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ON THE EFFECTIVENESS OF MODERN LOW-PRESSURE AMALGAM LAMPS

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ABSTRACT

A lot of attention is paid to the efficiency questions of modern amalgam lamps of low pressure in connection with more and more growing relevance of increasing energy efficiency of installations for water, air and surface disinfection. The real efficiency of a radiation source, as well as of the whole UV disinfection system, is an operational parameter much important for the customers. In this work, factors influencing efficiency of low pressure lamps are considered in detail. It is shown that efficiency of the modern amalgam lamps at the beginning of their lifetime is about (30–40)%.

Keywords: efficiency, performance factor, low pressure amalgam lamp, UV disinfection

Ultra-violet radiation is extensively applying in various fields of human activity and actively uses as a method of bactericidal treatment of water, air and surfaces [1]. For the last twenty years, UV disinfection method manifested a rapid growth. The technology is allowed the cardinal changing approaches to disinfection of environments, and in this case the UV disinfection method most considerably has been developed as a method of water disinfection [2]. Besides water supply and wastewater disposal, the UV disinfection is also widely used in various industries: food, pharmacological and electronic industry, medicine, recycling water supply, fish breeding etc., [1].

It is possible to say confidently that a certain equipment market is formed, and the most large-scale manufacturers of which are such companies, as _Trojan_ (Canada), _Wedeco Xylem_ (USA-Germany), _LIT Technology (Russia-Germany), HALMA Fluid Technology Group_ (Great Britain) and many others.

The UV technology success would be impossible without a significant progress of the bactericidal UV radiation sources. During the last twenty years, gas-discharge UV radiation sources and especially amalgam lamps of low pressure made a huge sudden scientific and technological change in their development. One can remember that ten or fifteen years ago lamps of up to 100 W power, generally lamps of so-called uviol glass (soft glass) or the same mercury lamps but made of quartz glass named _standard low pressure mercury lamps_ (standard mercury lamps of low pressure) were basic sources for UV installations. Then quartz mercury lamps of an increased power (high output) arose, and finally amalgam lamps appeared. With technology progress, amalgam sources of 200, 300, 700 and even 1000 W power appeared. This made it possible to decrease essentially capital investment costs due to the UV machine cost reduction when decreasing number of lamp needs at the same disinfection level and at the same water consumption passing through the disinfection installation. The most large-scale manufacturers of the modern amalgam lamps of low pressure are the following: _Heraeus Noblelight_ (Germany), _LSI/Lighttech_ (USA-Hunga-

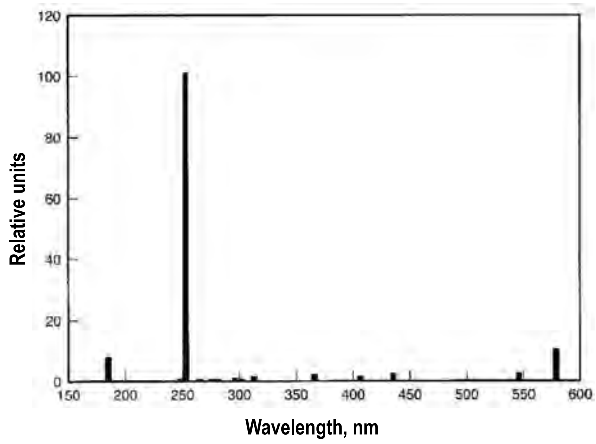

Fig. 1. Spectrum of the low pressure mercury discharge, the 254 nm line is accepted to be 100 %

ry), *Philips Lighting* (Belgium-China), LITAS (Russia), *Wedeco Xylem* (Germany), *UV-Technik/Hoenle group* (Germany), *First Light* (USA), as well as numerous Asian manufacturers [2].

