Title: The Growing Viability of UV LED for Wide Web Applications
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Extended Abstract: This paper will explain the basics of UV curing including peak irradiance (Watts/cm^2), energy density (Joules/cm^2), and spectral wavelength as well as the fundamental differences between electrode, microwave, and UV LED curing systems. This paper will further highlight the benefits of using UV LED technology, the trends driving its adoption into an increasing range of production technologies, and more importantly its growing viability in wide web applications.

Industrial Sources of UV Curing

Industrial sources of UV curing have long included medium pressure mercury arc and microwave powered lamps and more recently light emitting diodes (LEDs). Conventional UV curing utilizing electrode arc lamps dates back to the 1940s and microwave powered or electrodeless lamps to the 1970s. Both arc and microwave curing technology are widely used in manufacturing today. By comparison, UV LED curing is relatively new with the first devices appearing on the market in the early 2000s.

For many years, UV LED curing systems were of relatively low power and had limited commercial use. But after more than ten years of continued advancements in the areas of output, efficiency, reliability, operation, integration, formulation, and production economics, the technology is being utilized across an ever growing list of applications. The evolution of UV LED technology is ongoing and presents numerous opportunities for manufacturing processes going forward.

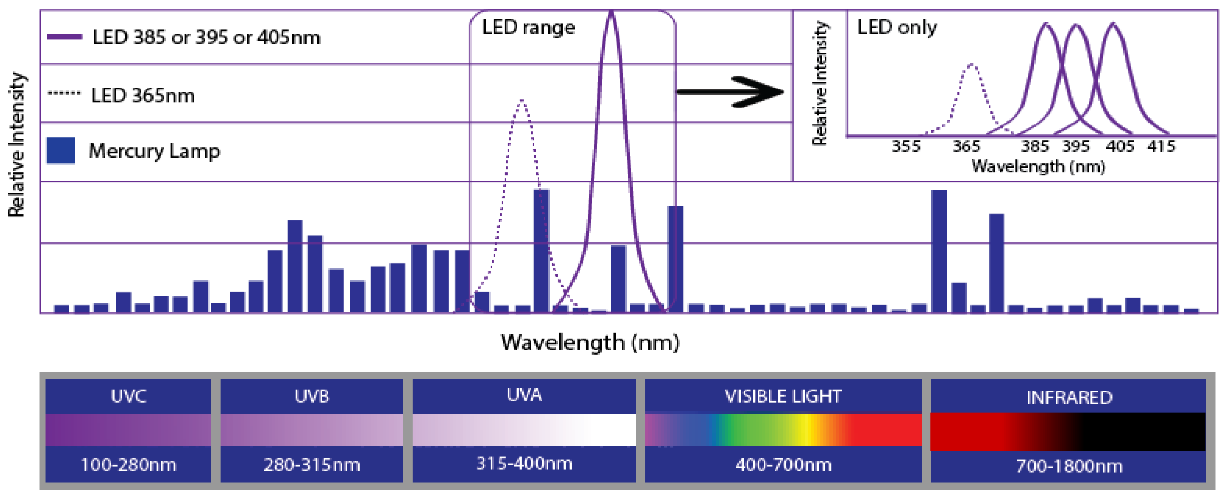
UV LED curing continues to capture market share in digital inkjet, screen, narrow web flexo, sheetfed offset, and structural bonding. So far, only a few companies have integrated UV LED curing into wide web coating lines; however, there is a growing level of interest in the use of UV LED sources within this wide web application space. Investment in lab and pilot line equipment and testing is increasing, and many companies are specifically including UV LED development in their R&D and engineering budgets. Others already have moved or are proactively planning to move toward UV LED curing on their production lines in the coming years. See chart.

