Advancements in UV LED Curing Performance for Digital Printing

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Abstract

Ultraviolet (UV) curing lamps based on Light Emitting Diode (LED) technology have progressed to the point that they represent a mainstream curing technology in the UV digital inkjet printing market. The historical obstacles of lamp power, cost, and optimized ink chemistry have largely been resolved and the result is a quantum leap in performance resulting from the inherent characteristics of properly designed UV LED lamps; high power, extremely long lifetime, exceptional reliability, consistency and uniformity of UV output, far lower heat load on the curing surface, superior health, safety, and environmental protection, and dramatic reduction in energy.

UV Curing Devices: Historical Perspective

Historically, the curing device used in UV printing applications is the medium pressure mercury lamp. This technology has been dominant in the UV curing market for many decades but has inherent characteristics that present engineering and operational challenges to both the supplier equipment builder and the end user.

A mercury (Hg) based UV curing lamp uses a glass bulb filled with mercury that is vaporized and ionized by either a high voltage arc or microwave energy source. This bulb has a finite lifetime degrading with use resulting in repetitive replacement and the associated costs of downtime, bub replacement, and Hg disposal. Typical lifetimes are 500-2000 hours of use. During the lifetime of the bulb, the UV output is not consistent; there is an overall degradation of output and this degradation can occur in a non-linear fashion across the length of the bulb impacting the uniformity of UV output. The traditional Hg lamp is a broad spectrum device that produces, in addition to the UV energy used in the curing process, visible light and infrared energy. In many cases, up to 25% of the lamps output is IR energy which can present a significant heat load on the print media and require special handling or restrictions of the type of print media that can be used. This heat must also be managed and in many cases requires extraction of the hot air from the manufacturing area along with the associated air-exchange. In some cases, the ozone generated from low-wavelength UV-C energy must be extracted and removed to ensure operator safety[2]. The relative high heat of the curing lamp itself also requires that the lamp be properly shielded from any potential contact with print operators and this can present some engineering challenges and potential liability for the users. The disposal of depleted UV curing bulbs is also a potential health/safety issue due to their mercury content.

Most Hg-based UV curing lamps require a "warm up" and "cool down" time and can be stressed to the point of failure if they are repeatedly cycled between on and off. As a result, most Hg-based UV curing lamps are left "on" during the production shift and isolated from the print media with mechanical shutters which are another complexity that can represent a possible failure mode and cost/downtime associated with preventative or reparative maintenance. The "always on" status of many Hg lamps also results in bulb degradation even when the lamp is in a relatively low-powered standby mode as well as energy consumption that is essentially waste. While microwave-driven lamps have an advantage in this area, the issues related to heat (IR) and bulb degradation remain.

Nearly all Hg-based UV curing lamps used for digital inkjet applications use a reflector system that concentrates the UV emission of the bulb to the printing surface. The cleanliness of the reflectors plays a major role in the amount of UV energy presented to the print media and is also a required maintenance item to ensure successful operation.

In spite of the inherent challenges associated with Hg-based UV curing lamps, this technology has been the backbone of the UV curing market and nearly all UV-curable inks have been formulated for these devices. However, in the past 5-6 years, a new curing technology has rapidly emerged that addresses the challenges associated with Hg-based curing lamps. This technology is based on Light Emitting Diodes (LED) designed to emit energy in the UV-A spectrum. UV LED's have progressed to the point where they are equivalent or superior in curing performance and are rapidly approaching price parity with the traditional Hg-based lamps used in the UV digital printing market space.

UV LED Basics

A light emitting diode is a semiconductor device that is designed to emit light energy when activated. These devices exhibit a phenomenon known as electroluminescence with the wavelength(s) of the emitted photons being a function of the energy band-gap fabricated into the semiconductor device. In the case of UV LED, the emissions are generally in the UV-A spectrum which is generally defined as 315-400nm. From a practical perspective, nearly all UV LED's used for curing applications are designed around diode technology emitting in the high UV-A spectrum; close to 400nm. While lower wavelength UV LED diodes are available, their relative high cost, combined with their dramatically decreased efficiency and power output precludes their use in the UV digital printing applications. Figure 1 shows the comparison between a high output UV LED lamp and the broad spectrum Hg-based bulb.

