Design of the optimal UV LED source for the efficient curing of protective coatings for pipes inner surfaces and compressed gas cylinders

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Abstract
The use of ultra-violet (UV) radiation for the curing of polymeric coatings is a new efficient, and sustainable technology, widely used for the coating of surfaces with easy access by a light source. The recent introduction of the UV-LED lamps has reduced the dimensions of the UV sources, opening the way to new applications such as UV inks for printers and UV protective paint for wood (1). However, the UV protective coatings of steel products with closed narrow spaces, like tubes and gas cylinders, is still an unexplored field. The study of UV irradiance in these environments has specific issues due to the closed geometry; the possibility of UV light reflection; dimensional restrictions; small space of movement and problems of heat disposal released by the lamp. Thus, the irradiation effectiveness of an UV-LED array source, has been here analyzed using as target surface to be irradiated, the inner surface of a cylinder. The study has been developed using an algorithm starting from the geometry of the internal surface and from the curing parameters defined by the UV LEDs producer, can determine an optimized irradiance model and the relative resulting UV-LED source.
As a result, the optimal UV-LED radiant source for a certain cylindrical surface has been here defined, based on a hexagonal extruded support with strip LEDs fixed on each side, for a total amount of UV LEDs of 120 units. This shape has been defined as the best compromise between the dimensional constraints and the uniformity of the light flow applied into pipes and gas cylinders diameters about 30 mm.

Introduction
Corrosion is responsible of high maintenance costs of steel made infrastructures for several working environments such as oil industries. (2) When working conditions have allowed, such as low temperatures and pressures, the structures made with steel have been replaced by polymeric equivalents, reducing the corrosion protection maintenance issues. However, for several other application fields, this approach, is not a strategy to consider due to the necessity to ensure high thermal and mechanical resistance. Thus, for these applications, such as oil and gas or chemical production plants, steel must be used, then, corrosion protection becomes pivotal to guarantee the continuous process operativity.
The carbon steel used for pipes and gas cylinders has optimal mechanical resistance, but it is not stable, as it undergoes corrosion processes that can be facilitated by working environmental conditions. For these

reasons, the use of steel protective coatings represents one of the best approaches to use to face corrosion occurring.
Currently, protective organic coatings, are based on thermosetting polymers which are used as two-component liquid paints, mainly solvent-borne, and powder paints. Up to now, liquid protective coatings have been considered better than powder coatings due to the possibility to create a smooth, thin and flexible layer with controlled and uniform thickness, but the production process is long and pollutant. The thermal cross-linking process used for this kind of coatings, requires long curing times at environmental temperatures, or expensive energy-intensive ovens at temperature ranging between 80 ºC to 150 ºC. Moreover, during the curing of liquid solvent-borne protective coatings, solvents are released into the air, rising volatile organic compounds (VOC) pollution issue. On the other hand, the powder coating, could

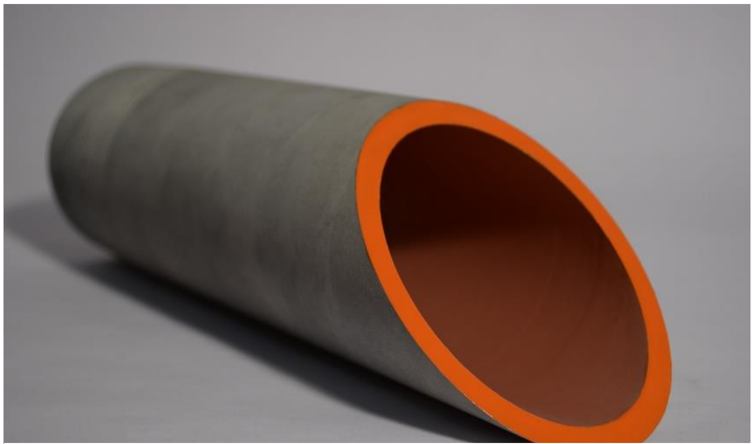


Figure 1- sample of tube NKT73 for oil well coated with liquid epoxy paint

represent a environment friendly approach to the corrosion protection, since they do not contain solvents. However, they have functional drawbacks: a) thermal curing process requires high energy, occurring at temperature between 225 ºC and 250 ºC; b) due to the application process, high thickness of coatings layer is achieved, and it is the reason of their high costs and low mechanical performance, and c) the barely gloss surface cause friction to the liquid flow.

Especially using the liquid coatings, the achieving of a uniform layer of coating when the steel structures are characterized by closed and narrow surfaces, is very difficult, because liquid coatings flow on the steel surface during the curing process. Thus, a faster curing process is necessary to obtain a uniform thickness coating layer. However, currently a faster curing process using a liquid coating need of at least two hours, and it is not enough fast to avoid the coating sag.
For this purpose, UV- curing coating technology, has started to gain great interest even into the corrosion protection coating field. The introduction of the UV-curing technology has brought significant advantages in the field of protective coatings, because of its process efficiency, environmental sustainability and its low energetic expense. In this context, UV cured coatings represent an optimal solution since they face the main drawbacks of the thermal cured coatings, such as: a) reduction of VOC pollution; b) the reduction of curing time from hours to seconds, and the decrease of the investment for production equipment.

Despite its optimal production process, UV cured coatings, have rarely been applied to inner surfaces and narrow geometries due to the dimensional difficulties of bringing the UV light inside these spaces. In the last years, the use of UV-LEDs has reduced the size of the UV source, also limiting the heat disposal issues, so that, small UV-light sources with high emission power, are today available [(2)].

