Energy Curing in Ink Jet Digital Production Printing

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Abstract

Energy Curable ink has become a popular ink technology choice in both scanning graphics applications and in the increasingly important ink jet digital production area, where single pass print engines are being used or designed. The choice of an ink which remains liquid in the print-head nozzles but which can dry "instantly" on the substrate is advantageous from a print-head stability viewpoint.

Various methods of curing are available ranging from LED, UV-mercury lamps of electrode and electrodeless type, UV-excimer, with or without nitrogen inerting through to electron-beam curing. Different markets will require and warrant different strategies and this paper reviews the various aspects of these curing technologies and their suitability for different applications.

Introduction

In UV-Curing ink systems the photoinitiators will upon exposure to light of the appropriate wavelength, become excited and thus potentially produce free-radicals. The spectral emission characteristics of the exposure system are therefore as important as the absorbance characteristics of the photoinitiators in the ink. In electron beam curing photoinitiators are generally absent and the curing proceeds via radicals created directly by the beam of electrons impinging on the ink.

UV-Curing Systems

The main curing system types are: Mercury vapour systems (comprising electrode and electrodeless lamps), Excimer lamps, flash systems and LED. Each of these has various advantages and disadvantages according to the application and each is at a different state of development in terms of equipment capability and sophistication.

Mercury Vapour Lamps

Mercury is particularly suited to use in curing lamps because of its inert nature and high volatility which allows significant pressures of mercury vapour to be attained at temperatures of only a few hundred degrees. In addition, it has a number of well positioned energy levels giving rise to many emission lines spaced throughout the UV region. The radiation emitted by a mercury vapour lamp is a consequence of electronic transitions occurring in the vapour phase as excited mercury atoms revert back to their ground state configuration.

The most commonly used lamps in curing of inks are the so called medium pressure mercury lamps. A typical lamp consists of a sealed quartz tube with an electrode at each end containing an exact amount of mercury and a low pressure of a starter gas, typically argon. The electrodes comprise a thoriated tungsten rod wrapped in tungsten wire and connected to the electrode leads by molybdenum foil seals. These foil seals are prone to problems, and to prevent failure they must be kept below 300oC, while the rest of the lamp operates at 600-800oC. Generally there is also an outer reflective and heat resistant coating of gold, platinum or Zirconium oxide on the quartz at the tube ends to keep them warm and prevent mercury from condensing behind the electrodes.

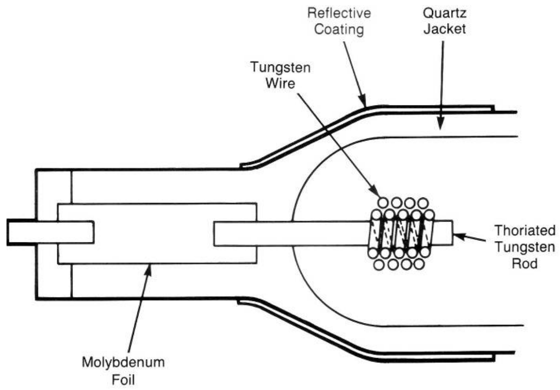

Figure 1. Schematic of a medium pressure mercury arc lamp electrode

In scanning ink jet applications, such as wide format graphics printers where the curing lamps are attached to the print head carriage, the electrode/connectors can be the cause of failure, due to the very high g-forces experienced upon acceleration/deceleration of the carriage. Such stresses can shorten the lamp life and some manufacturers have taken steps to address this issue.

Electrode deterioration generally results from the sputtering that occurs during the first few seconds of lamp operation, causing a gradual deposition of black tungsten metal on the tube walls near the electrodes. Although the argon starter gas does help to reduce the extent of this problem, it is the principal reason for lamp ageing; consequently, a lamp's lifetime will be considerably shorter if it is frequently switched on and off. The generally accepted lifetime for lamps is about 1000 hours but this varies according to; manufacturer, over/under cooling, overload, on-off cycles, airborne pollution (e.g. ink spray) and incorrect cleaning. The requirement to change a lamp is difficult to judge since it is characterized by a slow decline in intensity, particularly at short wavelengths, as the electrodes degrade and contaminate the quartz envelope.

