UV-Lamps for Disinfection and Advanced Oxidation - Lamp Types, Technologies and Applications

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ABSTRACT

An overview on state of the art of UV Lamps for disinfection and Advanced Oxidation applications is given. The different types of Low Pressure Lamps, such as Standard Low Pressure, Low Pressure High Output and Amalgam Lamps, are characterized and compared. Inner wall coating, essential for extended lifetime and excellent UV maintenance of Amalgam Lamps, is discussed and the latest developments in this field are presented. Background information on lamp envelope materials (Fused Silica, Softglass) are given and it is shown how tailored transmission properties of Fused Quartz materials can help to optimize lamp performance for disinfection or oxidation applications. Differences between Low Pressure and Medium Pressure Lamps are outlined and main application fields of the various lamp types are discussed.

A special consideration is given to Excimer Lamps as an alternative to mercury containing UV disinfection lamps. Characteristics, such as available wavelengths, UV disinfection efficiencies and others, are shown.

KEYWORDS: UV Lamps, germicidal lamps, mercury free lamps, Quartz Glass, disinfection, Advanced Oxidation Process, water treatment, air treatment.

INTRODUCTION

In the past, the acceptance of UV disinfection in commercial applications has progressed rapidly. UV disinfection of water and air, in the food and beverage industry and in UV based Advanced Oxidation Processes (AOP) for destruction of pollutants in water and air are used either in combination with traditional methods or as a stand alone solution (Bolton 2004). In a more and more competitive market, it is important to consider all relevant aspects of the UV source, in order to exploit the full technical and economical potential of UV lamp technology that is available today and in the future.

Mercury based UV lamps

Mercury based UV lamps have a filling composed of mercury and a starting gas – typically Argon. Two major types are differentiated by the mercury vapor pressure in lamp operation. Low Pressure Lamps (LPs) work with approximately 0.01 mbar (1 Pa) and Medium Pressure Lamps (MPs) higher than 1 bar (100 kPa). Further differences like typical emission spectrum, lifetime, wall temperature, etc. will be addressed subsequently.

Low Pressure Lamps

The spectral radiation from a low pressure mercury plasma is dominated by the two ground state resonance lines at 253.7 nm and 185.0 nm (for details see Heering 2004). UV radiation (200 – 300 nm) is absorbed by DNA disrupting its structure and leading to deactivation of living cells. Lethality depends on the UV dose and the wavelength with an optimum at 265 nm. Radiation at 254 nm, however, is well suited for this direct UV disinfection process.

Radiation at 185 nm, obtained from LPs, is mainly applied for Advanced Oxidation Processes, such as the UV/O_3 or UV/H_2O_2 processes, where direct photolysis produces highly reactive radicals (·O or ·OH respectively). Since ozone is produced via 185 nm radiation in combination with oxygen from ambient air, the UV/O_3 process does not necessarily need an external ozone source. In aqueous solutions, the 185 nm radiation is absorbed almost exclusively by water, bringing about its photolysis to yield ·OH radicals and ·H atoms.

The preferred envelope material for Standard Low Pressure Lamps is Fused Quartz. Due to the generally low wall temperature, it is also possible to use Softglass (Sodium-Barium-Glass). Softglass Lamps have a similar design as Fluorescent Lamps known from general lighting. The UV-Softglass does not transmit at 185 nm, hence all these lamps are "ozone-free" lamps.

In contrast to Softglass Lamps, standard Quartz Lamps are available in both "ozone-free" (G, GPH lamps) and ozone-generating (G…VH, GPH…VH – VH stands for Very High ozone) versions. As seen in Table 1, both the specific UVC-flux per unit arc length and the UVC efficiency are higher for the Fused Quartz types. This is caused by the lower transmittance of Softglass compared to Fused Quartz at 254 nm.

A breakthrough for economic UVC generation was the introduction of LP Amalgam Lamps. They are no longer pure mercury lamps, but a mercury amalgam (typically mercury/indium) is used, that reaches the optimum mercury vapour pressure (0.01 mbar) at wall temperature close to 100°C. Thus, compared to Standard LPs, six times higher absolute electrical power can be consumed by lamps of same lengths, leading by far to the highest specific UVC-flux per unit arc length [up to 1000 mW/cm (see Table 1)] of all LP lamps.