Segment	Innovators	Early Adopters	Early Majority	Late Majority
Inkjet	Accomplished	Accomplished	Accomplished	In Progress
Screen	Accomplished	Accomplished	In Progress	
Offset - Sheet Fed	Accomplished	Accomplished	In Progress	
Flexo - Narrow Web	Accomplished	Accomplished	In Progress	
Coating Lines	Exploring	Some Installs		
Flexo - Wide Web	Exploring			
Offset - Web	Exploring			

Characterizing Sources of UV Curing

All UV curing sources can be characterized according to spectral wavelength (nm), peak irradiance or intensity (Watts/cm^2), and energy density or dose (Joules/cm^2). As with all spectral emissions, UV light exhibits properties of both particles (photons) and waves and is defined according to its wavelength. For ultraviolet wavelengths, this distance is on the order of a billionth of a meter and is typically categorized into bands of UVC (100 to 280 nm), UVB (280 to 315 nm), UVA (315 to 400 nm), and UVV (400 to 700 nm).

While arc and microwave lamps are considered broadband sources in that they include wavelengths across the UVC, UVB, UVA, UVV, and infrared bands, UV LEDs are relatively monochromatic, much more intense, and presently limited to longer UVA wavelengths (365, 385, 395, and 405 nm). It should be noted that there is significant LED research and development in the UVC and UVB bands; however, the diodes are currently very low power, relatively inefficient, offer very short lifetimes, and cost hundreds of times that of UVA diodes. UVB and UVC diodes are generally thought to be three to five years away from practical commercialization. See chart.



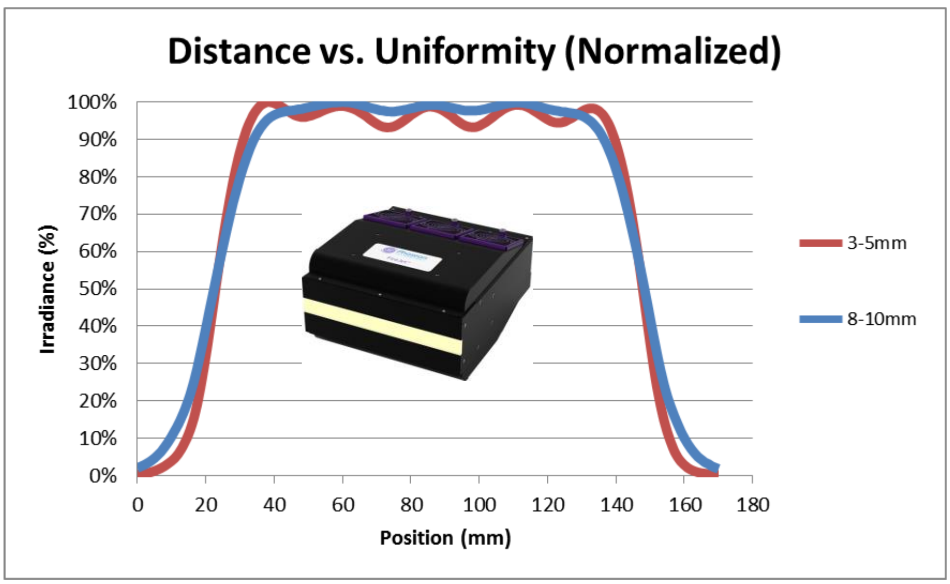
Peak irradiance (Watts/cm^2) is the radiant power arriving at a surface per unit area; whereas, energy density (Joules/cm^2) is the radiant energy arriving at a surface per unit area. In other words, peak irradiance is the delivered power, and energy density is the total delivered energy. Peak irradiance is affected by the output of the light source, the use of reflectors or optics, and the distance of the source from the cure surface. Energy density is a factor of the output of the light source, the number of UV sources, and the exposure time of the formulation. Understanding and managing spectral output, irradiance, and energy density is essential for formulating UV curable materials, selecting the correct UV sources for a production line, and ensuring the desired production speeds and cure results are achieved.

