UV Curing of Inks and Coatings in Digital Printing Applications

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Abstract

UV curing of inks and coatings is discussed in relation to the type of UV source and curing systems available for use in digital printing applications.

Comparison is made between classic arc, microwave powered UV and LED technologies. The advantages and limitations of each are critically reviewed for curing the wide range of materials as used in both the graphic arts and industrial processes.

Factors influencing cure are identified by detailed consideration of material and process. Variables include chemistry, substrate types, application requirements and optical design / spectral emission of the curing system. A method of lamphead characterisation is outlined using computer ray trace tools and dosimetry measurement techniques, with view to maximising dose efficiencies and optimising curing performance.

Selection of the most appropriate type of curing system is concluded as being based on simple cost to performance ratio for the given application.

Introduction

The UV process is well established and applies to traditional printing methods.

The change in state from liquid (wet) to solid (dry) is almost instantaneous as the ink is passed at high speed under a UV light source. The ink usually consists of 100% solids and is photo-reactive such that it will harden to give the required performance on exposure to UV.

UV Light Generation

Alternative methods of generating UV light suitable for ink jet applications include classic arc, microwave powered UV and more recently LED technologies. A comparison is given in Figure 1.

Classic Arc

Arc lamps have wide bore and are supplied in a range of lengths with different types of end-fittings for electrical connection. A high voltage is applied between the electrodes to ionise the inert gas within the lamp and form the arc.

Due to the rapid increase in temperature, the small amount of mercury (and other metal halide additives) also contained within the lamp then vaporises and enters the arc to form a plasma. Inter-atomic collision with the high speed moving electrons stimulates photon emission.

The Medium Pressure Mercury Arc (MPMA) lamp gives broad spectral output over the entire UV spectrum. Use of metal halide additives such as iron or gallium in doped lamps shifts the spectral output to longer wavelengths.

Microwave Powered UV

In comparison to arc technology, microwave bulbs are narrow bore, limited to 250 mm or 150 mm curing width and contain no electrodes. A uniform microwave field is created by means of a magnetron to energise the lamp and stimulate photon emission. An RF screen consisting of fine wire gauze positioned at the front of the reflector maintains the microwave energy within the cavity.

All microwave powered UV systems use high velocity positive air cooling of the magnetrons, bulb, reflectors and substrate. Bulb life extends beyond arc lamps as there are no electrodes to deteriorate. However, magnetrons also have a finite life and need to be replaced.

LED Technologies

LEDs are solid state devices only recently associated with UV light generation; their use in the visible and IR regions of the spectrum already being well established in the photonics industries.

Application of a potential difference across a pn junction consisting of two different types of semiconductor materials results in photon emission due to currents being induced from the recombination of holes in the p type semiconductor and electrons in the n type material. The wavelength emitted depends on the type of doping used: often this consists of arsenides of aluminium, gallium or indium.

Increased current flow through the diode produces higher light intensity: heat generated across the junction then needs to be effectively dissipated sometimes by means of water cooling otherwise the diode is destroyed. Alternatively, the diode can be switched intermittently, ramped at different power levels or pulsed to reduce the heating effect and extend useful life.

As the UV light intensity is relatively small, compared to conventional types of UV source, LEDs can be arranged in clusters to direct the energy to a common point. As the spectral emission tends to be very narrow, typically (20 - 40)nm, diodes of different type can be arranged together in a matrix to integrate the various emissions and extend the wavelengths. Given the intensity is relatively low, the resultant UV dose is also low. Often LEDs are positioned in linear or area arrays to increase dose levels and extend the curing width.

UV Curing Systems for Ink Jet Application:

The light from the UV source is collected and directed onto the ink by means of the reflectors. Dichroic coated reflectors are now