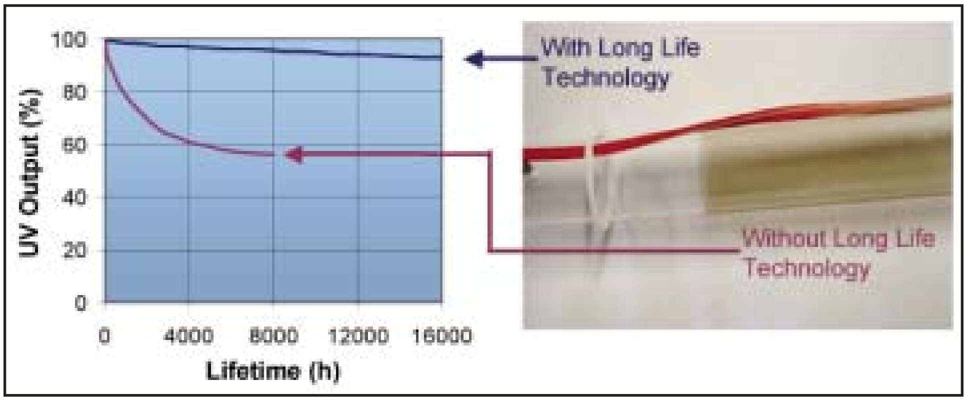
Another benefit of the higher operating temperature of Amalgam lamps is their strongly reduced dependency of UV output on the ambient temperature. While the UV output of Standard Lamps drops ~10% over a temperature range of only 25°C, Amalgam lamps are able to maintain a level above 90% over a range of ~60°C (van der Pol and Krijnen 2005).

Table 1: ***Differentiation of Low Pressure Lamp Types by key physical characteristics.***

Characteristic	Softglass	Fused Quartz		Fused Quartz
		Standard	High Output	Amalgam
Available UV spectrum	254 nm	185, 254 nm	185, 254 nm	185, 254 nm
Wall Temperature (°C)	30-50	30-50	> 50 cold spot 40	90 -120
Electrical Power (W)	5 - 80	5 - 80	10 - 150	40 - 500
Current (A)	0.2 - 0.5	0.3 - 0.4	0.8 - 1.3	1.2 - 5.0
Specific Electrical Power* (W/cm)	0.2 - 0.5	0.3 - 0.5	0.5 - 1.0	1.0 - 3.0
Specific UVC-Flux* (mW/cm)	< 175	< 200	< 350	**< 1000**
UVC efficiency, 254 nm (%)	25 - 35	**30 - 40**	25 - 35	35
Influence of ambient temp.	High	High	High	**Low**

* *per unit arc length*

Figure 1. ***Right: Amalgam Lamp partly with "Long Life Technology" coating; left: relative maintenance curve (254 nm) for coated and uncoated Amalgam Lamps.***



Amalgam Lamps are often categorized as Low Pressure High Output Lamps (LPHOs), also known as Germicidal High Output Lamps (GHO-lamps). However, these are merely enhanced Standard Quartz LPs. They have a long mount electrode assembly with a dead volume behind filaments. This region defines the cold spot temperature, which in turn determines the mercury vapor pressure during lamp operation. Therefore this region has to be kept at a low temperature of ~40°C to optimize the UVC generation. This design enables the lamp to operate at wall temperatures higher than 50°C between electrodes, and thus with higher electrical power consumption as can be seen in Table 1. Although, the specific UVC-flux per unit arc is slightly improved, it is still significantly below Amalgam Lamps. Thus to avoid confusion Amalgam Lamps should not be named HO-Lamps.

A particular challenge of Amalgam Lamps is to cope with a strongly UV absorbing mercury oxide layer formed on the inner wall surface of the lamp tube during operation (see brownish looking part of the tube on the right hand side of Figure 1). This layer originates from a reaction of mercury ions with oxygen in the quartz glass and is strongly dependent on the current density. Amalgam Lamps are driven with the highest current of all LPs, causing a strong decline of UV output within 8,000 h of operation (see left hand side of Figure 1).

Protective coatings can be used to diminish this effect. Commonly Al_2O_3 based coatings are used extending typical lifetimes up to 12,000 h. Voronov et al. (2003) were able to develop this coating technology to its highest level. The so called "Long Life Technology" avoids the layer formation completely and guarantees a stable optical quality of the lamp tube throughout the whole period of operation (clear part of tube in Figure 1). Amalgam lamps with Long Life Technology show almost stable UV-output (above 90%) over a lifetime period of >16,000 h. The data shown on the left side of Figure 1 are based on a lifetime test of two 300 W Amalgam Lamps at constant power and a cycling of 23 h on / 1 h off.

As mentioned earlier Standard LP quartz lamps are available as "ozone-free" and ozone generating versions, depending on different transmittance properties of quartz glass (see Figure 2). For "ozone-free" lamps Doped Fused Quartz is used (TiO_2 to cut transmittance below 235 nm).