The main goal of the following research is to define the optimal UV-LED source design, able to cross-link an UV liquid corrosion protective coating applied on the inner surface of a carbon steel cylinder.

To reach our purpose, we have considered first, the radiant flux of the UV-LED source, defined as the amount of radiation on an open flat surface [(4)]. However, since the inner surface of tubes and cylinders are not flat, we have developed for the radiant flux calculation, a shape that could be suitable for both pipes and gas cylinders, in details, a closed cylindrical surface. Using this approach, we have analyzed the UV radiation emitted by a LED array inside the cylindrical surface. The resulting radiant flux has been calculated using a software that gives the radiation pattern emitted from the UV source, considering even the fraction of radiation reflected by the internal surfaces.

The curing of the inner surface of a pipe or cylinder is a dynamic process, because it requires that the UV source goes inside them, and run the entire longitudinal length, allowing the successfully cross-linking reaction of the UV-cured coating applied onto the treated surface. In particular, the movement of the UV source into the cylindrical surface should be defined by a linear movement along the longitudinal axis of the cylindrical shape, and by a rotational movement, that we have assumed it worked on an axis coincident with the longitudinal axis of the cylinder. However, for our analysis we have eliminated the rotational movement of the source to obtain a simpler control of the moving equipment. Thus, the UV source must radiate 360° and the radiant flux on the cylindrical surface per unit time has been defined dependent by the speed of the movement. In order to accomplish the functional details reported above, four different polygonal models have been used to approximate the shape and the dimensional feature of the ideal UV LEDs source designed. The polygonal models selected for the following study have been a) squared; b) hexagonal; c) octagonal and d) decagonal.

To complete the UV-LED lamp design characterization, the relative dose values of each polygonal model, have been calculated. The dose of a light source, defined as the radiant flux delivered per unit of surface and measured as $\mu Ws/cm^2$, have been obtained plotting the emitted radiant flux in function of the speed of the linear movement of the UV source.

In this analysis, we have considered as target surfaces to be irradiated for our analytical models, tubes for wells or piping, having 40 to 200mm inner diameter (ID) and 6-12 m length, and cylinders for compressed gas having an entry hole 20-30 mm that limit the access of the equipment and an inner diameter from 200 to 300 mm. All these steel products need a high-performance corrosion protection and a coating that prevents flow friction in the pipes and gas permeability in the tank, and represent commonly, very difficult surface to protect by corrosion due to their geometrical features.

Experimental part and method

During the preliminary phase of the study here reported, we have evaluated the technical data of a LED source available on the market: LED Luminus SST-10-UV.

Using the technical data of the selected benchmark, the design of the possible optimal UV-LED lamp has been carried out using a double approach strategy: a) considering the radial irradiation on a section perpendicular to the axis; b) the linear irradiation on a section parallel to the axis of the cylinder. The analysis has been carried out by using the analytical software GNU Octave®.

Discussion of results

Evaluation of the technical data of the benchmark.

The goal of the project of which this study is part, is the development of an effective corrosion protection of tubes for wells or piping by applying UV corrosion protective coatings. In particular, the pipes object of the analysis is characterized by an inner diameter (ID) ranging between 40 to 200 mm and 6-12 m length, and cylinders for compressed gas having an entry hole of 20-30 mm that limit the access of the equipment, and an inner diameter from 200 to 300 mm.
Considering the dimensional features of the selected target surfaces, an optimal UV LED source must be designed, considering the following boundary conditions: a) the rotational movement has been avoided to facilitate the mechanical control of the UV LED source during the linear movement, and b) the dimension of the source must be suitable to allow the introduction of the UV LED source into small diameter pipes and gas cylinders.

In order to develop an effective UV LED source to apply to our curing purposes, a standard 1 W power UV LED, referred as LED Luminus SST-10-UV, has been chosen. In Figure 1 the dimensional features accurately measured, have been reported: the LED extension in plan is 3.5 x 3.5 mm, the center of the light point was 1 mm from the base, while the width of the LED strip measured 12 mm.

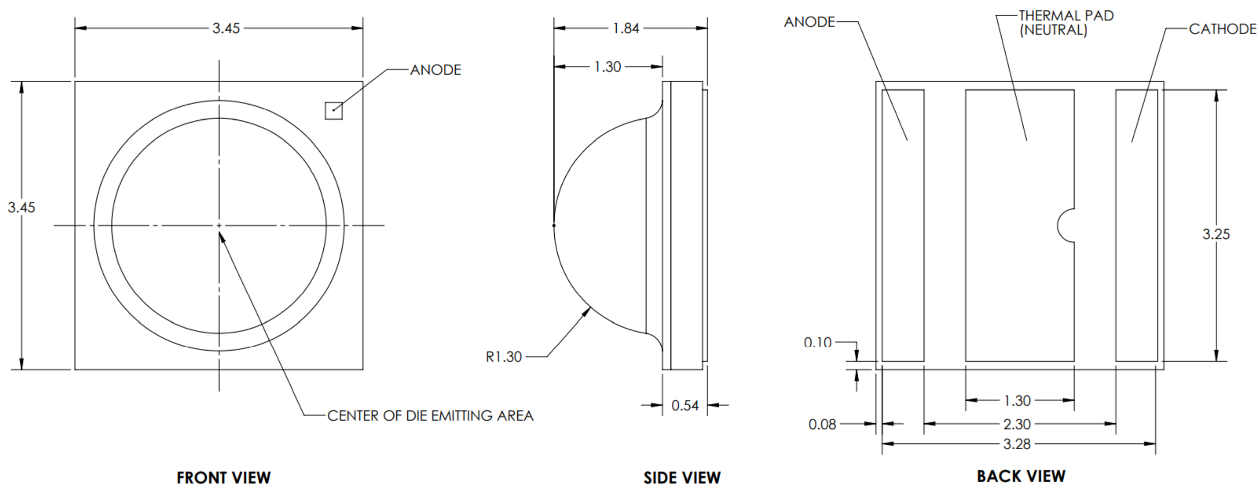


Figure 1 - PDS-002674 Rev03 © 2021 Luminus Devices, Inc.