Although predominantly still a line spectrum, the emission spectrum of the medium pressure mercury lamp shows lines that extend throughout the UV, visible and infra-red regions. In fact the overall conversion of input energy into UV light is only around 20%, with heat being the greatest output. Of the UV emissions from a typical medium pressure mercury lamp the visible lines at 546 and 578 nm are of no importance. The emissions in the UVA range 365,405 and 436 nm provide much of the deep through-cure, particularly when appropriate photo-initiators such as thioxanthones and phosphine oxide types are used. The short wavelength emission, in the UVC region 220-280 nm have little ability to penetrate into the film due to both refraction and strong absorption by most components in the film, but are responsible for most of the surface cure. The emissions in the UVB region provide a reasonable balance between these two regions. So called " ozone free" lamps use an additive in the quartz that prevents the emission of light below 240 nm and thus the formation of ozone, but also reduces much of the overall UVC emission. These ozone-free lamps are not widely used in curing printing inks because cure speeds are typically reduced by 20-30%.

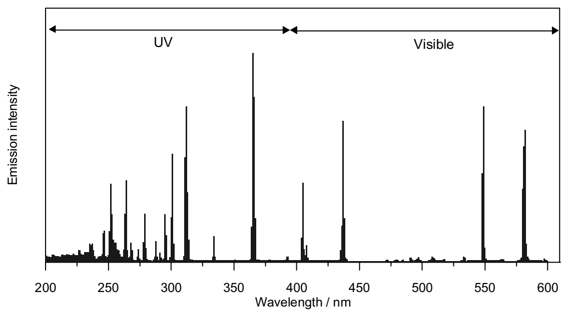

Figure 2. Typical Medium Pressure Mercury Emission Spectrum

Lamp length does not present any particular issues up to around 1m, at which point sagging of a long lamps and arc instabilities due to acoustic resonance become problematic. Arc instability is solved through the use of careful design or an electronic power supply where there is no sinusoidal power fluctuation that gives rise to the acoustic resonance. These technically demanding issues explain why there are dozens of suppliers for narrow web lamps in Europe but only two (Nordson and IST) successful manufacturers of very wide web lamps.

Lamp diameter can also affect the spectrum of the lamp, with narrow diameter lamps giving far more high energy UVC radiation because the self-absorption of UV light is minimized. Narrower diameter lamps also tend to run hotter and generate more heat management/ dimensional stability issues.

Light has to be directed towards the substrate and preferably concentrated into as narrow a beam as possible in order to maximize dose rate and intensity. This is achieved by the use of reflectors behind the lamps. Anodized aluminium is normally used as it has very high reflectivity in the region 200-400 nm.

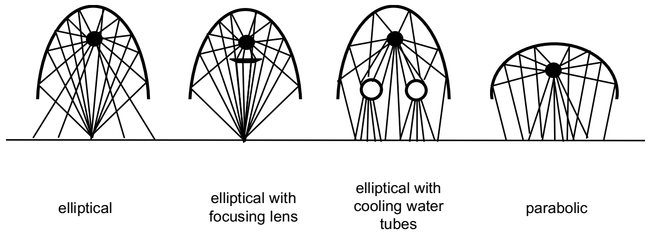

Figure 3. Typical Reflectors

Focusing the UV light is not as straightforward as it would seem and there is never a single light focal point but areas of higher or lower intensity. In theory the elliptical reflector gives the highest intensity narrow beam of UV; however this relies on an exact placing of the lamp to achieve the focal point at the substrate and is thus practically difficult, so parabolic "flood" irradiation is also commonly used. The use of water cooling tubes has been around for many years and is still favored by Nordson, even on their latest design of lamps. This has the advantage that ozone is degraded quickly by contact with the cooling tubes, thus avoiding the use of extraction equipment, but it does require the use of distilled/de-ionized water and careful maintenance to prevent bacterial growth and the loss of short wavelength light.

Other heat management solutions which have been used include chilled rollers behind the substrate and quartz plates in front of the substrate. Quartz plates remove 15-20% of the IR and then require cooling themselves, typically by a compressed air flow. They also cause some losses in short wavelength UVC light.

One of the most effective technologies for removal of the IR radiation is dichroic reflectors. These operate on the basis of cumulative constructive interference, so by vacuum deposition of around 50 carefully controlled layers of aluminium, titanium, cerium, silicon oxides, magnesium fluoride and zinc sulphide, the IR and most of the visible light radiation is allowed to pass through the coating whereas the UV radiation is reflected. Dichroic coatings can be used on chilled aluminium reflectors. Dichroic reflectors are quite expensive but are now also quite common, especially in higher specification systems. One limitation of dichroic reflectors is that they only remove IR from reflected light, so a certain quantity of IR still reaches the substrate by direct irradiance from the lamp.