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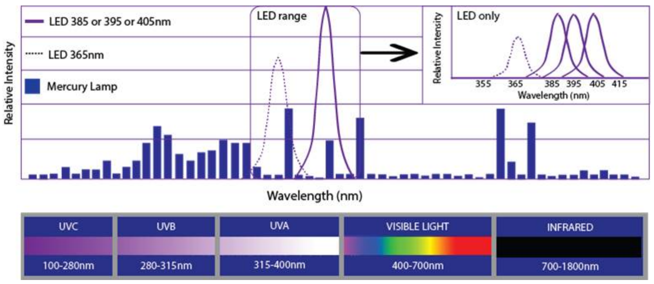

***Figure 1**. UV LED vs. Mercury Lamp Spectral Output*

Nearly all of the UV LED's used today for curing applications have a total energy wavelength output width of approximately 40nm with a peak frequency ranging from 365nm to 400nm depending on the diode technology used. Advances in UV LED diode technology have allowed the developers of UV LED lamps to increase power but the primary driver in high-power output has been the improvements in the implementation of these diodes on many fronts including thermal management, optical efficiency, and diode packaging. Today's best UV lamp designs can provide UV-A output that meets or exceeds the output of Hg-based curing lamps and do so in a way that solves many of the engineering issues associated with Hg-based systems.

UV LED Advantages

A properly designed UV LED lamp offers tremendous possible advantages for UV curing applications when compared to traditional Hg-based lamps. First, there is no inherent failure mode associated with UV LED diodes if the lamp is designed properly; particularly when it relates to the thermal management of the diodes. Lamps can be designed with an expected lifetime exceeding 30,000 hours. When this is combined with the fact that a UV LED can be cycled on/off nearly instantaneously and does not require the warm-up, cool-down or experience the thermal cycling stresses of the Hg lamp, the expected lifetime of the UV LED lamp is extended by the actual curing duty cycle since the UV LED lamp can be energized only when curing is taking place. The long lifetime and reliability of UV LED curing lamps is a major benefit for both the provider of UV digital inkjet printers and the end users.

A properly designed UV LED curing lamp can exhibit very repeatable and uniform UV output over the lifetime of the device resulting in a curing process that is consistent, predictable, and reliable. The relative narrow output (~40nm) of the UV LED lamps emitting in the high UV-A spectrum eliminates the IR emission and high heat associated with Hg-based lamps. The end result is the ability to successfully print on heat sensitive media with far less risk of distortion or damage and the elimination of hot air extraction systems and special safety shielding to protect the operators from hot surfaces. The longer wavelengths of the UV LED lamp also generally result in better depth curing of the UV ink, better adhesion, and the lack of UV-C output eliminates any generation of ozone.

Today's best UV LED lamps are smaller and lighter than traditional Hg lamps and can output more UV-A energy while consuming less than 50% of the input power. These advantages, when combined with inks optimized for UV LED, have helped speed the transition from Hg curing technology to UV LED in the digital inkjet marketplace.

UV LED Ink Chemistry Considerations

In spite of the inherent advantages of UV LED curing lamps, the adoption of this technology was previously hindered by the fact that ink reformulation was required due to the relative narrow high UV-A energy output of UV LED lamps. The reformulation effort was required to fully enable the advantages of UV LED technology and today, most of the leading digital inkjet ink suppliers offer commercially available ink sets optimized for UV LED. The reformulation effort usually involved the replacement, or modification of the photoinitiators used in the ink in order to best match the high UV-A energy. A few representative photoinitiator choices include Esacure ITX (Sartomer), Darocure and Igracure (BASF). In addition, a number of chemistry providers have applied for patents and/or are providing new, or blended photoinitiators that are optimized for the output of UV LED lamps without the associated side effects of excessive yellowing that was seen in early formulation attempts.