Parameter	Ideal	Classic Arc	Microwave Powered UV	LED
Operating Characteristics:				
time (sec) to reach steady-state from cold	zero	15-30	<=10	<1
instant switching (sec) - on/off	zero	<1 (mechanical shutter)	<1 (mechanical shutter)	<1
re-strike (sec)	zero	>30	<8	<1
operation	continuous	continuous	continuous	may have to be pulsed
power level	infinitely variable	stepped or infinitely variable	infinitely variable	infinitely variable
power drive	digital	ballast, transformer or digital	digital	digital
voltage	low	high (kV)	high (kV)	low (V)
current	low	high (A)	high (A)	low (A)
power consumption	low	high (kW)	high (kW)	low (W)
heat dissapation	zero	high to medium	high to medium	medium to low
Physical Characteristics:				
size	small	small to medium	medium to large	very small (unit source)
reflector	sealed	open aluminium or dichroic	open dichroic	sealed
light gathering mechanism	zero loss	elliptical or parabolic reflector	elliptical or parabolic reflector	clusters or arrays
curing width (mm)	infinitely variable	infinitely variable	multiples of 150 or 250 mm	infinitely variable
height (mm) to substrate	10mm	(10 - 50)	54	(5 - 20)
cooling	none	air, air/water, water	air	air or water
extract	none	duct to atmosphere (ozone) or none (water cooling only)	duct to atmosphere (ozone)	none
integration	simple	simple to complex	complex	relatively simple
Maintenance:	zero	lamps & reflectors	lamps & magnetrons	minimal
UV Source Life (Operating Hours):	infinite	1000 - 3000	3000 - 10000	10000
UV Output Chracteristics:				
wavelength	200-450nm	200-450nm	200-450nm	>340nm
bandwidth	broad	broad	broad	narrow <40nm
intensity	high	very high >5W/cm2	very high >5W/cm2	low (mW/cm2)
Dose (J/cm2) - (line speed dependent)	high	high	high	low (requires multiple sources)
Compatibility with UV Chemistries:				
free radical	high	high	high	limited to UV-A and UV-V
cationic	high	high	high	zero (unless dye sensitized)
through cure of inks	high	high	high	limited
surface cure of inks	high	high	high	limited (more suited to pinning)

Figure 1. Comparison of UV Sources Suitable for Use in Ink Jet Application

more commonly used than polished aluminium as they offer more effective heat management and also can exhibit much higher reflectivity in the UV-C region.

A cooling mechanism is required to maintain the lamp and reflector at the optimum operating temperature, in addition to directing infra-red or heat away from the substrate. Heat-management is therefore often a critical part of providing a UV solution and systems include water cooling, air cooling or a combination of both.

Irrespective of which technology is used to generate UV light, most of the UV curing equipment for use with ink jet printing has been adapted rather than designed specifically for the market. Traditional UV lamp systems are often too large, heavy and use simple high velocity air for cooling which can disrupt the ink droplets. Those systems operating at standard focal lengths can also cause pre-curing on the ink nozzles.

Often, the main requirement is to provide a small and compact high power UV curing system that can be readily integrated into the process.

Classic Arc

In cases where extreme high power is not required and heat sensitivity of the substrate is not critical, simple air cooled arc lamp technology can be used for "pinning" or final UV curing. As these types of system normally support the lower cost end of the market, the lamphead is usually fitted with a polished aluminium rather than dichroic reflector. Standard mercury or doped lamps often operate at a fixed power level from a ballast power drive.

The DropCure is one example of a high power UV curing system that has been designed specifically to meet the needs of the ink jet market. The system relies on high purity de-ionised water being re-circulated through a single quartz IR filter located beneath the lamp, dichroic reflectors and lamphead (Figure 2).

The direct IR is absorbed by the water and removed via a heat exchanger

The system is ideally suited to a wide range of substrates including very heat sensitive thin gauge filmic materials such as LDPE, PVC and foil coated paper. Being totally water cooled, there is no ozone generation and therefore no need for air extract.

Due to the effective heat management, the lamphead can be positioned very close to the substrate to provide extreme high intensities. The reduced operating distance also eliminates any pre-curing on the nozzles. Being water cooled, there is no disruption of the ink droplets from high velocity air.

The irradiance profile is also very uniform across the total curing width: the slight fall off towards the electrodes at the ends of the lamp being compensated by providing a lamp of slightly longer length.

