Continuous Wave (CW) and Pulse Width Modulation (PWM) UV LED systems: Technical Characteristics, Advantages and Applications

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Abstract

Continuous wave (CW) and pulse width modulation (PWM) are two technologies to control the output of a UV LED light source. CW radiation system uses constant-current drivers to deliver non-fluctuating output, and typically provides better curing results. CW UV LED system is preferred for most applications especially those require better curing quality. PWM technology controls the UV LED lamp through turning on and off the LEDs quickly and periodically. Traditionally, PWM UV LED system is only used in LED lighting applications to control the illumination level. A recent research indicated pulsed and CW UVC-LED irradiation have comparable inactivation effect on E. coli samples. However, pulsed light system exhibits lower temperature which significantly improved disinfection efficiency. Another study in PWM system showed using such system can help reduce the substrate temperature, which is very beneficial to the process on heat sensitive materials.

This article discusses the differences between the two technologies, the researches on both, the advantages of each, and their respective applications.

Keyword

Continuous wave (CW), pulse width modulation (PWM), high quality curing, heat sensitive material

Introduction

UV LED curing is becoming widely used in different manufacturing processes due to its inherent advantages. UV LED system has compact system size, instant switching capability, low power consumption and very long life time which are ideal for process optimization. Using UV LED system also ensures environmental friendly operation and provides better curing quality to enable value-added industrial solutions.

Higher optical output irradiance or intensity (mW/cm^2) is desired for most applications to realize faster curing to improve throughput. A minimum threshold of irradiance is usually needed to start the polymerization process. Other than this, energy density or dose (J/cm^2), which indicates the total energy absorbed over time (dwell time) is usually a specified parameter by the formulation manufacturers to determine the energy needed to cure. Irradiance and dose work together to affect the curing speed and quality.

CW and PWM system briefing

LEDs are normally connected in series and parallel to form a matrix as the elementary module to be controlled electrically. CW system uses constant-current drivers to supply non-fluctuating and continuous current to enable each matrix. The LEDs are either ON with no variability in irradiance or OFF with no irradiance. Figure 1 illustrates the CW UV LED system concept.

PWM system controls the UV LED lamp through turning on and off the LEDs quickly and periodically. For different applications, the frequency of PWM can vary from less than one kHz to a few MHz. The actual output irradiance of the system can be collectively effected by the peak irradiance within the ON time and the ratio of the ON and OFF time within each period. The ON duration of the pulsed current is also called duty cycle. Higher UV output level can be realized by increasing the duty cycle. Figure 2 illustrates PWM output levels of 50%, 75% and 25% duty cycle.

Applications and advantages of CW System

Research showed the emission behavior of the light source had a significant influence on the crosslinked micro-structure, and ultimately the final properties displayed by the cured materials. CW UV system should be adopted for applications that need high performance curing such as high resolution high quality printing applications.

As shown in Figure 3, two light sources, one with a near constant output and the other with an alternating output were applied in the experiment. The two light sources had the same UV dosage over the curing duration. The cured acrylate under these two systems were examined and compared. It was observed the micro-domain crosslinked structure turned to be more even under CW light source irradiation (Figure 4).

It is believed the UV-curing reaction creates a 3-D crosslink through photo-initiated polymerization. The polymerization reaction includes:

1. The initiation reaction under which the initiator molecules are excited and ground state radicals are generated, and

2. The propagation reaction (Figure 5) includes (a) Micro-gels are generated from the polymerization initiation points; (b) Growth from micro-gel into macro-gel; and (c) Formation of crosslinked structure (cured material), and

3. The termination reaction which the polymerization process stops

Under ripple-type irradiation, the relative long off time affects the initiation reaction stage, resulting time-bands in which only propagation and termination reactions occur. Thus excess amount of micro-gel is formed, bringing the formation of an inhomogeneous crosslinked structure, and affects the quality of the cure. On the contrast, since the polymerization reaction process can be initiated and finished completely and continuously, higher conversion rate and more homogeneous crosslinked structure were observed by curing under continuous wave UV light source.[1]

Applications and advantages of PWM system

A latest study tested both pulsed light and CW UVC-LED's irradiation effect on water disinfection. As shown in Figure 6, UVC-LEDs with emissions at 268nm and 275nm were positioned at 30mm from the microbial suspension surface. To test the difference on PWM and CW control, the light source was designed to output different frequencies and duty cycles, but equivalent dose of around 17.3mJ/cm^2.