The core of any UV machine is the UV radiation source, and this work is dedicated to UV amalgam lamps of low pressure. What is amalgam lamp? UV radiation source in mercury lamps of low pressure and in the amalgam lamps, which are widely used for disinfection, there is an arc discharge of low pressure in mercury vapour and in inert gases. The difference between them is a mercury vapour source: a small amount of liquid metal mercury is placed in envelopes of mercury lamps, and in amalgam lamps, amalgam is used, which is a solid alloy of mercury with metals. An optimum pressure of mercury vapour is about (0.7–1.5) Pa, and pressure of inert gases (most often neon or argon, or their mixtures) is (100–300) Pa. Under such conditions, (30–40)% of the discharge electric power transforms into radiation of mercury resonant line of 253.7 nm wavelength, which is near maximum of the bactericidal efficiency curve. The spectrum is linear (Fig. 1), and UV radiation portion at 185 nm and 254 nm lines is (90–98)% of all discharge radiation.

It should be noticed that lamp characteristics of many manufacturers are often very close to each other. For example, if to compare well-known standard lamps of about 300 W, such as *UV3000+, XPT240, DB300, UVI260, GPHVA1554T6L,* then it appears that their current, electric power, efficiency and UV radiation output are very close. Indeed, lamp current fluctuates from 1.8 A to 2.0 A, UV radiation power is within 87 W and 95 W, and electric power is within the range of (230–260) W. Thus, efficiency of these sources is approximately identical and lies in an interval of (35–38)%.

With increase of power and working current, the lamp characteristics are changing. The following operational characteristics of the lamps are reached to date: electric power is up to 1 kW, life time resource is (12000–16000) h, UV radiation decrease by the life time end is (5–10)%.

Many lighting companies actively co-operate and technology information exchange on lamp parameters, because such parameters as UV radiation power, efficiency of the source, lamp resource, the radiation decrease in the operation process are very important information for the customers. Almost all fore-quoted companies are members *of IUVA* (*International Ultraviolet Association)* and took part in development of a standardised protocol to measure low pressure amalgam lamps [4] based on the so-called *Robin Round* test. This allowed closer co-operating in terms of information exchange on the lamp characteristics.

It should be noticed that over the last years, an increasing attention is paid to efficiency of UV sources, which taking into account growth of electric energy tariffs and economics of treating environment (for example, water) has the great significance. And if UV radiation reduction/retention purpose or lamp lifetime increase are solvable engineering tasks, then lamp efficiency question is a question of the gas discharge physics.

What is UV lamp efficiency? Traditionally lamp efficiency is a relation of full UV radiation flux to electric power:

$$\eta = \frac{\Phi_{254}}{\Phi_{el}} \cdot 100\ \%. \qquad (1)$$

Are the (35–38)% efficiencies big or small, such as, for example, in the case of a standard lamp the *DB*300 type? Based on a comparison with other light sources, one can say confident that this is a much high efficiency, and this is an exceptional case when nature helped people, especially taking into account that 254 nm line lies close to the efficiency maximum of microorganism inactivation on the bactericidal curve.

An alternative in this UV area can only be xenon excimer sources with the correspondent phosphor or other sources with exciplex molecules, which efficiency can reach high values of (10–20)% under certain conditions [4, 5] as well, as UV light

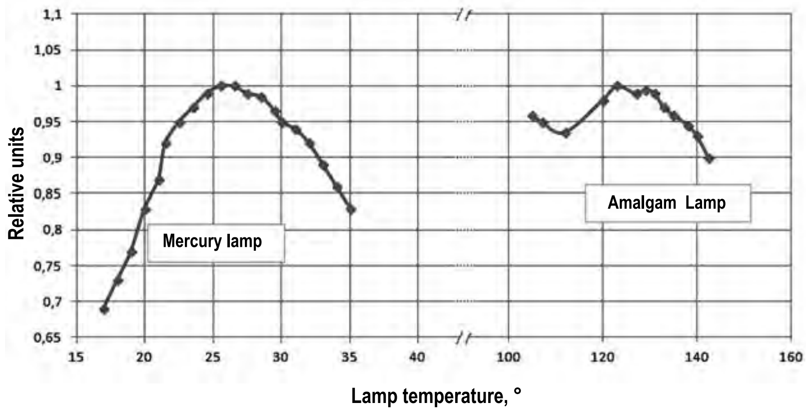

Fig. 2. Mercury vapour pressure depending on the temperature in a mercury and in amalgam lamps

emitting diodes of (260–275) nm wavelengths, which efficiency at present does not exceed several percents, and commercially available crystals have efficiency lower than 1 %. [6.7]

Let's consider factors influencing efficiency of low pressure amalgam lamps. From the view point of physical processes in the lamps, the following factors influence the radiation output: lamp current and frequency, the envelope diameter, thickness of the envelope wall, the lamp envelope coating, composition and pressure of ballast gas, isotope composition of mercury.