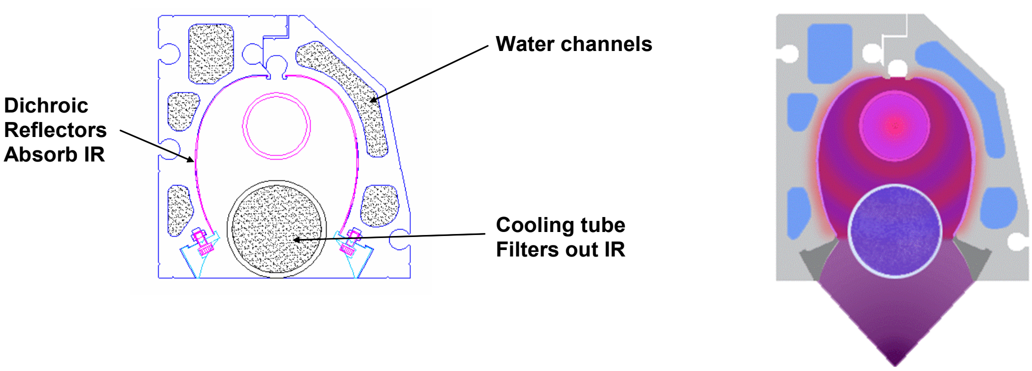

Figure 2. Example of High Power UV Curing System (DropCure)

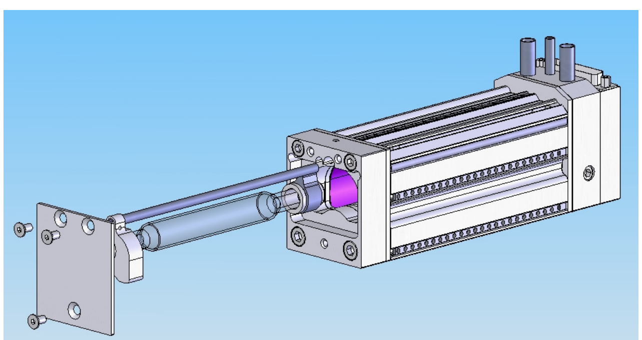

Figure 3. Example of Ultra Small Lightweight UV Curing System (TinyCure)

The UV system designers continue to make advances towards the ultimate solution that will meet all requirements of ultra small size, lightweight and high power. The TinyCure shown schematically in Figure 3 has a footprint of only 50 mm × 56 mm (cross-section). Again water cooling is used to effectively control heat management and totally eliminate the need for air cooling and exhaust extraction.

Microwave Powered UV

Although microwave powered UV has been successfully used for industrial ink jet applications, the physical size constraint makes this a less attractive solution for some applications requiring direct integration within a printing machine. However, these systems can be used with remote blowers to limit size. Some systems now offer an exhaust box accessory which allows UV exposure through a sealed quartz plate whilst extracting the exhaust by means of a separate fan.

LED Technologies

LED technology can be used effectively for "pinning" or partially curing the droplets immediately following contact with the substrate so as to reduce any absorption or spread and change in dot size. Final curing can then be provided down stream by more conventional UV sources.

The next generation of higher power LED systems require water cooling to ensure long life. The LED array can be connected to an umbilical cord supplying power and heat management. In this way, the array can be fitted into extremely small spaces.

UV Material Chemistry

The UV formulation is optimised to give a balance of physical (mechanical) and chemical properties. For example, ink must exhibit good inter-film adhesion with the substrate. Those inks used without overvarnish must also exhibit excellent slip and abrasion resistance whilst maintaining good moisture and solvent resistance.

Many UV inks rely on the free radical curing mechanism involving initiation, propagation and termination reactions that occur almost instantaneously during UV exposure.

The composition of a free radical cure acrylated ink system includes the oligomer, which gives the overall mechanical properties, reactive diluent to control viscosity & curing characteristics, photo-initiator, to kick start the polymerisation reaction, pigments, to impart colouration and additives to provide the final coating properties.

The lower viscosity can increase the rate of oxygen diffusion and inhibit cure. Some inks are therefore cured under nitrogen to prevent oxygen inhibition of surface cure via the formation of peroxide free radicals.

The photo-initiators are responsible for absorbing UV light at specific wavelengths: the longer wavelength UV-A (320-390)nm is usually required for most effective through curing and the shorter wavelength UV-C (<280nm) for surface cure.

The cure speed of the materials can vary across suppliers, particularly for difficult to cure colours such as black. Application thickness must also be controlled, as greater the thickness, further the UV light has to penetrate. The inks are applied at some 6 - 25 microns depending on end-application.

