UV-LED: Beyond the Early Adopters

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Introduction

The power, cost, and capability of ultraviolet light emitting diode (UV-LED) lamp systems have improved to the point where they now represent a viable alternative to traditional mercury vapor lamp curing technologies within a growing number of UV ink, coating, and adhesive applications. This paper will identify some of the advantages of the LED-based technology as well as the engineering challenges involved in transitioning from a traditional, mercury vapor curing system. This paper will also identify some of the critical performance criteria that should be used when evaluating UV-LED systems.

The UV curing system most commonly used to date has been based on mercury vapor lamp technology. Mercury lamp technology, whether arc or microwave driven, has existed since the late 1880s and has been refined over time to the modern designs commonly used today. However, the basic principles have remained the same. Typically, a mercury lamp emits a very broad spectrum of light energy (200-800nm) with specific emission peaks that are the result of selective doping designed to achieve a specific application objective.

UV-LED technology is relatively new and rapidly emerging to be a viable alternative to traditional mercury-based lamps. A UV-LED is a semiconductor device that emits photons of light in response to the application of a bias voltage across the device's p-n junction. The type of materials used in the fabrication of the device determine the wavelength(s) of light emitted and by adjusting the type and quantity of the materials used, a wide range of wavelengths are possible including wavelengths in the ultraviolet (UV) electromagnetic spectrum. A UV-LED system uses the semiconductor devices to generate the UV light and typically is an integrated lamp system; containing a large number of light generating LEDs, the driver electronics, control circuitry, and a package that can be provided in a number of form-factors that are application specific.

While UV-LEDs represent a new technology with some compelling technical advantages, it is critical to understand the fundamental differences between LEDs and mercury lamps in order to achieve a successful implementation.

UV-LED vs. Traditional Mercury-based Lamps

There are some important fundamental differences between traditional mercury-based lamps and UV-LED lamp systems that the next section will summarize.

Energy Input vs. Measured UV Output

Mercury lamp systems are typically rated in terms of the input power used to drive the bulb. These ratings are usually specified in terms of "watts per inch" (WPI) or "watts per cm". This metric specifies the input, not the usable UV output of the device. For example, a 600 WPI lamp does not produce 600 watts of UV energy; rather it consumes 600 watts per inch of bulb length. While engineers designing UV curing systems have established baseline correlations between input power and usable UV output, there are many variables that impact the delivered power including the quality of the UV system, the reflector design and condition, and the age of the bulb; all factors that force users toward active UV measurement programs to ensure that the expected UV energy is reaching the work surface [2].

UV LED sources are usually specified in terms of their output power – either total UV output (W) or peak irradiance (W/cm2)-energy density (J/cm2). The most practical way to specify the output is in terms of measured peak irradiance and total power output at the system emitter or at the working surface if the application specifies a specific stand-off distance. While some UV-LED systems have specified peak irradiance at the LED surface itself, such a metric has very little correlation with the actual energy delivered to the UV material when system losses are considered. Until recently, the total output of UV-LED based devices was far less than the output obtained from traditional mercury-based lamps. However, recent technological advances have resulted in UV-LED lamps that can generate peak irradiance and total UV power that is similar to the output of a mercury lamp rated at 600WPI input power.

Energy Spectrum

Most mercury vapor lamps emit a broad spectrum of light (200-800nm – with specific emission patterns dependent on doping) of which less than 20% is typically useful for UV curing while over 50% of the total energy is found in the infrared wavelengths (IR) that present a significant design challenge related to heat load on the substrate material (Figure 1).