As already covered, for reasons of electrode damage, lamp lifetime reduction and long make-ready time it is not desirable to keep switching lamps on and off. However in order to keep the lamps ready for immediate use the heat from the lamp has to be drastically reduced to prevent the substrate burning when the digital press is stopped. This is achieved by the use of shutters in front of the lamp which prevent the UV and IR light reaching the substrate, and/or having the lamps dropped to a low power but stable state. Low lamp standby powers are easier to achieve with modern electronic power supplies and can be as low as 15-20 % of full lamp power.

Shutters tend to be either something that slides in front of the lamp, a reflector that fully rotates to direct energy away from the substrate or the " clam-shell " type, where the two sides of the reflector assembly pinch together to prevent light reaching the substrate. The "clam-shell" type is most common but there are many different commercial shutter designs. In digital production printing equipment the use of shutters is of critical importance. One of the key benefits of digital equipment is the reduction of make-ready times and thus curing sources that can be "instantly" switched on and off is crucial. In scanning applications it can be important to "cut" the lamp exposure when the lamp goes past the end of the printed area, since reflections and scatter from the surrounding print table etc can lead to curing of ink on the printhead orifice plates.

In single pass printing implementations the considerations are somewhat similar to those of curing in a conventional UV-curing press (e.g. flexo, gravure) save for the fact that UV-curing ink jet is almost always more challenging to cure at high speed due to the relatively thick ink layers and very significant oxygen inhibition suffered by these low viscosity ink systems[1] .In such cases high power and high peak irradiance will be crucial to achieving the required curing. Under such high power conditions, control of heat will also be a significant issue.

In scanning applications there are some unique considerations in ink jet compared to conventional printing. Since the lamps are often scanning with the head there is a need for light-weight lamp assemblies, fast shuttering for the reasons stated above and high power/intensity. Some manufacturers have responded to the need for light weight equipment by the introduction of models especially aimed at the ink jet market. An alternative strategy that can be employed to reduce the mass of the moving carriage is to use some sort of low power exposure unit on the carriage to "pin" the UV ink in place and then to follow up with a later (off print axis) high power curing system, downstream of the print head carriage.

In very general terms few manufacturers are working on increasing power significantly, but are rather concentrating on increasing the usefulness and robustness of their offerings. There is much attention on power supplies e.g. improving balasts to allow low standby power operation, greater electrical efficiency, continuously variable power and more compact equipment.

Doped Sources

Doped lamps contain both mercury and a small amount of another metal which modifies the emission spectrum. The lower volatility of these additive metals is such that they are generally added as the metallic iodide which volatilizes and dissociates at the high plasma temperatures during operation to give the parent metal and iodine. The lower ionization and excitation energy of the typical metal dope means that, even at the low additive level, it can dominate the emission spectrum. The most common dope metals are iron and gallium but other metals such as Ag, Al, Cd, Mg, In, Pb, Sb, Bi, Mn, Co, and Ni have been used. Some new technology lamps for use in inkjet applications contain proprietary dope metals or dope metal blends.

Iron doped lamps have shown particular benefit in applications where the ink thickness is high and good through cure is needed. For example significant ink thicknesses (20 microns plus) can be built up in the heavy print areas of some wide format graphics printers. Although this layer is built up in layers and each layer gets some exposure during printing the better penetration of the doped bulb output can be very helpful in achieving cure.

In some single pass applications multiple lamps are used with perhaps an un-doped and a doped lamp in an attempt to optimize through and surface cure of the whole system.

Electrodeless Lamps

Around 20 years ago Fusion Systems Corporation developed a medium pressure mercury vapour lamp which has a similar emission spectrum to the conventional electrode-containing lamp but uses different technology to achieve it. The lamps have no electrodes, consisting of a sealed quartz tube containing mercury and a starter gas. The mercury fill tends to be slightly higher than in normal lamps but the effect of their smaller diameter results in a near identical emission spectrum.

The excitation power source is, instead of an electrical arc, a 2450MHz microwave field around the lamp created by two matched 1.5 KW or 3.0 KW magnetrons (emitting at slightly different frequencies to prevent the formation of standing waves in the microwave cavity). The microwave chamber consists of a semi-elliptical aluminium reflector with end plates and a fine wire mesh across the face to prevent microwave "leakage". The magnetrons are positioned behind the reflector and feed in energy via two wave guides at the ends of the reflector. Forced air cooling cools both the lamp and the magnetrons

The ignition process involves the microwaves ionizing the argon which heats up and causes the mercury to vaporize and become excited itself by the microwaves. This process is very fast, taking approximately 10 seconds, or 2-3 seconds if the magnetrons are kept in their standby mode, consequently, no shutters are required with this technology as the lamps are effectively instant on/off.