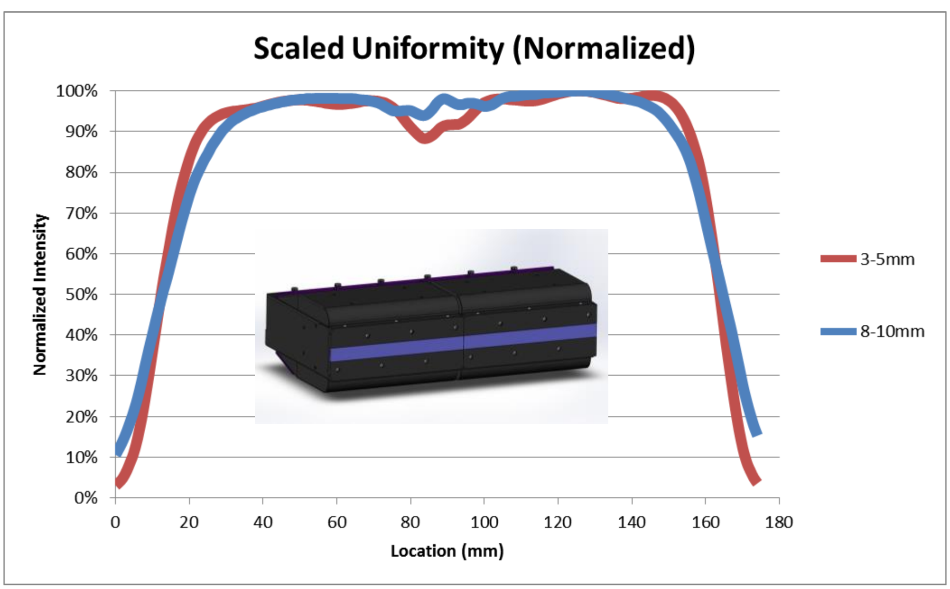
Conventional arc lamps typically emit in the range of 1 to 3 Watts/cm^2 while microwave lamps generally emit as much as 5 Watts/cm^2. UV LED curing systems, on the other hand, emit up to 16 Watts/cm^2 for air-cooled heads and 24 Watts/cm^2 for liquid-cooled heads. While the irradiance of UV LED systems is significantly greater than that of arc and microwave systems, the tradeoff is that the output is currently limited to the longer UVA wavelengths as previously stated. It is important to note that while energy density increases with increases in irradiance for a given UV LED source, a high irradiance does not necessarily guarantee a high energy density. It all depends on the construction and configuration of the

UV LED curing system. When evaluating different models from the same supplier or systems from different suppliers, it is important to understand both the irradiance and the energy density.

UV LED Uniformity and Output Profiles
When building a UV LED curing system, numerous raw or native LEDs are typically arranged in a matrix configuration. The UV output from each discrete LED follows lambertian characteristics in that there is no glare, no reflection, and no shift in brightness as the viewing angle changes. The output from each LED is divergent and blends uniformly with the output of neighboring LEDs. The uniformity further improves as the distance from the matrix increases.

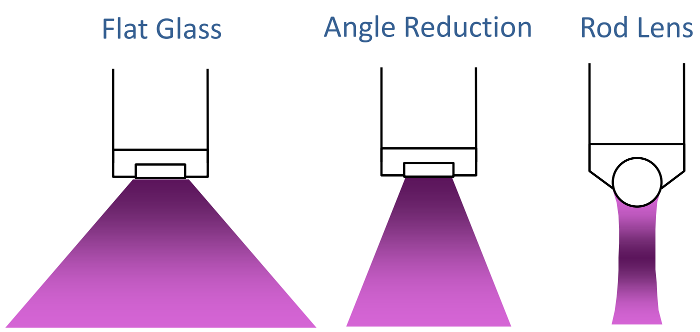
For most applications, it is critical to have uniformity of output along the length of the LED curing source as well as between mating sources. When individual UV LED sources are mated end-to-end, this is referred to as scaling the heads. It should be noted that not all commercially available systems offer the same uniformity characteristics, and it is recommended that uniformity be discussed with the UV LED supplier. Sources that exhibit better uniformity along the length of the head as well as between scaled heads deliver better quality and consistency of cure across the coated web. In all cases, uniformity improves as the distance between the matrix and the substrate increases. See images.





Most UV LED sources are equipped with a protective flat glass emitting window that is placed in front of the LEDs and is generally fabricated from quartz. This is meant to serve as both a physical impact barrier as well as a means of keeping dust and other foreign matter from depositing on the LEDs and creating localized hot spots. Hot spots impact the device's efficiency and useful life. Raw diodes and their corresponding solder joints are brittle and should not be directly handled without proper training or outside of a clean room. Properly designed UV LED assemblies are engineered to protect the diodes. As a result, the lamp assemblies can be easily handled but should not be taken apart. Doing so generally voids all warranties.