Measurement of Cure

Cure can be measured on a simple practical basis by the number of double rubs that the surface can withstand with a solvent such as MEK before the cured structure starts to breakdown.

A better but far more analytical technique (FTIR spectroscopy) involves measuring the reduction in the number of reactive chemical sites, as the curing reaction proceeds. The difference in the IR absorbance spectra at specific wavelengths corresponding to the reactive groupings between uncured and cured material can be monitored. Complete reduction in the availability of such chemical groupings is not possible as some are trapped within the cured matrix.

The % conversion of unsaturated carbon carbon double bonds can be so determined. This is often termed % RAU (reacted acrylate unsaturation)

The % degree cure is very much related to the UV curable material type, the final mechanical performance properties and end-use.

UV Dosimetry

UV materials require a certain minimum energy density or dose (J/sq cm) as measured over specific wavelengths, to give acceptable cure.

The UV dose is simply the integration of intensity with respect to time.

The UV intensity or irradiance level (W/sq cm) as measured over the same specific wavelength regions, is a function of the lamp power, reflector geometry and distance.

Thus for the same line speed, higher dose levels can be achieved by using higher lamp powers or higher intensities. Often as the intensity is limited, multiple lamps have to be used to achieve the required UV dose for curing.

Each chemistry type can react differently and often the optimum dose and intensity levels have to be determined empirically for the type of UV curing system. Although dose is additive, the resultant curing characteristics are sometimes not linear, particularly at lower and higher intensity levels.

In summary, cure is a complex issue and is influenced by the line speed, number of lamps, lamp power, lamphead efficiency, reflector design, lamp spectral quality, IR component from the UV, material temperature and film thickness.

The UV curing window defined as the range of UV exposure which gives acceptable material performance needs to be determined by practical experiment for each type of chemistry. Both under and over-cure needs to be avoided as this can adversely affect the performance and characteristics of the finished material.

Relative Spectral Energy Distribution and UV Dose

Most relative spectral energy distributions of the various bulb types themselves are measured without a reflector in place and are normalised to 100% corresponding to the peak output (Figure 4).

Dosimetry measurement from the lamphead itself is often more meaningful. The absolute dose for different bulb types compared to mercury is shown in Figure 5. The UV-A dose for an iron doped lamp is approximately increased by a factor of 2 and the UV-C region reduced by a factor of 0.5.

