uniformity.

different irradiance value across the illuminated area. For this reason, the uniformity must be determined at working distance in order to achieve good and repeatable curing results.

Few measurement points across the illumination area can be taken using the radiometer to map the irradiance uniformity as illustrated in Fig.6. If the irradiance map is constructed, the dimension of an effective curing area can be determined and matched to the curing application.

Temperature

All semiconductor based devices are temperature sensitive. In general, the operating temperature of the radiometer should not be more than 70^0C. If the temperature of the UV curing system is built up with long exposure of UV radiation on the detector, the performance of the detector starts to attenuate [19, 20]. Current technologies enable radiometers to perform the irradiance or energy density calculation at the milliseconds interval to avoid the error caused by temperature. Additionally, when the UV emitter turns on, it is recommended to measure its irradiance after the temperature reaches steady state to ensure the reading is consistent and accurate, and ensure that the radiometer has cooled down before performing a next measurement. One of the advantages of using UV LED based curing system is its shorter warm-up time in comparison to the conventional UV curing system.

Radiometer calibration and maintenance

Components of the radiometer will deteriorate over time resulting in the reducing the measurement accuracy, even more so if it is used very frequently. The radiometer is a very delicate system, its optical parts in particular. Slight change or debris in the optical parts can affect the result significantly. Therefore, it is recommended to maintain and calibrate periodically. Maintenance of the radiometer includes keeping the radiometer clean and storing based on its requirements.

Periodic calibration of the radiometer is necessary to maintain the lowest possible uncertainty of error. During calibration, the error of all important parameters of the radiometer is determined. The calibration process is usually performed on a standard artefact, traceable to national standards, and measured under defined environmental conditions. Most calibration laboratories follow the standard set by National Institute of Standard and Technology or NIST. The result and associated measurement uncertainties are recorded on a calibration certificate. The key factor in the calibration process is that it should display an unbroken chain of transfer comparisons originating at a national standards laboratory until the final products of the radiometer [21].

Conclusion

The market share of UV LED based curing systems is expected to continue increasing every year as the technologies become more mature. The inherent advantages of UV LEDs over the conventional UV bulb are not only about the performance but also environmental friendliness and safety. Some end-users may not have proper method yet to measure the output light using a correct radiometer which can lead to false measurement results although the result seems correct or close to the desired value. An appropriate measurement method of UV LED curing system is needed to ensure consistency of the curing result as well as eliminating the risks of using UV light. Furthermore, it is also important to question and evaluate that advertising data in a UV light curing system datasheet that do not list radiometer type, the location that irradiance is measured and means to couple the light to the detector. The presented report can be utilized as a guideline for end-users to accurate and repeatable measurement of UV LED curing system especially measurement using a radiometer.

Disclaimer

This manuscript acts as a reference document only and is sharing best practices. It is by no means fully exhaustive. Every user should always carry out their own due diligence and engineering sense to assess every situation in terms of risk and safety.

References

1. Yole Développement, *UV LEDs: Technology, Manufacturing and Application Trends*, 2014.
2. Allied Market Research, *UV LED Market Report*, 2019.
3. F.J.Arques-Orobon, N.Nuñez, M.Vazquez, C.Segura-Antunez, and V.González-Posadas, "High-power UV-LED degradation: continuous and cycled working condition influence," *Solid-State Electronics*, vol. 111, pp. 111-117, Sep 2015.
4. Phoseon Technology, "UV LED System Lifetime," Hillboro, OR, USA, 2017. Accessed on Dec., 15, 2019. [Online]. Available: https://phoseon.com/industrial-curing/technology/led-uv-system-lifetime.
5. D. Leonhardt *et.al.*, "Advancements in UV LED technology and its impact on UV curing applications," in *Proc. of 13th International Conf. on Radiation Curing in Asia*, China, 2013.
6. S.L.Mcdermott, J.E. Walsh and R.G. Howard, "Comparison of the emission characteristics of UV-LEDs and fluorescent lamps for polymerisation application," *Optics and Laser Technology*, vol. 40, pp. 487-493, 2008.
7. V. Landry, P. Blanchet, G. Boivin, J.F. Bouffard, and M. Vlad, "UV-LED curing efficiency of wood coatings," *Coatings*, vol. 5, pp. 1019-1033, 2015.
8. K.C. Anyaogu, A.A. Ermoshkin, D.C. Neckers, A. Mejiritski, O. Grinevich, and A.V. Fedorov, "Performance of the light emitting diodes versus conventional light sources in the UV light cured formulations", *Journal of Applied Polymer Science*, vol. 105, pp. 803–808, 2007.
9. UNEP, ILO, and WHO, *UV Radiation: environmental heath criteria 160*, Geneva, Switzerland, 1994. Accessed on Dec., 15, 2019. [Online]. Available: http://www.inchem.org/documents/ehc/ehc/ehc160.htm.
10. Dymax Corporation, *Guidelines for Exposure to Ultraviolet Light*, Torrington, CT, USA, October 13, 2010. Accessed on Dec., 15, 2019. [Online]. Available: https://www.dymax.com/images/pdf/literature/lit023_guidelines_for_uv_exposure.pdf.
11. K. Walsh, "UV radiation and the eye," *Optician*, vol. 237, pp. 26-33, 2009.
12. Dymax Corporation, *Dymax UV Light Curing System Safety Consideration*, Torrington, CT, USA, October 13, 2010. Accessed on Dec., 15, 2019. [Online]. Available: https://www.dymax.com/images/pdf/technical_bulletins/lit133_dymax_uv_curing_systems_safety_considerations_tb.pdf
13. WHO, *Ultraviolet Radiation as Hazard in the Workplace*, Geneva, Switzerland, 2003. Accessed on Dec., 15, 2019. [Online]. Available: https://www.who.int/uv/publications/en/occupational_risk.pdf.
14. S. K. Jain and N. K. Jain, "Multiparticulate carriers for sun-screening agents," *International Journal of Cosmetic Science*, vol. 32, no. 2, pp. 89-98, 2010.
15. Y. Muramoto, M. Kimura and S. Nouda ,"Development and future of ultraviolet light-emitting diodes: UV-LED will replace the UV lamp," *Semiconductor Science Technology*, vol. 29, pp. 084004, 2014.
16. J. Heathcote, *UV-LED Overview Part I — Operation and Measurement*, RadTech Report, July/August, 2010, pp. 23-33.
17. J. Heathcote, *State of UV LED Curing Applications*, UV+EB Technology, issue 1, 2019, pp. 18-22.
18. P. Mills and J. Raymont, *The UV-LED Paradigm Shift*, RadTech Report, issue 2, June, 2013, pp. 43-48.
19. J. Raymont and A. Kashyap, *Measuring the Output of Ultraviolet Light Emitting Diodes*, RadTech Report, issue spring, 2011, pp. 18-23.
20. J. Raymont, "Radiometer-best of intentions," *SGIA Journal*, vol. 6, no. 3, pp. 39-47, 2002.
21. "*Gigahertz-Optik's Calibration Laboratory for Optical Radiation Measurement Quantities*," 2019. Accessed on Dec. 15, 2019. [Online]. Available: https://www.gigahertz-optik.de/en-us/service-and-support/knowledge-base/calibration-laboratory-measurement-quantities.