Other UV LED source designs incorporate reflectors and optics to produce narrow, columnated, or directional output that better maintains the peak irradiance over a distance. The goal of these systems is to cut down on stray UV reflection and/or cure at a greater distance. It should be noted that the use of reflectors or rod lens optics produce systems that deliver less energy density when compared to flat glass sources. This is due to the physical limitations in the width of the matrix when incorporating the use of optics and reflectors. The result is a more narrow matrix with fewer diodes. See image.

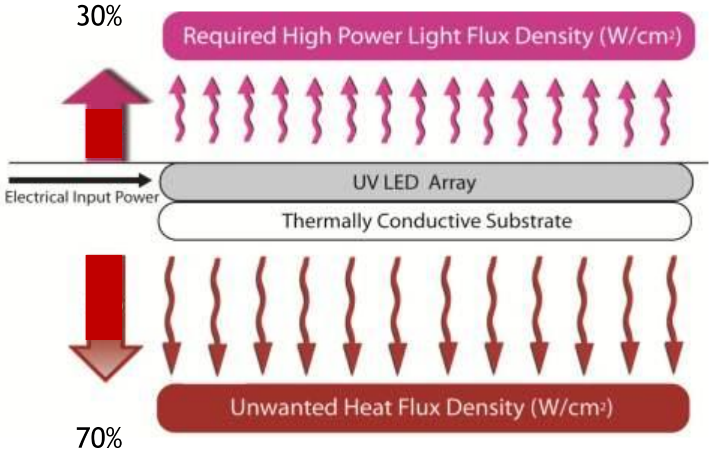


It is generally recommended that the UV LED source be mounted such that the emitting window is between 3 and 15 mm from the substrate. For applications that do not require high irradiance, sources are sometimes mounted as much as 75 to 100 mm from the substrate. The optimal distance for a given application is formulation and process specific. It should be noted that while irradiance decreases significantly as the distance between the UV LED source and the substrate increases, the corresponding energy density is constant.

UV LED Thermal Management

Thermal management of UV LED curing sources is critical in maintaining proper irradiance and uniformity as well ensuring a long lifetime. The thermal component in UV LED systems is not the radiated infrared energy typical with conventional curing sources. Instead it is energy created by the electrical inefficiencies that are present in any solid state device. While significantly greater in magnitude, the nature of this thermal heat is similar to that produced in cell phones, lap tops, and chargers as well as other high tech electronic devices.

With UV LED curing, approximately 30 to 40% of the input power is converted to useable UV output while 60 to 70% is converted to unwanted heat. If this unwanted energy is not removed, the LEDs will overheat and fail catastrophically. As a result, it is necessary to engineer an optimal cooling system that is balanced against the power of the device. See image.



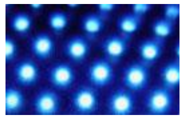
In general, a UV LED curing system is an electrical device with strict requirements on maximum LED junction temperatures. Either forced air or circulated liquid coolant can be used to remove the unwanted electrical heat and maintain the desired operating temperature, thereby, optimizing the efficiency of the LEDs and prolonging their useful life. Higher powered systems are generally cooled with liquid circulation. The peak irradiance of air-cooled systems, however, has increased in recent years and currently lags only slightly behind that of liquid-cooled systems.

UV LED Curing Benefits

UV LED curing systems are digitally controlled, instant ON/OFF, solid state devices that offer superior performance and operating benefits when compared to conventional curing systems. Other than the fact that a UV LED curing system emits ultraviolet energy, the device has more in common with a typical smart phone than it does with an arc or microwave curing system. Because UV LED systems emit longer UVA wavelengths and no UVC or UVB, LED systems are better at penetrating more heavily pigmented and opaque formulations. The lack of UVB and UVC means that no ozone is produced eliminating the need for exhaust and conditioned plant make-up air. No infrared energy also means that UV LED curing systems work across a greater range of heat sensitive substrates.