Result showed the PWM and CW irradiation brought comparable inactivation on E.coli bacteria (Figure 7). However, by properly control the frequency and duty cycle of the pulsed light system, the operating temperature is greatly reduced (Figure 8). Lower operating temperature prevents the shift in LED wavelength and optical power output reduction, which in term helps to improve disinfection efficiency.[2]

Another research system in disinfection and sterilization applications also indicated low-frequency low power pulsed LED system may have greater germicidal ability to inactivate pathogens than continuous irradiation. The experiment compares the curing of biofilm under a 365nm UV LED system with irradiance of 0.28mW/cm^2 at either CW or PWM low frequency (<1kHz) modes. The lamp was operated for 5 mins under either mode with the same dosage. Microscope morphology observation and statistical analysis indicated the biofilm inactivation efficiency under pulsed mode irradiation is higher. It is believed the higher instantaneous irradiance in pulsed system is multiples step by step many folds through each pulse, and thus gets stronger and more effective to kill the bacterial. Also additional inactivation mechanisms of pulsed UV LED light generates the localized heat and the constant disturbance to destroy bacterial structure more effectively.[3]

PWM system was also found to be beneficial for curing adhesives on subassemblies made from or using heat sensitive materials. Materials such as certain electronics and medical devices that can experience shrinkage, stress, dis-coloration and micro-cracks if UV-induced heat is getting too much. Decreasing the UV intensity in the constant current curing system can reduce the generated heat, but then it requires longer curing. By using the PWM technology, during the "ON" phase, irradiance can be kept high to increase the depth of cure and thus maximize the polymerization process to allow faster curing. While during the "OFF" phase of the pulse, the heat on the substrate is dissipated which reduces or eliminates damage during the cure. Through reduction of substrate heat damage, the scrap cost is reduced and the yield is improved. Faster curing also helps to increase production throughput.

During the experiment, a 365nm UV LED system was configured to either PWM or CW mode. The PWM system tested with a 25 seconds stream, 21ms, 85% duty cycled and 460mW/cm^2 peak irradiance delivers a total dose of 10J/cm^2, which is very close to the CW system outputs 370mW/cm^2 for 27 seconds continuously (Figure 9).

The curing, temperature and damages on the UV-absorbing substrate were recorded and observed. Figure 10 shows the comparison. In the CW mode, substrate damage occurred at irradiance above 220mW/cm^2 with curing temperature of 41°C, but a sufficient cure was not achieved until irradiance reached 520mW/cm^2, corresponding to a total UV dose of 14J/cm^2 and the cure temperature of 65°C. Whereas in the PWM mode, a cure was achieved in just

25s at an irradiance of 440 mW/cm^2, which corresponded to a dose of 10.2 J/cm^2. At this stage the temperature of the cure site reached 40°C compared to a damaging 56°C at a similar UV dose with continuous operation.[4]

Conclusion

This article compares the difference between CW and PWM irradiation system, and focus on the discussion about the set up, analysis and result of several tests of the two types of irradiations systems on a number of applications. Results indicated CW system is ideal for high quality curing applications as the continuous uniform and stable optical irradiation optimize the crosslinked structure formation process on cured material. PWM system showed consistent benefits on lowering the system and substrate temperature, which helps to improve system efficiency and performance, and reduces curing damage. PWM irradiation system should be considered in disinfection application or heat sensitive materials curing.