The other ink reformulation consideration was to address the relatively inefficient effect of UV-A energy to achieve maximum surface cure due to the lack of more energetic UV-B/C photons. The challenge ink providers faced was to develop techniques to minimize or eliminate oxygen inhibition effect on free radical UV chemistry. While UV LED typically exhibits superior depth cure, even in heavily pigmented inks when compared to Hg curing technology, effective surface cure was an early challenge in UV LED ink development. This issue has been successfully addressed on several fronts; more power from the UV LED lamp minimized this issue while additives to the ink chemistry, primarily specialized amines, addressed the surface oxygen resulting in successful surface cure. In some special cases, inerting of the ink surface using Nitrogen has been used to obtain even faster curing during UV LED exposure and the relatively small gap between the UV LED lamp and the print surface, combined with the availability of relatively low-cost N2 generation systems, makes this a viable option in some situations. The R&D effort required to reformulate inks for UV LED has paid off in most instances. Some users have experienced up to fifty percent more print volume with UV LED technology.[3]

UV LED Lamp Configurations

Today's UV LED lamps are generally available in two basic configurations; air-cooled or water cooled. This differentiation points to the techniques used to keep the UV LED diodes within an operating temperature that results in high UV output without compromising diode lifetime [4]. In general, water-cooled UV LED lamps have a smaller footprint but require a recirculating chiller and the additional water delivery/plumbing systems. Since water cooling is more efficient than air-cooling, higher UV output is possible with water cooled UV LED systems. Water-cooled UV LED lamps are now available with UV output of 20W/cm2 from its entire emitting window. Since water-cooled UV LED systems require the chiller and water lines, they are usually not preferred for digital applications where the lamps are moved by a carriage but instead, due to their smaller size, are better suited for single pass applications where the lamp is mounted in a stationary position. Air-cooled UV LED technology has rapidly progressed over the past 3 years. Formerly unimagined power outputs are now commercially available. Figure 2 shows an air-cooled UV LED lamp that is capable of 12W/cm2 of UV-A measured at the emitter window. This type of system is very popular for bi-directional printing applications such as wide or grand format digital printers. Air-cooled systems are currently available in a variety of sizes and configurations and can be used for a relatively large number of UV digital inkjet implementations.

***Figure 2**. High Powered Air-cooled UV LED Lamp*

UV LED Applications: Pinning

Pinning refers to the partial polymerization of the UV ink after each color's deposition. This technique was devised to reduce the dot gain, or spreading of the ink deposit during the delay between jetting and final cure in order to achieve better print definition and visual quality. UV LED pinning lamps require less power since full cure is not required, or desired for this process step. However, pinning lamps have other associated challenges; small size to fit in between the print heads, an air-cooled design that does not disrupt the ink deposits or subject the lamp to ink mist contamination, and a relatively low cost since pinning, if used, requires multiple lamps; one after each jetted color. Figure 3 shows an example of a small air-cooled pinning lamp that is capable of 2W/cm2 of UV output and can be equipped with specialized optics that restricts the spread of UV energy, thus protecting the inkjet heads from accidental nozzle curing.

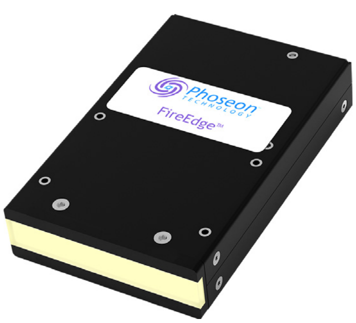

***Figure 3.** UV LED "Pinning" Lamp*

UV LED Applications: Full Cure

A growing number of digital inkjet UV printers have adopted UV LED for full curing of the ink. These systems cover the entire range of digital inkjet applications, from small single pass coding/marking systems to grand format, bi-directional digital printers using media that is 5m wide or more. The combination of high powered UV LED lamps and optimized inks has driven this rapid transition from Hg lamps to UV LED. A visit to any of the digital print industry's trade shows will show that nearly all of the newly released digital UV printers are utilizing UV LED technology.