Although the size is limited to 6 or 10 inch lamps, the lack of electrodes and the very thin end walls means that longer lengths is easily achieved by stacking lamps end to end. No significant dose loss occurs at the meeting points and this arrangement has been successfully used on conventional presses. No electrodes results in much greater bulb lifetime (8000 hours currently guaranteed by Fusion) but this is partly outweighed by the fact that the magnetrons also have to be replaced every 5000 hours. Probably the biggest advantage of having no electrodes is that it is easy to make long lasting stable doped lamps.

Although the electrical efficiency of UV generation is comparable to that of arc lamps, the additional power losses of the magnetrons means that overall these lamps are less electrically efficient than arc lamps. They are however generally accepted as being much more effective in cure terms because the small bulb diameter and semi-elliptical reflector allows for a much more tightly focused emission and hence a much higher dose rate for a given power output.

In recent years the patents on this technology have expired allowing other companies, notably Nordson, to develop their own microwave based lamp technology.

Excimer Lamps

Excimer lamps, originally developed by ABB Infocom Ltd, Switzerland were commercialized by Heraeus Noblelight GmbH, Germany. In contrast to the polychromatic emission spectra of conventional medium-pressure mercury lamps, these have largely monochromatic emissions, the wavelength of which is dependent on the gas mixture used in the bulb. Their operating principle is based on the excitation of two otherwise un-reactive molecules within a gas mixture to form excited dimers (excimers), which then revert back to the ground state giving out light of a characteristic wavelength. A large number of such excimers have been identified but only 3 commercialized [Xenon (172 nm), Krypton chloride (222 nm) and Xenon chloride (308 nm)], with the most useful being the mixture of xenon and chlorine. The original Heraeus excimer lamps commercialized in 1994 were too slow curing to be of use in inks curing. A modified form using nitrogen inerting technology was launched in 1997 which was a significant improvement but was still somewhat slow and expensive for commercial success.

The most common type of excimer lamps operate by a dielectric barrier discharge process rather than a with gas plasma. The design consists of a jacketed hollow tube with the gas mixture in the jacket and cooling water and an inner electrode inside the tube. The outside of the tube is covered with a fine wire mesh which acts as the second electrode. Current flows and light is generated via a large number of randomly distributed micro discharges.

Excimer lamps offer a number of unique advantages over conventional curing lamps, such as instant ignition and lifetimes of 2-3000 hours. One of the biggest selling features for this technology is that that the lamps are cold and have no IR emissions. This is only partly true, since there is significant heat generation but it is all removed by the cooling water flowing through the tube. The end result is still however the same; no significant amount of heat reaching the substrate. Moves by manufacturers to develop heat management solutions for conventional medium pressure mercury lamps, however, and the relatively low lamp power of excimers have resulted in their limited use in the curing of inks.

Flash Curing Lamps

Flash lamps are based on the discharge of a capacitor through a tube containing xenon gas. This charge and discharge process can be many times a second. Flash lamps have a huge power density relative to conventional lamps but the pulse is very short lived so the problems of heat build-up are greatly minimized. Ozone is also not generally a problem as the lamps have a fairly continuous emission spectrum throughout the UV and visible regions but with negligible emission below 240 nm, so no ozone production. Flash lamps also have the advantage that the bulbs can be shaped quite easily so, for example, circular bulbs for CD/DVD curing are possible.

Using flash lamp technology in any moving web application can lead to “banding” due to the presence of areas of ink with differential cure. It does not seem likely that flash lamp technology will expand significantly in digital production printing, other than where the final article is stationary at the point of cure – e.g. when a CD has been printed and is then cure with one “hit”.

LED Curing

UV Light Emitting Diodes (LED’s) have recently become an area of significant interest. At this stage the power outputs are low and they have yet to make any significant movement into the graphic arts markets. Systems are available e.g. from Phoseon and these are being looked at, if not for full cure then “pinning” of the ink before a final conventional cure.

Research in this technology is fairly rapid in pace, or at least has been up to now, and there could significant developments in the next few years. At this stage most offerings are “chipset” solutions based on custom mounting of individual LED‘s. These chipsets are still very small and very expensive and already have heat management problems resulting from the rapid drop in light emission intensity at temperatures above 40 to 50° centigrade. The biggest single issue surrounding this technology at the moment is however not the provision of an optimal wavelength (which many suppliers are focusing on) but of insufficient emission intensity. In terms of formulating for UV LED lamps, because the emissions tend to be in the 300-400 nm range phosphine oxide technology is likely to be the most important, but with no short wavelength UV light, surface cure is always likely to be a problem. High photoinitiator contents are required to achieve curing at anything approaching the required speeds, as can be seen in Figure 4. This is likely to lead to high ink formulation cost and possibly undesirable environmental labeling of products.