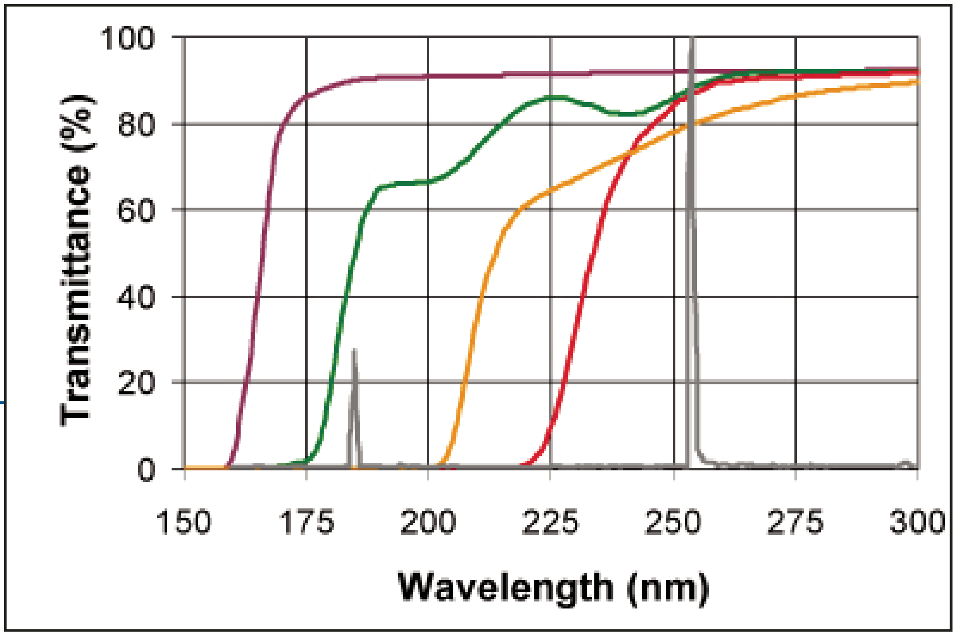


Figure 2. ***Comparison of the cut-off wavelength of different quartz glass types and softglass. (——) synthetic fused silica; (——) clear fused quartz; (——) softglass; (——) doped fused quartz. For reference a mercury low pressure spectrum (gray curve) is included.***

The so called Very High ozone (VH type) lamps are made from Clear Fused Quartz. This terminology is misleading, since transmittance is only ~50% at 185 nm. Lamps made from Synthetic Fused Silica (~90% transmittance at 185 nm) are by far a better option for very high ozone generation.

Generally, the grade of quartz glass depends on preparation method and starting material (Pegmatitic Quartz Sand, Synthetic Grown Crystals or Hydrolysis of $SiCl_4$). Synthetic Fused Silica is the highest grade with ultra high purity and excellent transmittance. For further information about the influence of quartz glass materials on lamp performance see Witzke (2001).

By combining the high transmittance quartz glass material with the Amalgam Lamp technology, one can achieve a fully optimized lamp with the highest possible specific flux at 185 nm for a given geometry. The 185 nm output of such a lamp is about 5 times higher (e.g. compare a G36T5VH with a NIQ 125/84 XL – same diameter, same length).

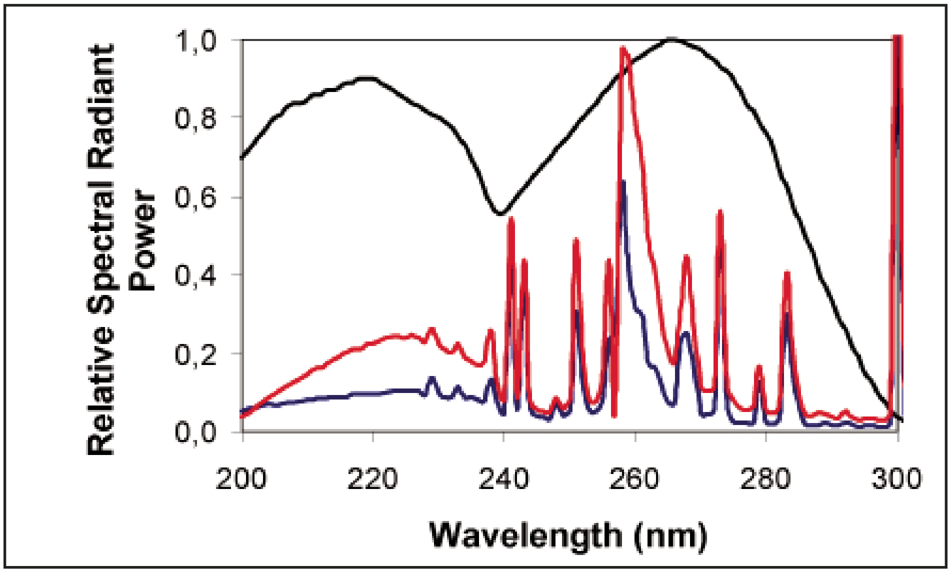


Figure 3. ***Spectrum of Medium Pressure Lamps and cell deactivation curve [Deactivation of Escherichia coli Bacteria according to DIN 5031 (2000)]. (——) MP high performance; (——) MP standard; (——) cell deactivation action spectrum.***