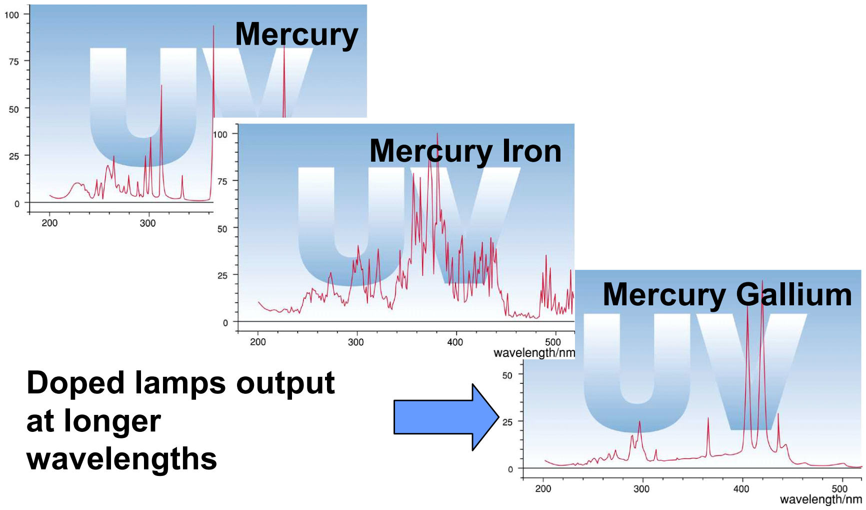

Figure 4. Relative Spectral Energy Distributions

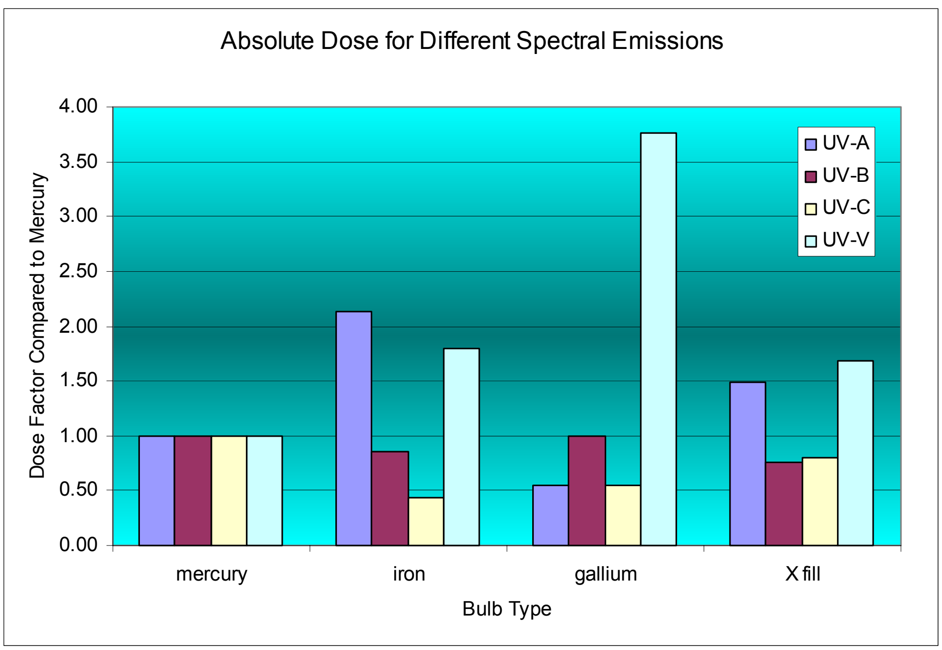

Figure 5. Absolute Dose for Different Bulb Types

As the iron bulb contains metal halide additives to generate the spectral shift towards longer wavelengths, high operating temperatures must be maintained. Over cooling the bulb at lower power levels can reduce the UV-A output and the percentage spectral distribution then changes to one which is more characteristic of a mercury bulb.

Selection of the optimum UV source is essential for effective cure of ink jet chemistries. Special lamp fills can be used to change the balance of surface and through cure characteristics (Figure 6). The X fill lamp has a spectral distribution which is a hybrid between mercury and iron. Ink cure is improved for this specific ink chemistry due to the combined higher UV-C and UV-A compared to iron and mercury lamps respectively.

Some chemistries are more intensity sensitive and higher lamp powers provide a higher degree of cure: comparison being made at the same dose levels (Figure 7).