As shown in figure 2, each LED strip contained 20 LED units and the step between two consecutive LEDs measured 8 mm.

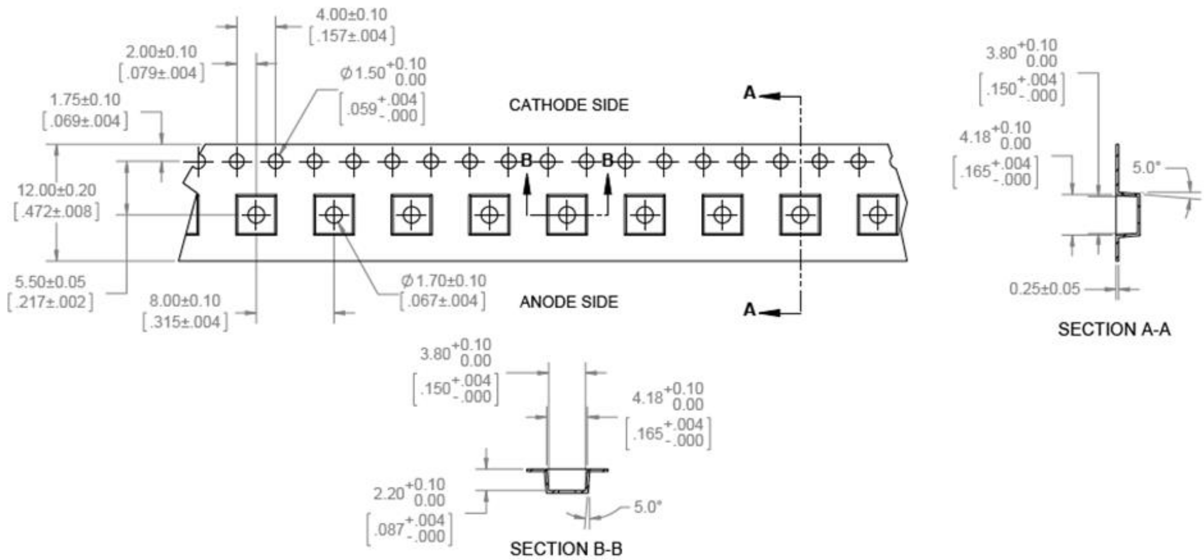


Figure 2 - PDS-002674 Rev03 © 2021 Luminus Devices, Inc.

Known the dimensional features of the LED unit, and respecting the boundary conditions above reported, an array able to radiate 360° must be designed. For this purpose, a polygonal extruded support with a certain number of sides must be used to place the selected UV LED strips.

In figure 3, the picture of a possible polygonal UV LED source model is reported.

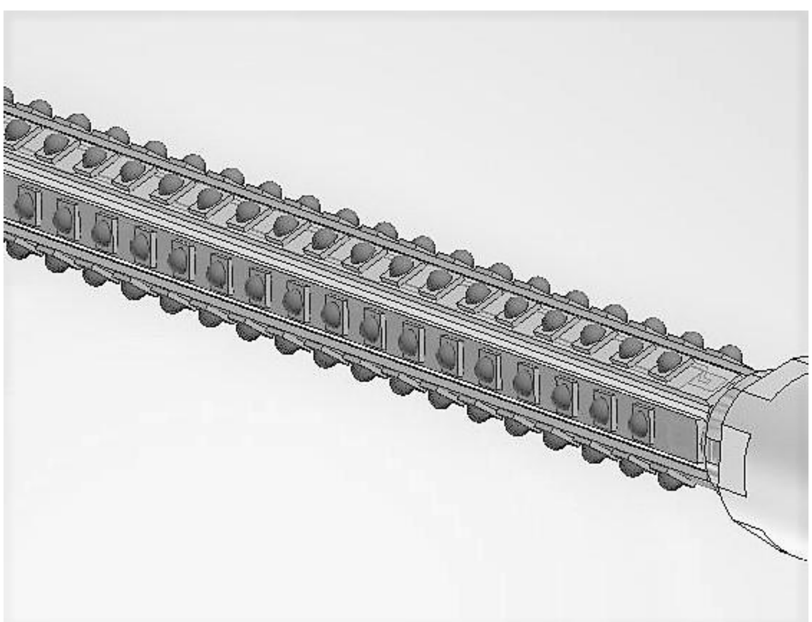


Figure 3 – possible layout of a UV LED source

Known the size of the UV LED strip, the dimension of the supporting face was defined: 12 mm. By the number of the faces of the UV LED polygonal support, the radius of the equipment and therefore the minimum diameter of the cylinder that can be radiated, can be defined.
For our purposes, four possible polygonal models have been selected: square, hexagon, octagon and decagon. For each polygonal model the dimension of the support as the radius of the circle circumscribed to the polygon (R_{ext}), has been calculated and below reported:

Polygonal model	R_{ext} (mm)	Total amount of UV LEDs units
square	8.48	80
hexagon	12	120
octagon	15.68	160
decagon	19.42	200

Table 1.: different studied polygonal model with external diameter and the total number of used LED units.