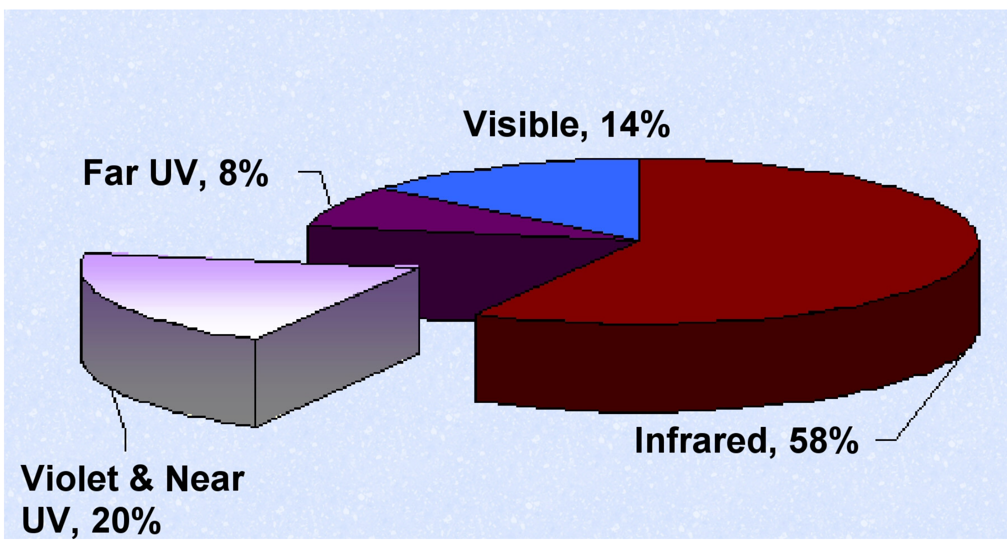

Figure 1: Typical Mercury Lamp Spectral Distribution

In contrast, UV-LED systems emit a very narrow range of UV energy (typically 30-40nm) and typically, due to limitations in the commercially available UV-LED semiconductor technology, the energy peak resides in the high UV-A or low UV-V spectrum (typically 350-405nm, See Figure 2).