Medium Pressure Lamps

Medium Pressure Lamps have significantly higher electrical power input compared to LPs. This results in a higher mercury vapor pressure, leading to a continuous spectrum mainly composed of broadened and partly self absorbed resonance lines (see Figure 3). A comparison of the key characteristics of LP Amalgam Lamps (as high end representative of LPs) and MPs is given in Table 2. It has to be pointed out, that the wall temperature of MPs is extremely high. It covers a range of 500°C to 950°C. This may cause problems with heat sensitive materials and may require sophisticated heat management. The biggest advantage of MPs is their very high specific UV-flux per unit arc length with up to 35 W/cm compared to Amalgam Lamps with ~1 W/cm. The benefit of high flux, however, is diminished by a far lower UVC efficiency in the range of 5 – 15% (depending on lamp type) and a significantly shorter life time of at best 5000 h, if the highest possible specific UV-flux is realized.

Table 2: *Comparison of Low Pressure and Medium Pressure Lamps*

Characteristic	LP Amalgam	MP
UV spectrum	185, 254 nm	polychromatic
Hg vapour pressure (bar)	1 x 10^{-5}	1 – 6
Surface Temperature (°C)	90 – 120	**500 – 950**
Electrical Power (W)	40 – 500	400 – 60,000
Specific Elect. Power (W/cm)	1 – 3	50 – 250
Specific UVC flux* (W/cm)	<1	**<35**
UVC efficiency (%)	**35**	5 – 15
Lifetime (h)	**<16,000**	<5,000

* *per unit arc length*

APPLICATIONS

Tables 1 and 2 show the main characteristics of the different lamp types. Lamp prices are generally higher for lamps with higher UV-fluxes. Mainly the characteristics and cost determine the optimum UV source for a specific application. Standard quartz LPs and LPHOs are used across the whole range of water applications for disinfection and/or oxidation processes (e.g. drinking water, waste water, domestic water, ground water, industrial water, ultra pure water and public pool water) with small and medium high flow rates. High UV-flux lamps, such as Amalgam and MPs, are widely used also with the exception of small residential drinking water systems. Water treatment systems with Amalgam Lamps are highly energy and cost efficient. MPs are used if space efficiency is of primary consideration. Softglass Lamps are mainly used in POE (Point Of Entry) and POU (Point Of Use) drinking water disinfection systems and domestic water treatment systems for aquaria, fishponds, private pools, etc. Small flow rates and low investment costs are key values in these markets.

Air treatment applications can be clearly separated into disinfecting and oxidizing processes. In air conditioning systems, UV lamps are used in washer tanks (encapsulated lamps), cooling coils or to disinfect the air stream directly. Light fixtures with UV lamps are installed in special locations, such as in surgeries, hospitals, clean rooms, store houses, cold rooms, etc. to disinfect the ambient air. In all of these applications, LPs are used most often. UV air oxidation is used for odor removal (in sewage plants, rest rooms, hotels, restaurants, catering, senior citizen homes, caravan trailers and cars), grease destruction in kitchen hoods and industrial exhausts. For air temperatures below 40°C, standard ozone generating LPs are utilized. For higher temperatures it is essential to use ozone generating Amalgam Lamps. They show stable operation up to 120°C ambient temperature (see Table 1).