UV LED Economics

While the engineering and operational advantages of UV LED are significant, the adoption of this technology would not have occurred if the economics and return-on-investment were not viable. The primary economic advantages of UV LED in the digital print space are dependent on the specific application but in general are distilled to several primary factors. (1) The greater reliability and consistency of UV LED generally results in higher utilization of the capital asset (printer), more productivity, and higher yields of high-quality product. (2) The costs associated with bulb, shutter, reflector, dichroic filter, and/or magnetron maintenance and replacement are eliminated. (3) The far lower heat load delivered to the print media enables a wider range of possible print jobs, allows for thinner, more heat sensitive print media and results in reductions in raw material and shipping costs of the finished products[5]. The lack of high temperature exhaust eliminates UV related infrastructure blower/HVAC investments and eliminates the regulatory requirement of ozone scrubbing. (4) The liability issues associated with harmful UV wavelengths (UV-B/C) are eliminated as are the operator safety issues related to hot operating surfaces. (5) The dramatically reduced energy requirements of UV LED, compared to Hg lamps, 50-90% for most applications, reduces the end user's carbon footprint and provides direct energy cost savings. (6) No RF emissions which can disrupt factory communications and are a side effect of microwave driven curing lamps.

UV LED: Practical Considerations

The rapid emergence of UV LED technology in the digital inkjet marketplace has resulted in the inevitable inflow of new suppliers and products to fill the demands of market growth. As a result, new design concepts can be rushed to market associated with unsubstantiated, and in some cases misleading claims. Since the UV LED market is relatively new, and in spite of the efforts of industry associations such as Radtech (www.radtech.org), industry standards to define the performance of UV LED lamps are a work in progress. As a result, care should be taken to understand the performance of a UV LED lamp from several key perspectives.

First, the UV output should be understood from a wavelength, peak irradiance (W/cm2) and total power perspective. Peak irradiance, or power density is the maximum intensity of the UV spectrum and is critical for initiating the UV ink curing process. But power is also very important for most applications since total power and exposure time energy density (dose) is a critical component in curing speed. For nearly all UV LED digital inkjet applications, the total UV power is the limit to effective performance at industry required speed. Specifying peak

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irradiance without indicating the total power output of the lamp is akin to specifying revolutions per minute without specifying horsepower in the mechanical world. Radiometers are available to measure the peak irradiance and total dose (Joules) but care should be taken that the radiometer is designed specifically for UV LED since most common instruments are designed for broad-spectrum Hg lamps and may not be accurate, repeatable, or reproducible on UV LED systems.

The uniformity and consistency of UV output across the length of the UV LED lamp is also an important consideration for most digital inkjet applications; particularly graphics applications where image artifacts can result from non-uniform UV output or "hot spots".

Additional factors relevant to digital inkjet applications involve the implementation of the UV LED with respect to thermal management of the diode system. The push toward higher and higher power UV output must not be done in a way to compromise the lifetime of the LED's. All UV LED lamps are not created equally in that regard. It's important to understand the basis of lifetime claims from a potential UV LED supplier and the data used to support such specifications.

Finally, the ability of the potential UV LED lamp supplier should be evaluated from a commercial perspective. The technological, research and development capabilities, manufacturing, quality systems, and intellectual property position of the potential supplier are all areas that a potential end user or OEM partner should explore and understand.

Conclusions

UV LED curing lamps now represent the mainstream of UV curing technology in the UV digital inkjet marketplace. The lamps have rapidly evolved to the point that they equal or exceed the performance of mercury-based during lamps. The advantages of UV LED include performance, operational, economic, and environmental/safety factors that have been realized with the wide availability of UV digital inks optimized for UV LED wavelengths. This trend will continue as the cost of UV LED lamps continues to decline while their capabilities continue to improve.

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