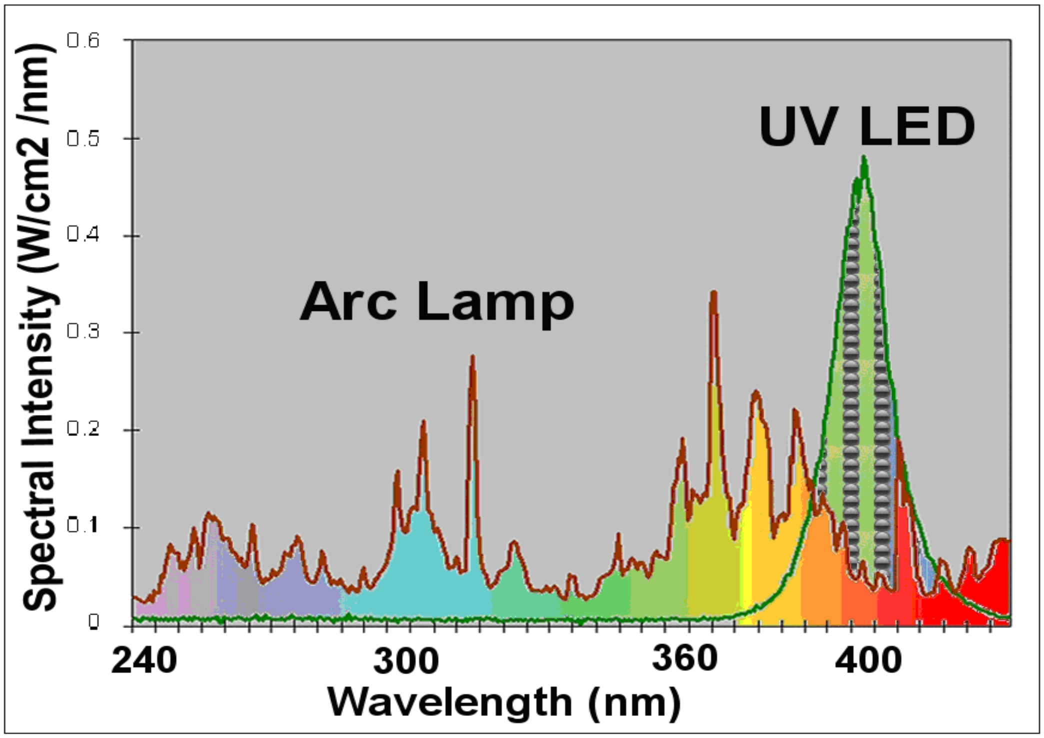

Figure 2: Mercury lamp vs. UV-LED Spectral Output

Advantages of UV-LED Lamp Technology

Lamp Lifetime

UV-LEDs are made from semiconductor devices which have inherently long-lifetimes. If the diode is used correctly within the lamp design, with thermal management being the most critical issue, a UV-LED lamp can be designed to outlive the typical service lifetime of the machine in which it is installed. In contrast, mercury bulbs are considered a consumable item with replacement typically expected every 1,500 – 2,500 hours of operating use. The failure mode of an LED is most commonly related to the breakdown of the diode's p-n junction and this is usually the result of excessive heat applied to that critical region. Therefore, effective thermal management at the device level is a critical element in ensuring that LED based lamps can perform to theoretical diode lifetimes.

Instant on/off

Solid-state UV-LED lamps can be switched on and off instantly (<10ms) which represents a substantial design advantage since shuttering systems are not required. Furthermore, the ability to run the UV-LED system on an "as needed" basis reduces the overall duty cycle of the device and can substantially extend the practical lifetime of the lamp. In contrast, mercury-based lamps typically require a warm-up period and are often required to be kept in a standby mode and/or shuttered when not actually curing. Such low-power use does impact the overall lifetime of the mercury lamp and lamps in standby or low-powered mode can still use substantial quantities of electricity during operational hours.

Substrate Heat

Since more than half of the total energy created by a typical mercury lamp is output in the infrared (IR), managing heat load is an engineering issue inherent in most UV applications. While filters and other techniques have been used to minimize the heat delivered to the substrate and while media cooling systems, such as water chilled drums have been used, the issue of heat can limit the type of materials suitable for UV ink, coatings, or adhesives, and can increase the operational system costs due to hot air extraction/treatment, media cooling, etc.

In contrast, UV-LED based lamps emit a very narrow range of UV energy (typically UV-A) with zero IR energy emitted. Therefore, an important driver behind the interest in UV-LED technology is related to heat sensitive material. This is not to say that a high-powered UV-LED system delivers "no heat" or is "cold technology". While the heat delivered to the substrate is far less with a UV-LED system, the high UV energy levels absorbed by the UV cured material and substrate/media itself can result in significant heat if the lamp is left stationary over the curing area for an extended time. However, the instantaneous on/off nature of a UV-LED lamp plus the ability to vary the output power level minimizes any risk to temperature sensitive substrate material.

Power consumption

The reduction in electrical power used to power a UV-LED system when compared to an equivalent UV-output mercury lamp can be substantial. For many applications, a total power consumption reduction of 50-75% can be realized [3]. This power savings can be even more substantial when air extraction, substrate cooling, and energy required to maintain a mercury lamp's standby mode are included.

Environmental and Safety

While traditional mercury-based UV lamps have been deployed and accepted in a wide variety of industrial and printing applications, care must be taken to ensure that no operator or person near the UV curing system is exposed to potentially dangerous UV wavelengths or heat. This fact has an impact on the total size, weight, and portability of a traditional mercury-based UV system that typically has to be fully enclosed and shielded so that no human can see or touch the enclosure while the lamp is operating. In contrast, UV-LED systems emit no UV-B or UV-C wavelengths which are inherently more dangerous to the human eye. Also, most UV-LED designs do not transmit substantial heat to the lamp enclosure reducing the design constraints placed on the curing system designer. Since mercury is not used within an LED system and because no ozone is created as a byproduct of the narrow-band UV-A energy, LED-based systems are inherently environmentally friendly.

Challenges in Transitioning to UV-LED

While UV-LEDs now approach or even exceed traditional mercury lamp power and also offer substantial engineering and operational benefits, there remain some challenges, primarily on the chemistry/formulation side that should be understood in order to determine if UV-LED technology is appropriate or even feasible for a specific application.

Material formulation

In general, UV-LED lamps are not suitable for "drop-in" replacement of existing mercury-based lamp systems. Nearly all UV material formulations have been optimized to react with the spectral characteristics of mercury lamps in an array of doping configurations. The commonly used free radical UV chemistry uses photoinitiators that are formulated to react with the multiple spectral peaks output by a mercury lamps. Transitioning from a polychromatic mercury vapor lamp to a near-monochromatic UV-LED lamp often requires that the ink/coating/adhesive be adjusted and optimized in order to achieve the proper curing and material properties.

