Heat Management Methodology for Successful UV Processing on Heat Sensitive Substrates

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Abstract:
Now in 2005, UV systems possess heat management controls that fine tune the exothermic and delivered heat in the UV curing process. This paper will explore the various methodologies and controls that allow converters to cure UV adhesives, UV inks, and UV coatings when applied to heat sensitive substrates.

UV Fundamentals:

The UV curing process generates two types of heat, exothermic heat and delivered heat. Exothermic heat is created by a chemical reaction such as the polymerization of the UV chemistry (Figure 1). Delivered heat is generated from the UV lamp. This delivered heat must be monitored and controlled to avoid damaging any of the components that comprise the UV processing unit, as well as to maintain substrate integrity.

UV lamps are made of quartz glass and can come with electrodes internal to the lamp’s ends or without electrodes. Electrodeless UV lamps are generally limited in length up to ten inches and have narrow lamp diameters. The diameter of an electrode UV lamp can vary tremendously. Typically, the higher the lamp wattage - the larger the lamp diameter needed to dissipate heat created from the bulb. Also, the longer the length of the UV lamp - the larger the diameter needed to maintain structural integrity. A narrower UV lamp provides less surface area from which to dissipate the heat. Consequently, narrower lamps typically emit a higher level of IR energy.

All UV lamps require heat to generate UV energy. The heat produced by the lamp is necessary to emit peak UV intensities along the length of the lamp. Heat must be kept constant along the length of a UV lamp. Doing so provides consistent UV output across the entire lamp length and greatly reduces the likelihood of either hot spots or cold spots developing at the surface of the lamp. Either hot or cold spots can rapidly destroy the structural strength of the UV lamp and generate a defective product.

The most common UV lamp used in the printing and converting industries today is the standard mercury lamp. The standard mercury lamp generates peak intensity at 365nm (Figure 2a). Total UV output ranges from 200nm – 440nm (Figure 3). Some UV chemistries require a metal halide lamp for curing. Metal halide or doped bulbs shift spectral emissions. Two common doped bulbs are Iron, concentrated from 330nm – 390nm, and Gallium, concentrated from 400nm – 440nm (Figures 2b & 2c). Metal Halide lamps require higher striking voltages and also have higher operating temperatures than standard mercury lamps.

While energy distribution of UV lamps vary among UV manufacturers. Typical UV lamp energy distribution is approximately: 1/3 UV +1/3 light + 1/3 heat.

For many UV curing applications heat generated from the UV lamps is of minor concern. However, for converters, monitoring and minimizing delivered heat to the substrate is of fundamental significance. The converter must limit the peak temperatures reaching their substrates. There are a wide variety of methods utilized to control and limit heat to the substrate.

Heat Management Methods for UV Systems:

All UV curing systems need to employ a cooling process to effectively remove heat generated from the UV lamp. The two most common means of removing this heat is either air-cooling or water-cooling.
Air-cooled UV processors utilize a high volume of air directed either perpendicularly or parallel to the UV lamp to remove a large portion of the heat generated from the UV lamp. The remainder of the heat transfers to the UV processing unit and to the substrate.

Water-cooled UV processors circulate chilled water through extruded aluminum reflectors and housing components to remove the majority of the heat generated from the UV lamp. Water-cooled UV processors still need some air-cooling to scrub heat from the surface of the UV lamp. The remaining heat typically gets removed via the substrate.

As stated above, both air-cooled and water-cooled UV systems, in addition to UV energy, transfer IR energy and visible energy to the substrate. To further reduce and control IR and visible energy transferred to the substrate, UV system manufacturers utilize a variety of heat management methods.

Please note that the effectiveness and costs associated with any of the materials discussed below may vary greatly between UV system manufacturers.

UV processors will have one of the following reflector / shutter designs; parabolic, elliptical or a combination of the two. (Figure 4) Parabolic systems are designed to flood the substrate and maximize the UV exposure time, in conjunction, the exposure period of IR to the substrate. An elliptical design maximizes the UV peak irradiance and typically minimizes the time period of exposure thus reducing the time permitted for IR absorption by the substrate.

UV systems can be designed to automatically vary power output as a function of process speed. By monitoring the UV energy needed for process speed and automatically matching the UV output to this need, the converter can avoid issues associated with over cure and reduce the heat transfer to the substrate.

Dichroic coatings can also be used to reduce delivered heat. Cold mirrors, which are dichroic-coated liners / shutters, reflect UV towards the substrate and transmit IR away from the substrate. Cold mirrors typically provide maximum UV reflectance between 220nm to 380nm and reduce heat via the absorption or transmission of visible and IR energy. These coatings can be applied to aluminum, stainless steel, fused silica or other glass substrates and exhibit formability on metal reflectors. Cold mirrors can also be customized with angles of incidence such as 0, 21, 45 degrees, or a range of other degrees (Figure 5). These coatings are fairly hard and must be cleaned regularly to remain effective.

Although effective, dichroic coated materials, whether glass or metal, must be cleaned consistently to demonstrate the very properties for which they were purchased. Dichroic-coated mirrors and plates are expensive and are costly to maintain.