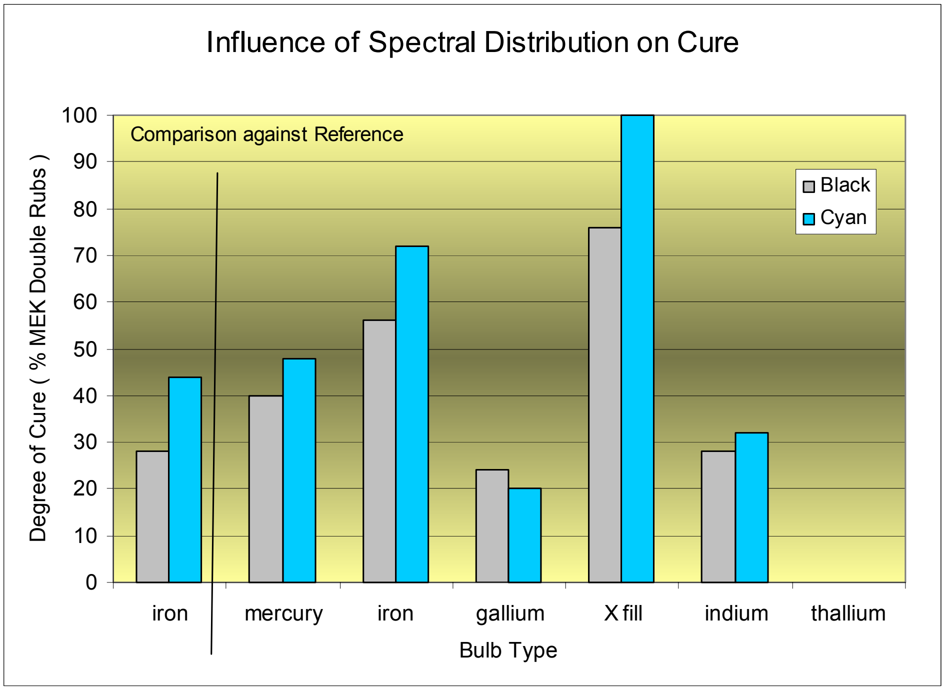

Figure 6. Example of the Influence of Spectral Distribution on Cure

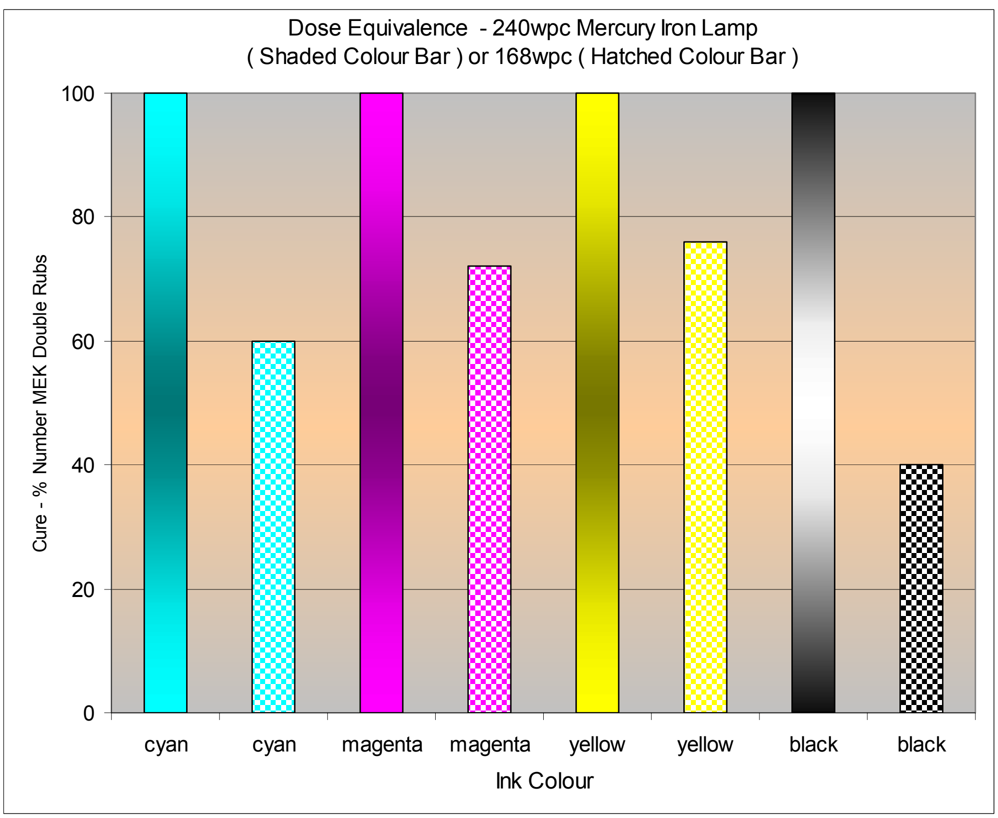

Figure 7. Effect of Intensity on Cure (Equivalent Dose Levels)