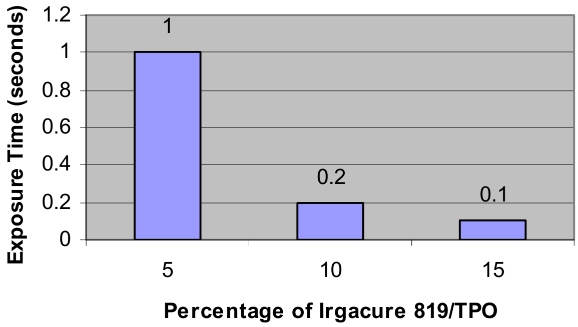

Figure 4. Cure speed versus phosphine oxide photoinitiator content.

Nitrogen Inerting

The presence of oxygen inhibits cure dramatically in ink jet systems[1] and so there can be great benefit in carrying out the cure under a nitrogen "blanket". Such operation can greatly increase achievable print speed and increase surface cure properties. The main application of this approach will be in single pass printing where the implementation will be more straightforward and more suited to an industrial press type environment. Correct lamp and inerting chamber design are critical to achieving satisfactory curing improvements. In practice very low oxygen levels are not needed and around 0.5% residual oxygen is to be satisfactory.

As well as the benefits of increased cure speed, the nitrogen environment can allow lower photoinitiator levels to be employed, thus reducing the odor of the cured coating and so be useful in packaging applications etc where print odor is an important factor. Taking this further, the lower photoinitiator content and superior cure will also assist in lowering migration.

Nitrogen inerting in scanning applications is generally harder to implement and a less attractive option, although it is known. It is almost certainly necessary if low power curing systems such as LED are to be used.

Electron Beam Curing Systems

In electron beam curing systems electrons are generated and directed at the ink to bring about cure. In one implementation from Advanced Electron Beam, electrons are generated from a heated tungsten filament within a permanently evacuated unit. The electrons are accelerated by an electric field and then exit via a thin beryllium window. The advent of these smaller, lower cost, more compact electron emitters make the possibility of e-beam implementation onto digital production printing equipment much more likely. Given their weight though and the issues surrounding their use, they will only be appropriate for single pass printing systems.

The two most significant issues which must be addressed with electron beam systems, are firstly the effective shielding (provided by lead sheet usually) of equipment and surfaces where electrons impinge, in order to avoid the escape of secondary X-rays and secondly, the need for low residual oxygen levels. It is generally accepted that residual oxygen levels below 200 ppm are required although curing has been seen at higher levels dependent on the exposure dose and chemistry of the inks used.

Due to these two requirements it is clearly easier to implement this technology with web systems where it is more straight-forward to have effective shielding and to effectively nitrogen blanket the substrate. Sheet fed systems could also be implemented and indeed there are examples, albeit very limited, of sheet fed systems in conventional energy curable printing (offset).

Electron beam curing offers several advantages when it can be implemented: very efficient cure of thick layers of ink, better odor and migration performance due to the better cure and removal of photoinitiator. These factors mean that it is likely the first implementation of e-beam will be in a packaging printing application where high speed, low odor and possibly migration performance are key requirements and where it is likely to significantly outperform UV-Curing systems.

Conclusion

There are a wide variety of curing methods and techniques available for curing of energy curable ink jet. Correct choice of which to use will be critical for the success of the digital production equipment, since it will impact on the technical performance achieved, equipment capital cost and system running costs.

There is continuing further development of the various systems and as the ink jet market grows and matures, manufacturers of all curing systems will look to tailor more suitable solutions to the specific requirements of ink jet.

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Biographies

Nigel Caiger received his Chemistry degree from Oxford University in 1985. He joined SunJet (formerly Coates Electrographics) in 1989 and is now Technical Manager, overseeing the activities of a development and customer support team, working on various ink jet technologies including UV-Curing, phase change, water, oil and solvent based inks. He has several patents in the field of jet inks.

Shaun Herlihy graduated in Applied Chemistry from Trent polytechnic in 1987. He joined the Group Research Department of Coates Lorilleux in 1989 and has been completely dedicated to the field of radiation curing ever since. He completed his PhD from the University of Kent in 1997, in the field of photoinitiator chemistry. He is now a Principal Scientist within St Mary Cray Research.