Surface curing

The primary challenge in optimizing chemistry for UV-LED is effective surface curing which can be hindered by oxygen inhibition resulting in an improperly cured or "tacky" surface. Material formulations that are optimized for mercury vapor UV sources take advantage of the lower UV-B and UV-C wavelengths to achieve effective surface curing. Formulations created for UV-LEDs achieve effective surface curing via the addition of compounds that can consume the oxygen, such as amines or aminoacrylates [2] or in some cases by curing in an inert (nitrogen) environment. Overcoming surface curing issues has been a fundamental issue for UV material suppliers and formulators. However, the combination of much higher total UV-A energy levels now available and the combination of oxygen consuming additives has resulted in commercially available ink, coating, and adhesives that are optimized for UV-LED lamps.

UV-LED Lamp Thermal Management

While UV-LED lamps do not generate the macroscopic heat issues related to mercury vapor lamps, the thermal management of UV-LED diodes is a critical factor in being able to achieve the power levels and lamp lifetime required for most curing applications. Various heat management techniques have been developed including active air and water-cooled systems. Water is inherently more efficient than air cooling and can result in higher overall LED lamp power. Since the UV lamps are stationary on many single pass and narrow-web digital inkjet printers, water cooling is not a substantial design limitation for that family of applications. However, since wide format digital printers utilize UV curing lamps (typically two) on the carriage containing the print heads, water cooling presents additional design challenges which is resulting in the push for manufacturers of high-powered UV-LED to develop effective air-cooled lamp systems.

UV-LED Lamp Performance Criteria

As UV-LED technology continues to emerge, standards will eventually be developed that will result in a standardized way of defining and characterizing the performance specifications of UV-LED lamps. The section below suggests a baseline of criteria that could be used to compare UV-LED lamps.

Wavelength

The wavelength of the diodes used by a UV-LED lamp has implications on curing performance, power, and lamp lifetime. Many ink, coating, and adhesive formulators initially request that UV-LED lamps emit a peak around 365nm; a wavelength that matched one peak within existing UV systems.

However, testing has shown UV-LED lamps developed around a different die set with a peak at 395nm (or 405nm)have several potential advantages including; cost, availability, and a more robust structure than can result in higher UV power outputs.

Recent research has indicated that peak irradiance and total UV-A power delivered are more important than a precise wavelength match on many materials developed to cure in the UV-A region. The summary finding is that "The peak intensity and total energy of a UV-LED source in the UV-A region is relatively more important for cure performance than the specific peak wavelength of the UV-LED source in the UV-A region (365nm vs. 395nm). For many materials, energy trumps wavelength in terms of the reaction – at least when the wavelength ranges are relatively close together in the spectrum. Figure 3 shows the results of a comparison of Fourier Transfer IR (FTIR) results analyzing the curing performance of a black digital ink that was cured with a standard mercury arc-lamp and UV-LED lamps designed around the 395nm diodes [3].