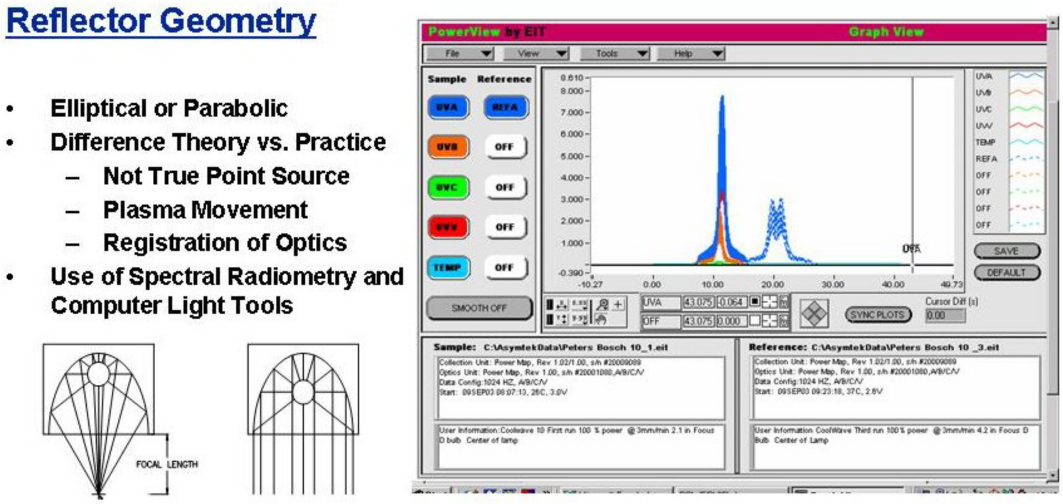

Figure 8. Lamphead Characterisation

Lamphead Characterisation

Lamphead characterisation is defined by means of spectral radiometry, thermal imaging and computer ray trace.

A UV lamp is rated in terms of its electrical power expressed in watts per linear cm of the lamp. Higher the electrical power rating, greater is the lamp intensity or brightness.

Spectral radiometry is used to measure the UV output from each type of UV source over specific wavelength intervals. Depending on instrument type, the interval can be extremely small to give high resolution spectra, narrow band or broad band to cover the whole of the UV wavelength range.

Inter-instrument agreement is not particularly good especially between instruments of different manufacture. This is likely due to differences in total system response and calibration. Thus instruments are best used for relative rather than absolute measure.

A dosimeter is passed under the lamp system at constant speed so as to measure the UV energy or dose (J/sq cm) and peak irradiance or maximum intensity levels. (W/sq cm); often simultaneously measuring at 4 wavelength intervals corresponding to the UV-A, UV-B, UV-C and UV-V regions of the spectrum.

A highly focused system will exhibit a high peak intensity and relatively narrow irradiance profile. As the height between the lamp and substrate is increased, the light intensity will decrease and the UV energy is effectively spread-over a greater distance.

Accurate mapping of the intensity of irradiance profile is achieved by means of a spectral radiometer with full data logging capability. The light detector with known bandpass filter to measure over specific UV wavelengths is again moved at constant speed under the UV source and the individual UV intensities recorded. (Figure 8) In this way, the profile can be accurately measured and mapped for the specific lamp head geometries. Complete characterisation of the lamphead is therefore possible.

Depending of the lamphead design and light gathering capability of the reflector, each type of UV system can output very different amounts of UV energy, even though the electrical power rating of the lamp is the same. In effect, each system exhibits a different performance in converting electrical lamp power into useful UV energy. (Figure 9).

By calculating % dose efficiency, comparison can be made across systems operating at different electrical lamp power and line speed.

The % conversion of energy into heat can also be determined by measuring the temperature rise on a metal bar of known type and mass over a given time

Conclusions

Selection of the most appropriate type of UV curing system for ink jet application is based on cost to performance ratio.

The UV system must provide the required amount of UV energy for curing at the highest line speed whilst maintaining the necessary heat management for the specific substrate type.

Simple low cost air cooled arc lamp technology is usually restricted to lamp power levels of <=150wpc. Use of cooling and extract fans to remove heat and ozone makes this type of curing system non-ideal for many applications. Substrate heating also becomes an issue as lamp powers increase.