Figures

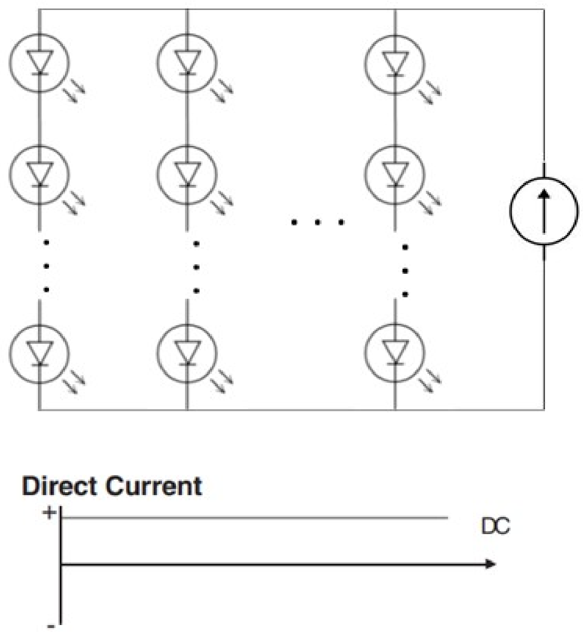

Figure 1 Constant current UV LED system concept

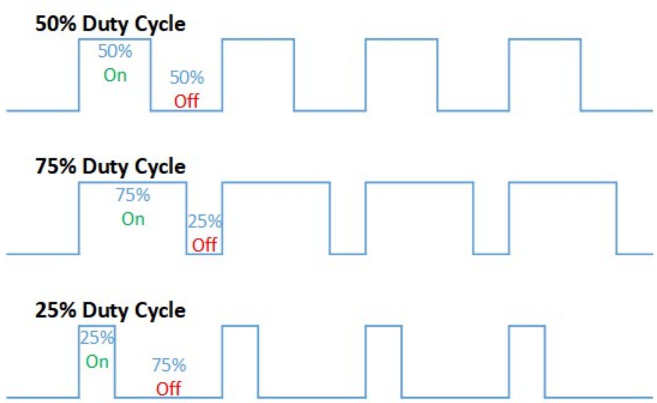

Figure 2 PWM output with different duty cycles

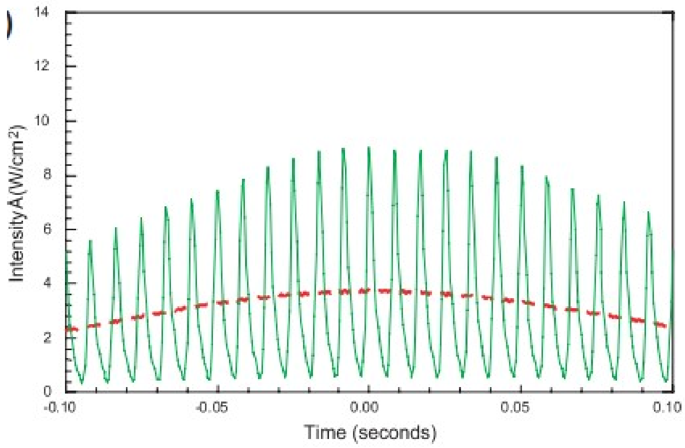

Figure 3 Two light sources with continuous and ripple emission profiles

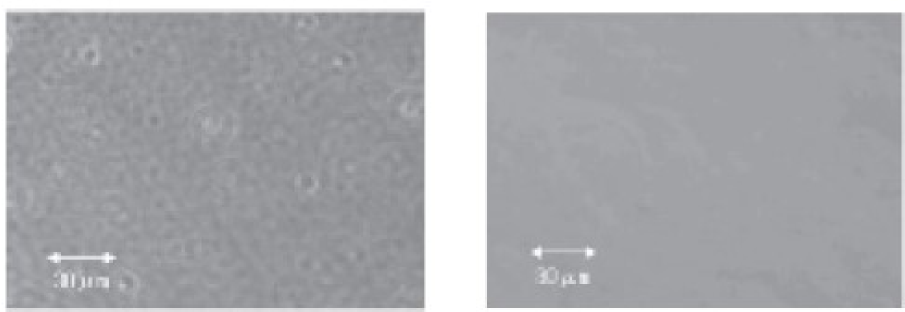

Figure 4 Phase contrast micrographs of cured film formed by ripple-type (left) and continuous UV irradiation (right)