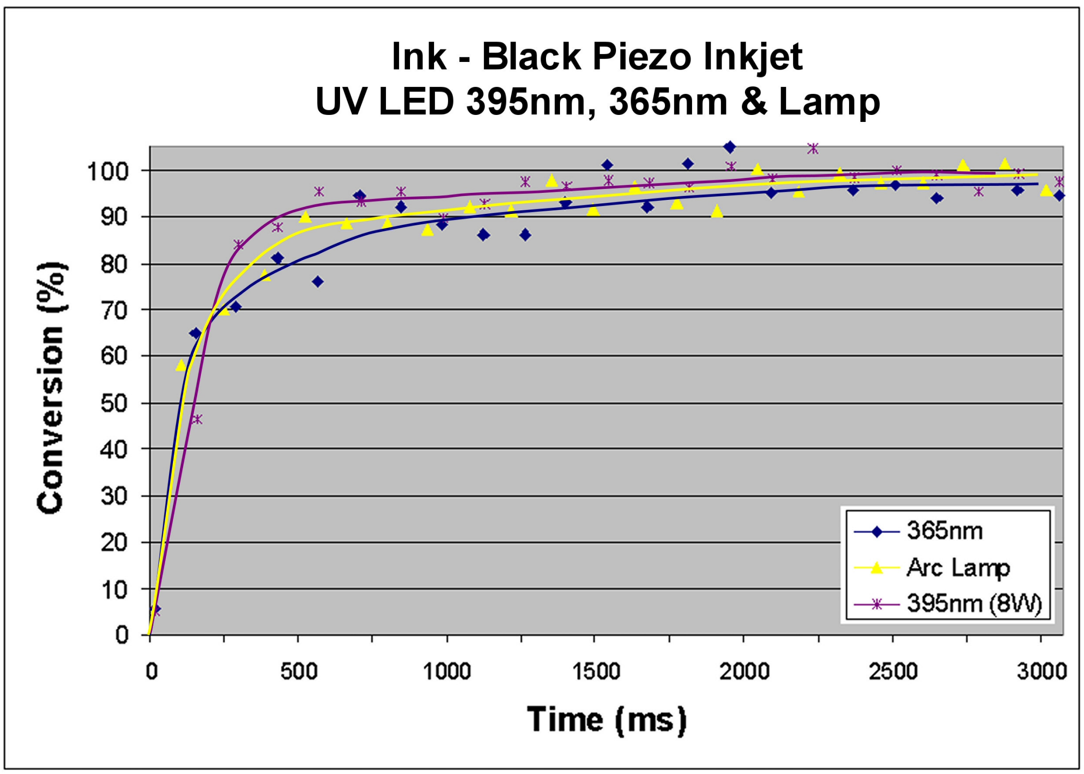

Figure 3: FTIR Comparison: Arc-lamp, 365 and 395nm UV-LED

Peak Irradiance – and Dose: Total Power Delivered

Peak irradiance is an important metric since intensity is required to initiate the polymerization of the UV ink, coating, or adhesive material. Higher peak irradiance results in a more aggressive polymerization mechanism which is important in obtaining full cure, helping to overcome oxygen inhibition at the surface, and achieving the required cure rate. However, peak irradiance is only one important variable. Optics and reflector schemes can focus energy to obtain high peak irradiance over a relatively small area, often at the expense of total power delivered to the ink due to optical losses.

Research indicates that total power, the photons delivered to the material, or "dose" delivered to the chemistry is a critical variable in achieving cure rates that are acceptable for most applications. Figure 4 illustrates the difference between a high peak intensity achieved optically at the expense of total dose delivered.

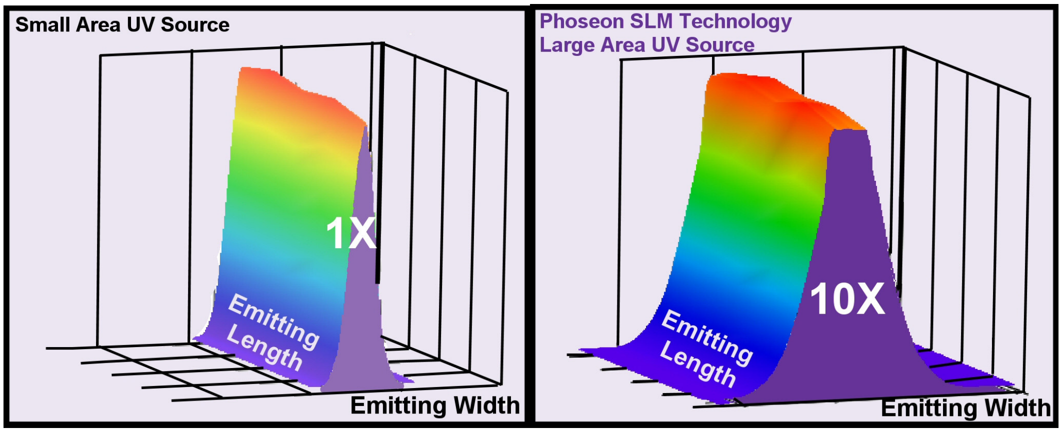

Figure 4: UV-LED Peak Intensity vs. Total Power

Uniformity

Uniformity of UV energy can be an important characteristic for many UV applications; particularly those targeting graphic arts applications. Uneven UV energy emission patterns, hot spots, or gaps in the UV output can have severe negative effects on the quality of the printed material including partially cured areas and gloss and color banding. Characterizing the uniformity of a UV-LED lamp should be an important consideration when comparing lamp designs.