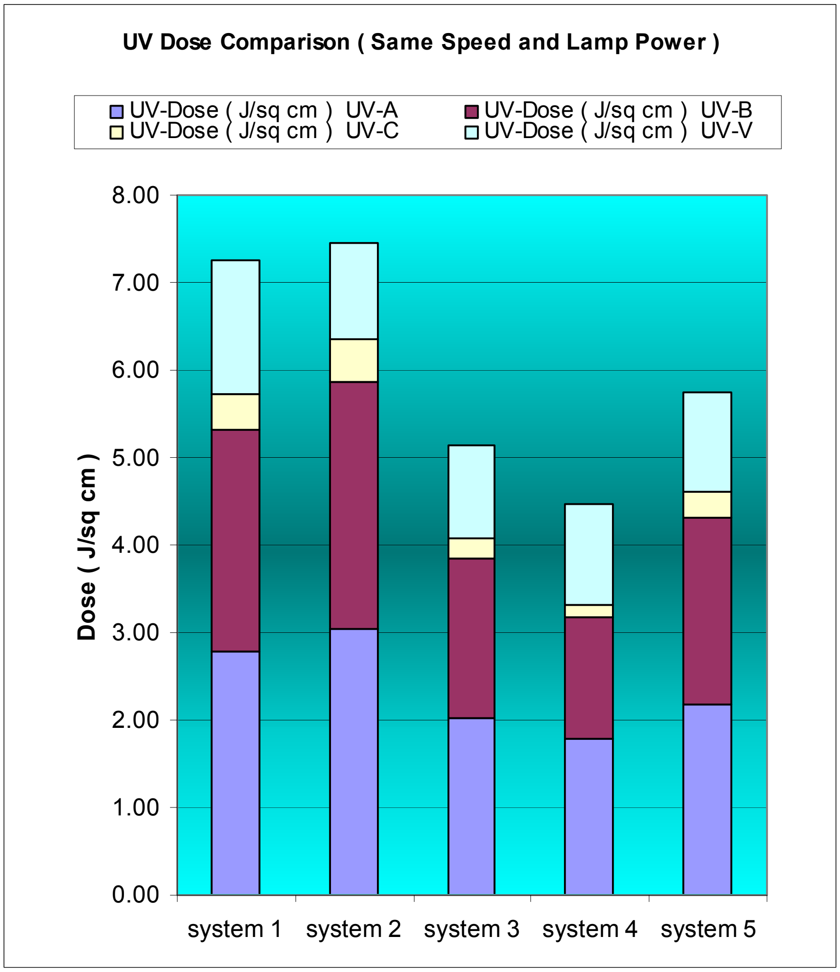

Figure 9. Different UV Curing System Performance

The DropCure has been designed specifically rather than being adapted for the ink-jet market. The system provides high dose efficiency and offers the following advantages particularly for heat sensitive substrates and single pass applications:

- High lamp powers <=240wpc, infinitely variable via digital control
- High Intensities for effective light penetration and more efficient curing
- Water rather than air cooling eliminates disturbance of droplets
- No cooling or exhaust air, no ozone extract: nitrogen inertion available
- >=7 mm height to substrate gives high intensity and reduced light spillage
- Effective heat management: removal of both reflected and direct IR

The market now demands even more compact and lightweight units for simple integration particularly for wide format scanning applications. The same basic operating principles used in DropCure have been applied in the latest generation TinyCure system which provides effective high power curing up to 200wpc yet has a small footprint.

In comparison, the microwave powered UV source has the added advantage of quick start and very long lamp-life. Many ink jet chemistries appear to have been developed in the laboratory using this type of UV source. Often the physical size restricts this type of UV curing system being integrated within a printing machine, other than larger industrial coding equipment. Ideally the same UV curing system used for final production requirements should also be used for ink development so as to eliminate any step-changes in performance and resultant cure.

LED is still an emerging technology, more applicable to static rather than dynamic curing at this time. Given line speeds are now approaching 150m/min for some commercial printing applications, the available intensity and dose levels are too low to provide complete curing. Restriction of wavelengths to >=340nm excludes their use for those ink jet chemistries reliant on shorter wavelength UV-B and higher energy UV-C regions. However they are becoming increasingly used to provide gel curing or pinning to help eliminate changes in dot size, prior to full curing using more conventional types of UV source.

Author Biography

John with a PhD in Silver Halide Emulsion Chemistry has responsibility for Managing the UV Applications Laboratory at the new Nordson UV Facility in England.

Specialist knowledge includes Photo-Chemistry, Formulation of UV Inks and Coatings and UV and Visible Spectral Radiometry.

He has been a member of numerous professional bodies including the Institute of Printing, Colour Group of Great Britain, British Standards Institute, Article Numbering Association and Radtech Europe. He has also acted as a Sub-Editor for the RPS Journal of Photographic Science.