UV LED curing systems eliminate all of the spare parts and accessories typically associated with conventional curing systems. This includes bulbs, reflectors, shutters, magnetrons, RF screens, and exhaust ducting. Conventional bulbs typically last between 500 and 2K hours and begin degrading from the first second they are powered. Properly engineered UV LED systems, on the other hand, have demonstrated lifetimes between 20K and 50K hour with degradation of less than 15 to 20% of peak output. UV LED curing systems operate on DC power as opposed to an AC transformer or ballast and generally consume 50 to 75% less energy. UV LED curing systems also eliminate mercury and ozone as well as UVB and UVC wavelengths all of which make for a much safer operating environment.

UV LED curing systems offer better performance and quality control than conventional sources. UV LEDs eliminate the constantly degrading, short life quartz bulbs that produce a broad band spectral output that is essentially non-alterable due to the physics of vaporized mercury. Instead, UV LEDs produce a consistent spectral output with a nearly infinite adjustment in peak irradiance that can be scaled up and down with web speed. Knowing that UV LED sources will produce the same output across production shifts, days, weeks, months, and years eliminates the troubleshooting aspects typically associated with conventional UV curing systems. This generally results in increased throughput and reduced scrap. See chart.

BENEFIT		FEATURE
Advanced Capabilities		Heat-sensitive, thin substrates. Deep, through curing. Controlled curing irradiance.
Operating Economics		Faster speeds. Energy efficient. Long lifetime & low maintenance. Low operating temperatures. Lower total cost of ownership.
Environmental Advantages		Mercury & ozone free. Safe UV-A wavelength. Near-ambient housing temp. Workplace safety.
Ease of Use & Integration		Solid-state. Instant ON/OFF curing. No warm-up/cool-down cycles. No shutters or exhaust ducting.

Wide Web Coating Applications

Most of the UV LED formulation work over the past ten years has been in the areas of inks, adhesives, and over protective varnishes. Many coatings companies are just now starting to evaluate UV LED curing systems for use in curing b-stage, functional, and hard coat chemistry. The fact that there is dedicated attention being given to UV LED coating formulations suggests that the latest improvements in the technology are making it more viable for use in wide web coatings applications. In addition, the success that UV equipment suppliers have achieved in designing and producing UV LED curing systems in short head lengths (<700 mm) is now being transferred to the design and production of mid and wide web curing lengths. Today, companies are producing both continuous length longer heads as well as scalable heads that can be configured to span any range of curing widths.

The reduction in costs achieved through high volume sales of shorter length UV LED systems, greater UV irradiance and energy density output per device, longer unit lifetimes, general advancements in production and yield, as well as increased competition have resulted in a decreasing cost curve for both the initial investment and over the total operating life of the system. As a result, wider web UV LED curing systems which were initially cost prohibitive are now much more feasible. Work still needs to be done in the area of formulation, but many companies are embracing the development opportunity.

The following photo is of a 1,575 mm (62”) wide bank of 12 Watts/cm2, 395 nm UV LED systems that were installed on a coating line in 2015. Four 375 mm heads and one 75 mm head were scaled end-to-end in order to span the width of the 58” wide web and allow for some web tracking. Speeds on this particular line range from 8 to 60 fpm depending on the gauge of the product being produced.

There are many successful ink, adhesive, and coating applications utilizing UV LED curing today. While most of these applications are in printing and structural bonding, there is a growing interest in UV LED for web coating. Presently, the wide web market almost exclusively uses conventional curing systems, but businesses are starting to invest time and resources into developing UV LED solutions for their respective coating applications. While it is likely that various applications may not yet be viable for LED, there are several coating lines that are successfully being converted. In addition, wide web UV applications that were never possible with conventional arc or microwave systems due to the large degree of heat transfer are becoming possible with LED, thus expanding the total UV curing market.

Over the next few years, the coatings industry will plug away within the technology development network one application and one market at a time, learning more and more as it anticipates the next big UV LED application breakthrough. Benchmarking where UV LED technology is today, where it is headed, and how it could possibly address various process needs over the coming years is always a great place to start.