MERCURY FREE UV-LAMPS

One of the most promising of the mercury free UV-lamp technologies for disinfection is the Excimer technology. The word Excimer originates from the expression Excited Dimer – an excited Xe_2 molecule, that forms in a dielectric barrier discharge. For this kind of discharge a modulated electrical field is applied to a quartz glass body filled with Xe gas (e.g., several hundred kHz; several kV high voltage). The quartz glass serves as a dielectric barrier and prevents the forming plasma from short-circuiting the electrodes, which are placed on the surface of the quartz body. There are Excimer lamps in planar geometries, but typically these lamps have a coaxial geometry with an inner and outer electrode and a double cylindrical quartz body (Voronov et al. 2004). In addition Excimers can be composed of a rare gas and a halogen. Two mechanisms of formation are possible: the harpoon reaction or an ionic recombination. Depending on the type of rare gas and halogen used different quasi monochromatic radiations can be obtained. Most important for disinfection are the KrCl* Excimer lamp radiating at 222 nm and XeBr* with 282 nm radiation (see Figure 4). Table 3 compares 282 nm Excimer lamps with low pressure Amalgam Lamps. Most significant is the higher specific UVC-flux per unit plasma length of the XeBr* lamps. Further, they are mercury-free and instant on lamps with no warm up time. These Excimer lamps, however, suffer from a low UVC efficiency of ~8% compared to 35% for Amalgam Lamps. Another drawback to date is the high investment costs for lamps and power supplies.

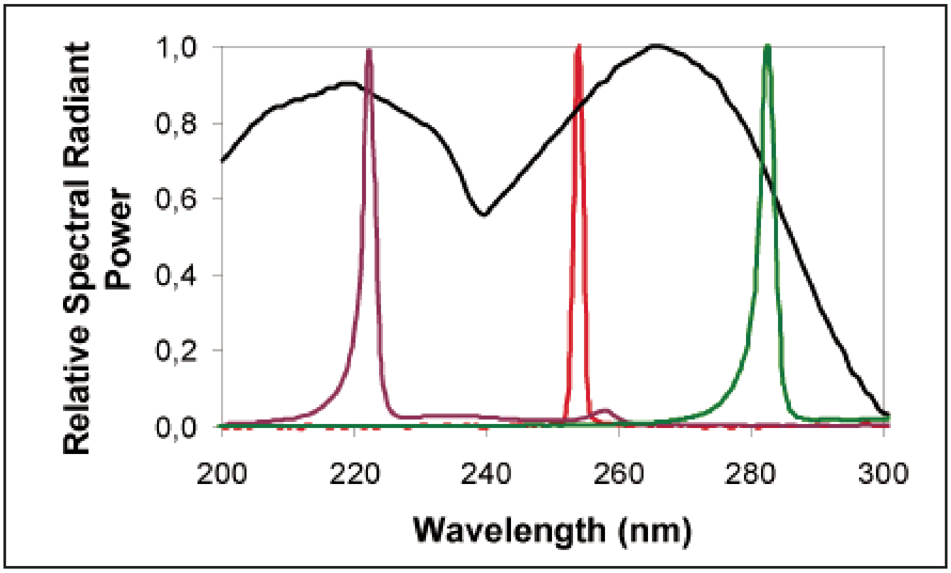


Figure 4. *Spectrum of a Low Pressure Lamp, a KrCl* and a XeBr* Excimer lamp and cell deactivation curve [Deactivation of Escherichia coli bacteria according to DIN 5031 (2000)].*
(—) Hg low pressure lamp;
(—) 222 nm Excimer lamp;
(—) 282 nm Excimer lamp.

Table 3: *Comparison of mercury based lamps and Excimer lamps*

Characteristic	LP Amalgam	Excimer XeBr
UV spectrum	185, 254 nm	282 nm
Mercury Free?	**No**	**Yes**
Surface Temperature (°C)	90-120	<100
Plasma length (cm)	20 – 150	15 – 60
Electrical Power (W)	40 – 500	60 – 2,000
Specific Elect. Power (W/cm)	1 – 3	30
Specific UVC flux* (W/cm)	<1	**<3**
UVC efficiency (%)	**35**	8

* *per unit arc length*

SUMMARY

A wide variety of state-of-the-art lamp types and lamp technologies for disinfection and Advanced Oxidation Processes is available to date. Low Pressure Lamps show the strongest diversity, amongst them the high end type in this category – the Amalgam Lamp. The notation High Output Low Pressure Lamp should be avoided in this context, since Amalgam Lamps differ in technology and key performance characteristics significantly. They offer high UVC output, excellent lifetime, good UV efficiency, high temperature stability and enable operation in high ambient temperatures. This combination makes them the right choice for compact, efficient and economic disinfection and Advanced Oxidation systems.

It was demonstrated, that the high transmitting Synthetic Fused Silica lamp body material combined with Amalgam technology results in a lamp with optimized output at 185 nm. For a given geometry the output will be up to 5 times higher compared to a standard LP Very High ozone (VH) type lamp.

Medium Pressure Lamps are applied if space efficiency is first, due to their very high UVC output and their compact lamp design.

Excimer lamps offer a future alternative for mercury free disinfection lamps with instant on operation. Until now they suffer from lower UV efficiencies and significantly higher investment costs.

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