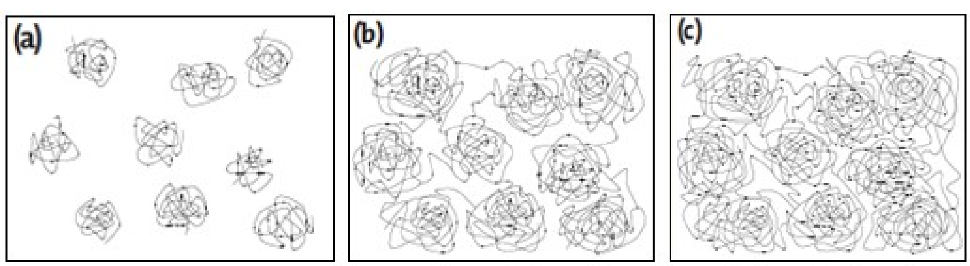

Figure 5 Propagation reaction steps

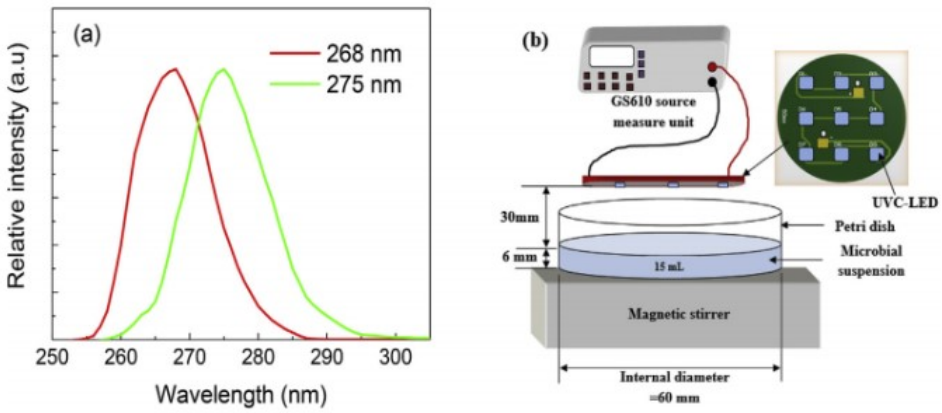

Figure 6 (a) Emission spectra and (b) Set-up of the batch inactivation experiment

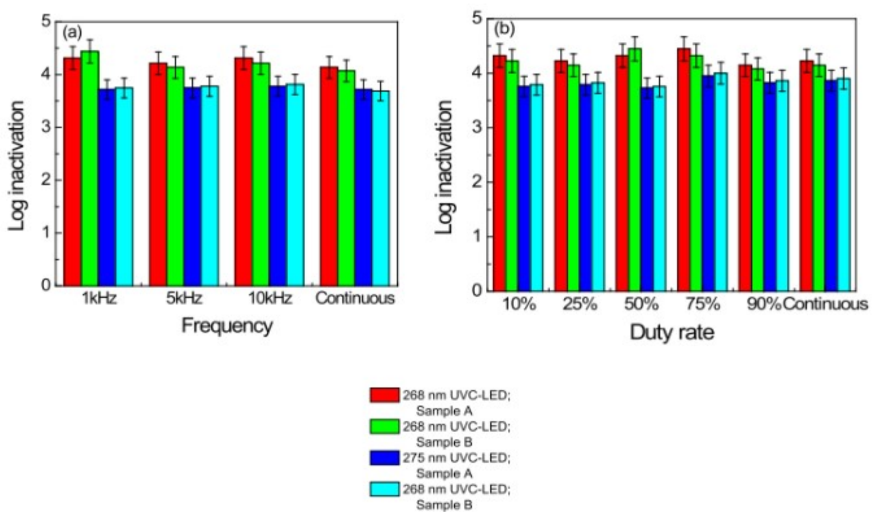

Figure 7 Inactivation at equivalent fluence (dose) on E.coli by the Pulsed and CW UVC-LED irradiation