As highlighted by the size of R_{ext} reported above, increasing the number of the sides of the polygon, increased R_{ext} dimension. However, a bigger R_{ext} means a larger circle circumscribed the selected polygon. To accomplish the dimensional condition, the number of polygonal sides should be limited to avoid a big support that could not across the pipes.
Moreover, the dimensional features of the polygonal support of the lamp must be defined considering even: a) the possible occurring of an oscillation movement during the linear movement of the lamp, due to speed rate variation during its run along the entire length of the pipes; and b) the necessity to have as many UV LED unities as possible, to achieve a uniform radiating flow without the rotational movement.

Since the object of this study was design an UV source small enough to be introduced in tubes with ID≥40 mm and gas cylinder with entry hole ≥24 mm, octagon and decagon polygonal models were not selected as optimal for our purposes. The resulting UV LED source stemming by the application of the octagonal and decagonal models were characterized by a diameter of 31.36 mm and 38.84 mm respectively. Clearly, the decagonal geometry resulted bigger for the gas cylinders entry hole and for pipes with inner diameter equal to 40 mm. About the octagonal model, the resulting diameter cannot be used for the gas cylinder treatments due to its dimension, and nor for the treatment of tube with a diameter equal to 40 mm, due to possible oscillation movements occurring during the linear moving, which ones cannot be easy controlled.

Thus, considering the constraints above reported, the squared and hexagonal models appeared as the best balancing of dimensional features and UV LED unities number.

To calculate the radiant diagram, we have settled an irradiation angle of 130° and applied the UV LED characteristic "radiation pattern", as defined by the LED Luminus SST-10-UV producer and reported below in figures 4 and 5, respectively.

Optical & Electrical Characteristics (T_{hs} = 25°C)

UV						
Parameter	Symbol	Values[5]				Unit
Peak Wavelength Range	λ	365-375	380-390	390-400	400-410	nm
Test Current for binning[6]	I	500	500	500	500	mA
Peak Wavelength Typ.	$λ_p$	370	385	395	405	nm
Forward Voltage	$V_{F min}$	3.0	3.0	3.0	3.0	V
	V_F	3.7	3.4	3.3	3.3	V
	$V_{F max}$	4.0	4.0	4.0	4.0	V
Radiometric Flux[7]	$Φ_{typ}$	875	1015	1015	930	mW
FWHM at 50% of Φ	$Δλ_{1/2}$	10	10	10	10	nm
Viewing Angle	$2Φ_{1/2}$	130	130	130	130	degrees

Figure 4 - PDS-002674 Rev03 © 2021 Luminus Devices, Inc .

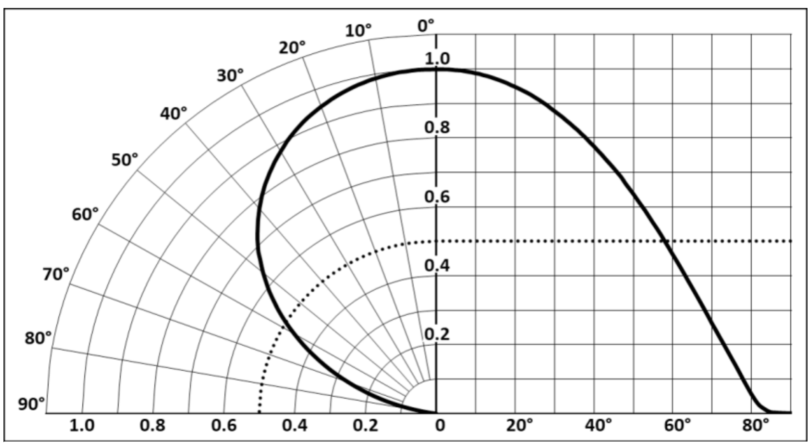


Figure 5 - PDS-002674 Rev03 © 2021 Luminus Devices, Inc .

The amount of irradiation i [W/cm^2] required to cross-link the polymer coating layer depends on the radiant flux φ [W] emitted by the UV source and by the area to be irradiated. Setting an irradiation angle, the area to be irradiated increase with the distance from the source [(5)].

In the case of a cylindrical surface, the irradiation decreases with the distance by a factor equal to 2π, which is proportional to the increase of the surface to be irradiated. Therefore, the surface to be irradiated is S =2πdL where L is the length of the cylinder that is supposed to be a unit value giving as a result the following relation:

$$i = \varphi / 2\pi d L \qquad (1)$$

where i is the amount of irradiation (W/cm^2), φ is the radiant flux (W), d is the distance between the cylindrical surface to be irradiated and the imaginary circle circumscribed to the polygonal model used to approximate the shape of the UV LED source (cm), and L is the length of the cylindrical surface (cm).