UV-LED Applications

Digital Inkjet

A growing number of commercially available inkjet systems have incorporated UV-LED lamps successfully for both pinning (partial cure in order to stabilize an ink dot) and full cure. At the low-end of the price scale are single-pass thermal inkjet (TIJ) based printing systems that are typically designed for addressing, label, or variable/barcode printing applications. These applications find UV-LED attractive due to the relatively small size and easy integration of LED based lamps compared to traditional mercury-based systems. Due to cost constraints, TIJ-based inkjet systems require small, affordable air cooled UV-LED systems that offer acceptable cure rates on a variety of print media.

At higher price-points, faster and more capable multi-color Piezo drop-on-demand inkjet systems are used. Within this marketplace, heat sensitive media, power consumption, and environmental factors are the driving factors behind the acceptance of UV-LED technology. Wide format printing is another market space where UV-LED based systems are playing an important role. Expanding printing options on heat sensitive media and a more favorable cost of ownership/operation are the drivers in this application.

Analog Printing Applications

UV-LED curing systems are not as common in the analog printing markets including the flexographic, offset, gravure, screen, and pad printing arenas. However, the potential energy savings combined with the reduction in heat related process issues have pushed the customers and suppliers within this market to evaluate the viability of UV-LED curing systems. In several cases, analog printing systems utilizing UV-LED curing stations have been successfully demonstrated. As in the other printing areas, the enabling technology is the ink formulation which typically has to be optimized for the narrow spectral output of LED-based lamp systems. Other challenges that UV-LED systems have overcome are the high process speeds associated with these printing methods and the relatively wide sheet/web sizes frequently encountered. With the continued improvements of the peak irradiance and total power delivered of UV-LED systems, many more of these applications will be candidates for the UV-LED technology.

Industrial Coating Applications

UV-LED lamps have been used to cure appropriately formulated coatings in a growing number of industrial applications. The lower heat load delivered by an UV-LED lamp system expands the applications of UV coatings into materials which may be very sensitive to heat damage. These applications range from furniture and flooring coating applications to coatings used on sensitive medical devices. The relative small size and light weight of most LED based curing lamps provides a design advantage for applications requiring curing of 3D objects. The challenge associated with the adoption of LED technology for some UV coating applications is related to the surface cure issue identified earlier and the fact that many performance coatings applications have more stringent criteria related to scratch and damage resistance. In some cases, removing the oxygen in the cure zone by introducing nitrogen or carbon dioxide gas has proven to be successful.

UV Adhesive Applications

A growing number of commercially available UV curable adhesives are now available that cure efficiently in the high UV-A region making UV-LED-based lamps a viable alternative for adhesive applications where heat sensitivity is a primary driver. Applications ranging from medical device manufacturing, lamination processes related to flexible photovoltaic and display technologies, and consumer products that exploit the fast process speeds associated with UV curing but contain thin polymer or similar heat sensitive components have been installed with very positive results.

The Future of UV-LED Lamps

UV-LED will continue to gain acceptance as the output increases and the initial investment costs decrease. Over the past 2-3 years, the price per watt of UV-LED systems has decreased dramatically. As more ink/coatings/adhesive suppliers are pushed by their customers to develop UV-LED optimized materials, additional applications will adopt this technology. In the next year, additional UV-LED lamps will be commercially available in a growing number of sizes, configurations, and form-factors. While this rapidly growing technology will prove to be extremely effective in many marketplaces, the limitations related to the chemistry required to meet all of the customer's performance characteristics should be fully appreciated before deciding UV-LEDs are the right solution for a particular application.

Acknowledgments

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