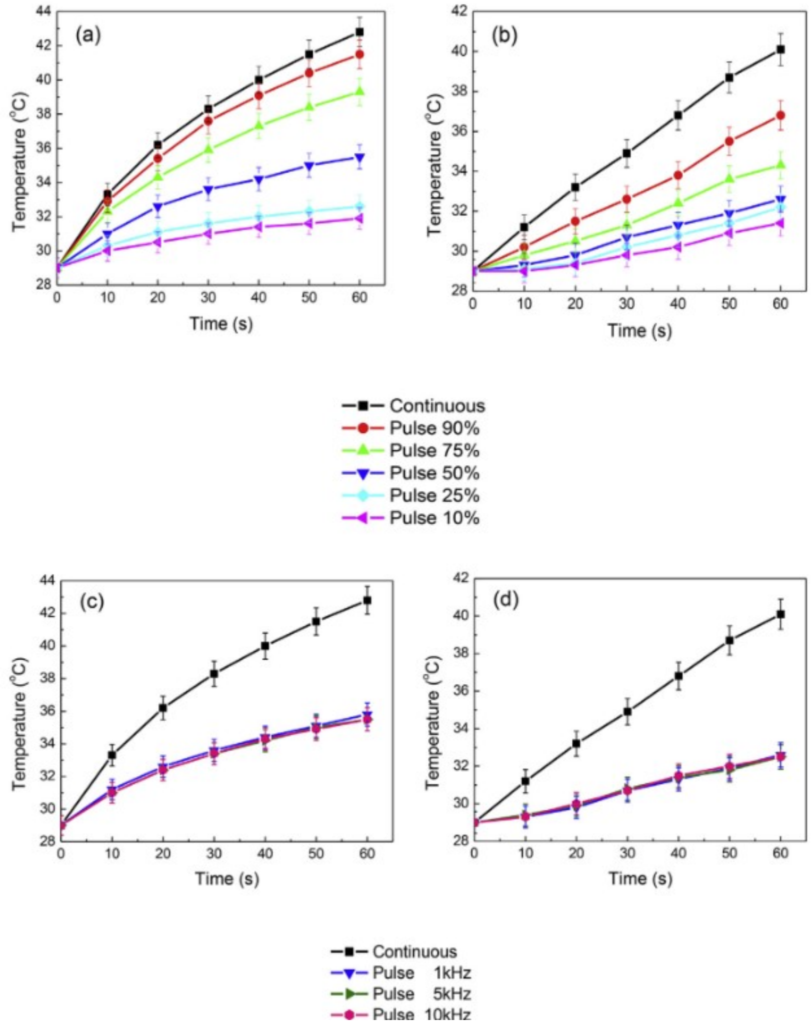

Figure 8 Operating temperature of pulsed wave and CW systems under different pulse width and frequency

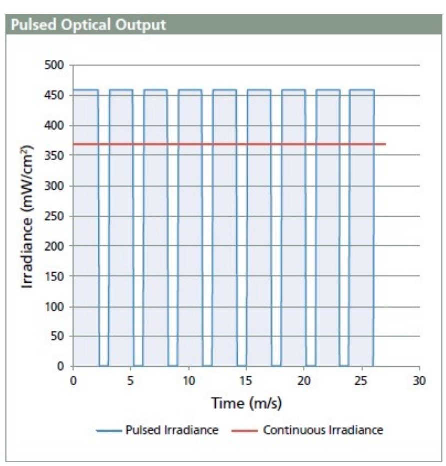

Figure 9 Pulsed and continuous irradiance output with the same total dose

Data for continuous wave (CW) operation					
Irradiance mW/cm²	Time (s)	Dose J/cm²	Temp. °C	Sufficient Cure	Substrate Damage
590	27	16	70	YES	YES
520	27	14	65	YES	YES
450	27	12	60	YES*	YES
370	27	10	56	NO	YES
300	27	8	50	NO	YES
220	27	6	41	NO	NO

Data for pulsed (PWM) operation						
Duty Cycle %	Irradiance mW/cm²	Time (s)	Dose J/cm²	Temp. °C	Sufficient Cure	Substrate Damage
80	380	27	8.3	38	NO	NO
80	440	28	10	40	NO	NO
85	440	27	10.2	40	YES	NO
85	460	25	10.0	42	YES	NO
80	390	37	11.4	45	YES	NO
85	520	27	12.1	49	YES	NO

Figure 10 Comparison of temperature and curing on CW and PWM

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