In figure 6 has been reported by picture the case of the calculation of the amount of irradiation of an UV LED source using the hexagonal model.
Designing a hexagonal UV LED source using LED Luminus SST-10-UV strips providing 1W radiant flux per each LED unit, and known that the distance between two consecutive LEDs was 8 mm as previously reported in figure 2, the achievable irradiation has been calculated for a cylindrical surface long 1 m:

$i = 1\text{W} \times 6 \times 125/2\pi d \times 100 = 1.19/d\ \text{W/cm}^2$ *(2)*

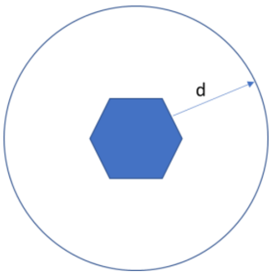


Figure 6 - Surface to be cross-linked at distance d from the source

Using the irradiation as obtained in equation 2, for the case of the inner surface of a cylinder characterized by an ID ranging between 40 mm and 100 mm, a source-surface distance ranging between 8 mm and 88 mm can be irradiated obtaining an irradiation ranging between 1500 mW/cm^2 and 15 mW/cm^2 respectively.

Radial radiation

Here, the polygonal models of 4-, 6-, 8- and 10-sided support profiles have been evaluated, studying their performance for the irradiation of cylindrical surfaces diameter from 10 mm to 100 mm. Every diagram shows the radial level of irradiation from 0 to 100%; the parameters are: the number of the sides (**n**), the distance of the light source from the center (**lr**) pre-defined **lr**=7 mm by the producer, and the radius of the irradiated surface (**pr**).

Generally, small is **pr,** less uniform is the irradiation. The emission diagrams of an UV LED source based on the hexagonal model are reported in figure 7. As it is shown by the picture 7A, for a small **pr** the irradiation appeared localized onto small surfaces, suggesting the possible occurring of a not uniform UV curing reaction. An irradiation profile like the one shown in picture 7A using a **pr** =10 mm has not acceptable if the rotational movement of the UV LED source has not been allowed.

As highlighted in figure 7, starting from a **pr** of 20 mm the flow starts to become uniformly distributed onto the cylindrical surface to be irradiated, reaching a medium level of irradiation of about 95%, which slowly increase up to 100% increasing **pr** up to 100 mm.

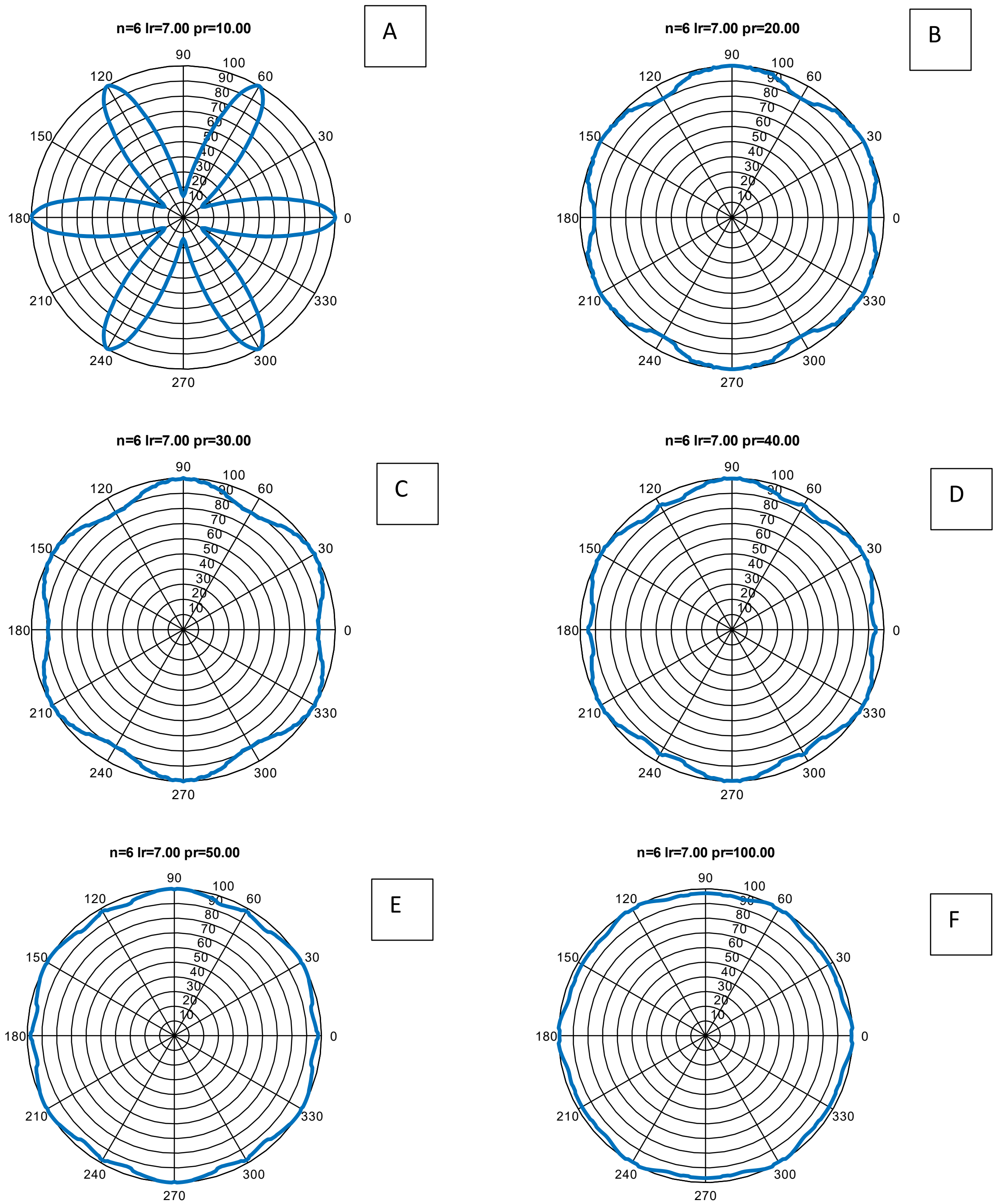


Figure 7. Radial emission diagrams for an UV LED source based on hexagonal model applied to the irradiation of cylindrical surfaces characterized by pr ranging between 10 mm to 100 mm.