Quartz windows or fused silica barrier plates can be positioned between the UV lamp and the substrate. These barrier plates transmit UV. These barrier plates can also have dichroic coatings applied to them. Unlike cold mirrors, these coatings reflect IR energy and transmit UV energy. These barrier plates are called hot mirrors.

Hot mirrors typically provide maximum UV transmittance from 220nm to 400nm and partially reduce heat to the substrate via the reflectance of both visible and IR energy. If greater IR rejection is necessary, it is possible to air space more than one of these hot mirror elements in a parallel array (Figure 6).

Only one heat management method utilized actually works in a reverse process of removing both delivered heat and exothermic as they are transferred to the substrate. Rather than reducing the IR energy and visible energy delivered to the substrate, a UV manufacturer can mount the UV processing unit directly over a water-chilled roller.

With the substrate running over the chill roll, the heat created by the chemical reaction (exothermic) and delivered heat from the UV processor is removed from the substrate as they are being transferred to the substrate. Both the temperature of the water and the volume of water delivered to the chill roll can be easily changed thus effectively and efficiently producing consistent and controlled substrate temperatures throughout the process application.
In addition, the chill roll method eliminates the high costs associated with maintaining many of the aforementioned heat management methods.

**Objective:**

Illustrate the effects of the above stated heat management methods on the UV dosage (J/cm²), peak UV intensity (mW/cm²), average and maximum temperature rise (ATR & MTR). Review the capital equipment, operational and maintenance costs related to each heat management method.

**Tests:**

Tests were performed on the following: Prime UV Optimum Series Air-Cooled UV processor, Prime UV Diamond Series Water-cooled UV processor, Prime UV Transport Conveyor and an 18 inch-long, 22mm diameter, 600 watt mercury vapor UV lamp. UV dosage (J/cm²), peak UV intensity (mW/cm²) and temperature readings were measured and collected with the UV PowerMAP from EIT. UV spectral graphs were created using the Sola-Scope and Sola-Check system from Solatell Ltd.

The following heat management methods were tested:

- Reflector / shutter design – elliptical & parabolic
- Power output varies as a function of process speed – 50 fpm & 100 fpm
- Dichroic coated reflectors / liners – i.e. – cold mirrors
- Quartz barrier plates
- Combination of quartz plates with dichroic reflectors
- Dichroic-coated barrier plates – i.e. – hot mirrors
- Combination dichroic-coated barrier plates (hot mirrors) with dichroic reflectors.
- Chill roll (Tests conducted on-site at customer utilizing high efficiency chill roll system belt driven by press drive shaft)

Capital equipment costs are estimates as to industry average for a 42-inch UV processing system operating at a maximum 600 watts per inch offering 8 power levels.

Maintenance costs assume operating time of 4000 hours per year and do not include costs associated with time needed to replace or clean components, as this would vary widely among UV manufacturers. Consumable costs do not include cost of UV replacement lamps or the costs associated with having plant personnel replace or clean these consumable components.

**Results:**

**Conclusion:**

First determine the temperature limits of the products being produced or may be produced in the future. Only with this information in hand is it possible to effectively evaluate which heat management method(s) discussed would be best for his or her operation.

As previously shown, the costs and effectiveness of the various heat management methods can vary tremendously. Certain methods are better suited for specific applications and UV chemistries.

Linking UV output to process speed is one of the least costly yet most effective ways to limit heat transfer to the substrate. Although the initial investment may be the highest, installing the UV processor over a high efficiency chill roll is the most effective way, if desired, to maintain a specific substrate temperature. An additional benefit of this heat control method is that it necessitates the least amount of maintenance time and dollars. However, this method isn’t practical for some converting processes nor for certain UV retrofit applications and linking UV output to process speed may not be enough. In these cases employing one method, or any combination of the other, needs to be considered.
When researching the other methods, the converter should collect the costs associated with replacing all consumable components (i.e. – reflector liners, shutters, hot mirrors, cold mirrors, UV lamps, etc.) and maintaining these materials (i.e. – cleaning and checking the effectiveness.) Be aware that these dichroic-coated materials may lose much of their effectiveness if not kept clean. Consequently, one must consider the cleanliness of the process as well as the time restraints inherent in one’s process before investing in any one of these heat management methods. A harsh operating environment can significantly reduce the life expectancy of many of these materials.

The heat management methods do reduce temperatures, but in some cases, also affect the UV dosage and UV intensities being delivered to the substrate. Whether these effects are detrimental or beneficial to the process needs to be evaluated as well.
Figure 1. UV Curing Process Comparison

Figure 2a. Standard Mercury Lamp

Figure 2b. Metal Halide, Doped Bulb - Iron

Figure 2c. Metal Halide, Doped Bulb - Gallium
Figure 3. UV Output Range Spectrum

Figure 4. Parabolic vs. Elliptical Reflectors
Figure 5. Hot Mirror

![Diagram of Hot Mirror]

- Reflected energy
- Direct energy
- Irradiation zone

Figure 6. Cold Mirror

![Diagram of Cold Mirror]

- Visible/IR
- Ultraviolet
- Optical baffle
- Irradiation zone