Increasing the number of sides (n), the flow resulted uniform also with smaller diameters. As reported in figure 8, a 12-sided source (n=12) can irradiate uniformly a cylindrical surface with a diameter of 60 mm corresponding to a pr = 30 mm. On the other side, a source with more than 6 sides, that must across a cylinder of 60 mm diameter, would require very small 1W UV LEDs, currently impossible or difficult to find on the market.

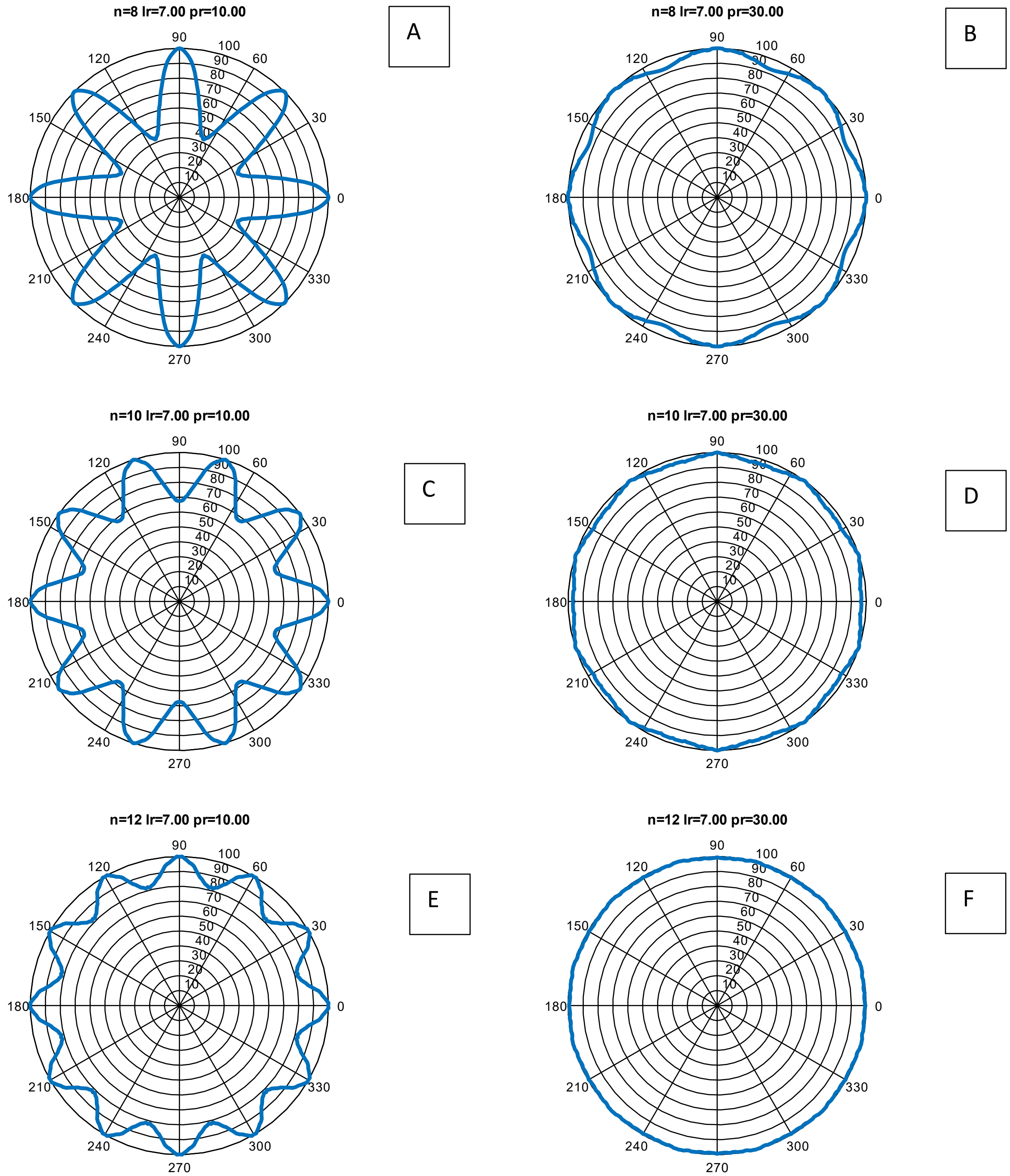


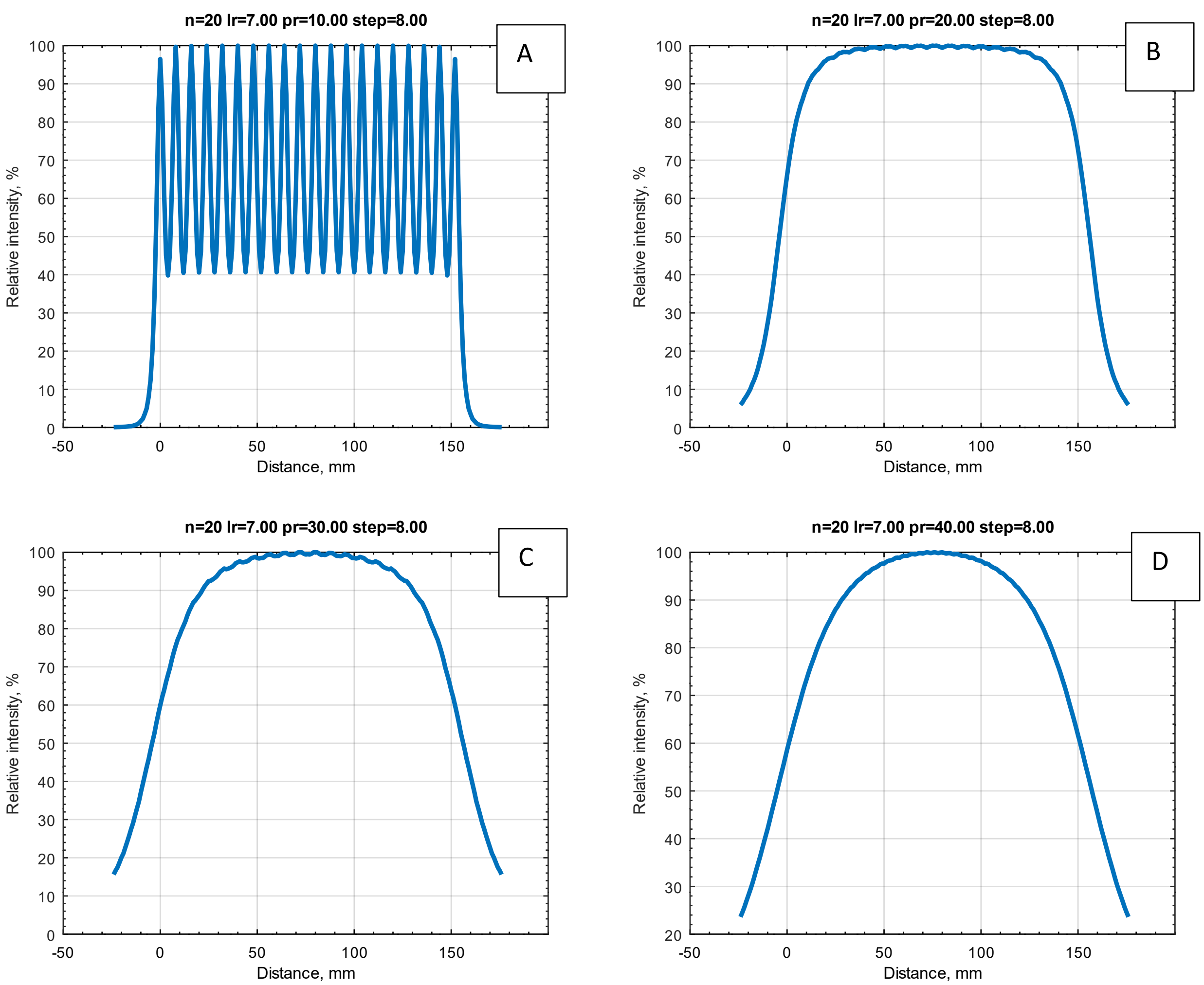
Figure 8. *Radial emission diagrams for an UV LED source based on A) and B) octagonal; C) and D) decagonal; E) and F) dodecagonal model applied to the irradiation of cylindrical surfaces characterized by **pr**= 10 mm and 30 mm.*

Thus, considering the actual LEDs availability and the dimensional requirements explained previously, the results obtained by the radial radiation analysis, the hexagonal model appeared to be the optimal geometry to choose for our purposes.

Linear radiation

The radial flow and the cross-section geometry of the support were not enough to define an optimal UV source. Thus, the radiant flow parallel to the axis of the cylinder, which should be emitted when the lamp run along the entire length of the treated pipe or gas cylinder, has been analyzed. In this direction the flow does have to remain as uniform as possible to facilitate the calculation of the flow dose emitted on the surface.

Applying the hexagonal model, and using the same setting used for the radial analysis (lr=7 mm), the resulting radiant flow can be obtained. Below, in figure 8 the emission diagrams of an UV source using the hexagonal model are reported. As shown, the minimum **pr** at which the linear radiation flow starts to appear uniform is 20 mm, corresponding to cylindrical surface diameter to be irradiated of circa 40 mm. As well highlighted by the emission diagrams obtained applying a **pr** bigger than 20 mm the emitted radiation started to become a parabola, becoming a cup when **pr** has reached 100 mm. This behavior suggests that the uniformity of the irradiation decrease increasing **pr** size. This result implies that increasing **pr**, even the UV curing reaction could occur not uniformly into the coating layer [6].



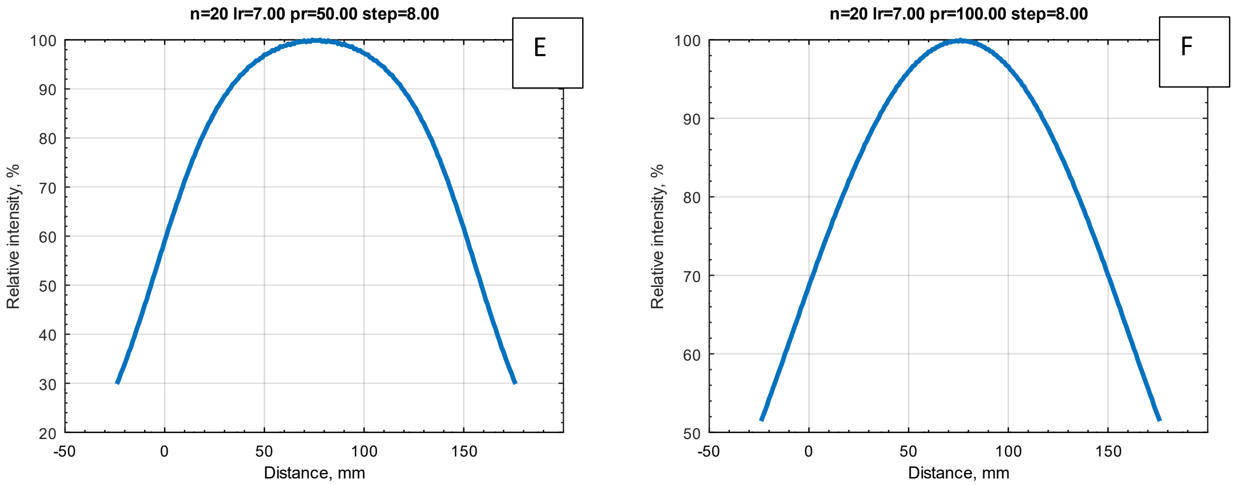


Figure 9: *Linear emission diagrams for an UV LED source based on hexagonal model applied to the irradiation of cylindrical surfaces characterized by pr ranging between 10 mm to 100 mm*.

However, as reported in figure 10 below, the parabola profile could be avoid increasing the length of the step between two consecutive LEDs units. Increasing the step of the LEDs up to 30 mm a less uniform but linear profile has been obtained.

Thus, longer supports, even with bigger distance between LEDs, could assure better uniformity, specially considering that non-uniform zones can be irradiated with the movement of the equipment.

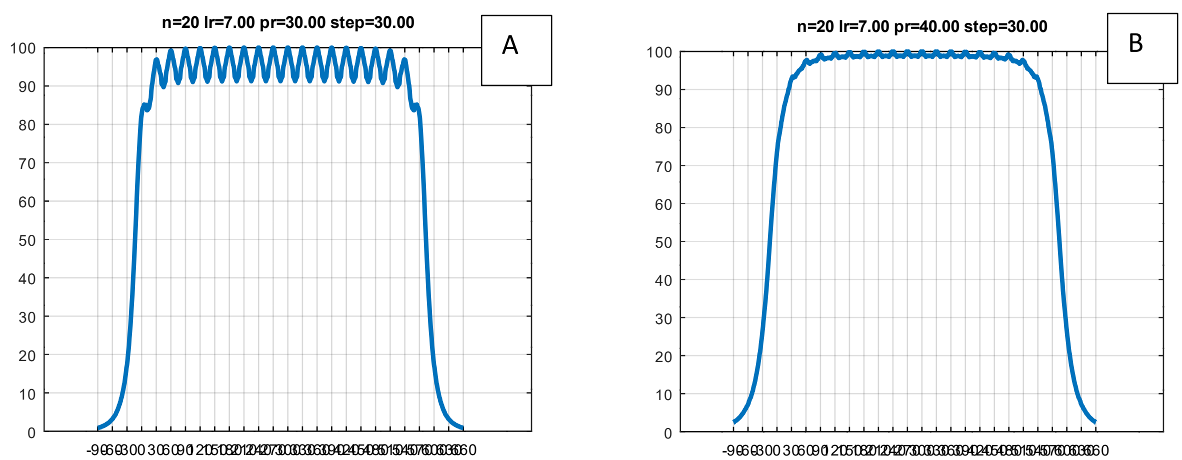


Figure 10. *Linear emission diagrams for an UV LED source based on hexagonal model applied to the irradiation of cylindrical surfaces characterized by A)* ***pr****=30 mm and B)* ***pr****=40 mm using a step between two consecutive LED units equal to 30 mm.*

Conclusion

The purposes of the reported study, were the definition of an optimal UV LED source designed able to provide an effective, uniform irradiation respecting the dimensional constraints due to the dimentional features of the entry hola of gas cylinders and the tubes used for pipes and welling. The analysis has soon suggested that the application of the hexagonal model represented the optimal equilibrium between a) dimensional requirements due to the very small diameter characterizing pipes and gas cylinder; b) total

number of LEDs for array combination and c) minimum diameter of a cylindrical surface that could be uniformly irradiated considering the radial and the linear radiation equal to 30 – 40 mm.
Larger diameters of the cylinder to be irradiated need wider supports that can be obtained increasing the number or the dimension of the sides.
The definition of a correct UV LED source is a necessary step to properly curing a UV polymer used for protective organic coatings. Based on the physical characteristics of the source, it is easy to subsequently calibrate the parameters by replacing the LEDs themselves or by changing the speed of the linear movement of the source.
The goal for an equipment is to limit movements that introduce complexity and possible inaccuracies into the process. Therefore, avoiding rotational movement, aiming to use a source with an almost constant luminous flux on 360°, is a suggested solution.
Following the result of the analysis, the UV LED source that has been chosen to continue the experimentation is based on a 120 UV LEDs Luminus SST-10-UV array composed of 6 strip of 20 LEDs

each, step 8 mm, fixed on a hexagonal aluminum support. The overall resulting radiant flux is $\Phi = 120$ W with an irradiation (or flux density) equal to 130 W/cm^2 calculated on a flat open surface and necessary to cross-link an epoxy photocuring paint.

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