In our opinion, detailed and deep from the view point of the gas discharge physics consideration of influence of different factors on the radiation output (full flux) with wavelength of 254 nm is rather laborious, therefore we will only consider these processes qualitatively.

PRESSURE OF MERCURY VAPOUR

Whether mercury vapour pressure influences UV radiation output of amalgam lamps? Of course, when mercury vapour pressure increases and other discharge parameters are invariable, UV radiation output also increases as number of the excited and radiating atoms grows. However, when some optimum level is exceeded, efficiency decreases again (Fig. 2). This is caused by influence of re-absorption of resonant radiation and by increase of effective life time of the excited level, as well as by decrease of electronic temperature.

It should be also noticed that a part of energy is lost due to collisions of the excited atoms with each other and with electrons.

Method of achieving an optimum pressure of mercury vapour, for example, maintenance of a certain temperature mode of the amalgam is only an engineering problem and is implemented in each case differently by the manufacturer of a specific lamp type (multicomponent amalgams, pellet technology, cold point). To obtain UV radiation output higher than some maximum is impossible at an optimum mercury vapour pressure in the lamp.

FILLING THE LAMP WITH GAS, ITS COMPOSITION AND PRESSURE

It is possible to show that the main factor to pump a needed 6^3P_1 level is electronic temperature of plasma. The problem is to reach its optimum value. Whether mercury vapour discharge can work without ballast gas in general? Of course and moreover, the first mercury lamps were constructed in such a way. Without ballast gas, electrons and then ions, under influence of ambipolar diffusion go to the wall too quickly, and to maintain a balance of the particles, plasma provides a high speed of forming ion – electronic couples. And this leads to an increase of electronic temperature. A high electronic temperature allows pumping energy not only into the 254 nm needed line but also into other unnecessary lines, which leads to losses.

The most important function of inert gases is reduction of the electron diffusion rate towards the wall. One can adjust electron temperature up to an optimum level by changing pressure of the inert gas. The optimum level is the one, at which energy portion for excitation and radiation of mercury atoms considerably surpasses the energy losses portion for elastic impacts. Excitation and radiation losses depend on the electron temperature exponentially, and elastic impact losses depend linearly. Electron temperature should not be too high

Fig. 3. Quartz walls of a new lamp envelope (above) and of an exhausted lamp envelope

since it is necessary that 6^3P states were mainly excited, and that more high levels were not noticeably excited. To some limit, reduction of the inert gas pressure leads to increase of discharge UV radiation generation efficiency and energy distribution over the spectrum can change. However, this dependence has a non-monotonic character, and, among other things, because of the previously mentioned influence of the inert gas on the absorption processes of the resonant radiation. If the lamp pressure is too low, ion and electron flow towards the wall is abruptly increasing, and the ionisation energy losses portion is growing.

It should be noticed that if the pressure is lower than 1 mm Hg, resource of the oxide cathode becomes a limiting factor: barium oxide particles due to high values of diffusion coefficient “go” into plasma, thereby reducing the electrode resource to unacceptable values. Mechanisms of emission substance consumption of the low pressure lamp oxide cathodes are fully described in [8].

Thus, it is possible to say that the typical pressure interval of buffer gas is rather narrow and is within (0.8–2) mm Hg.

A high electron temperature required for the UV radiation optimum output can be reached by replacement of one buffer gas with another, in which mercury electron and ion diffusion speed is greater, and by use of lower pressure with retention of the same tube diameter. Indeed, velocity of electron and ion disappearance changes according to change of ambipolar diffusion coefficient of ions in inert gases, which in this case is determined by mobility of ions. Approximate values of mercury ion mobility in three lightest gases at 0 °C and with pressure equal to 100 kPa (760 mm Hg) are equal to the following: for helium – 19.6 $cm^2/(V \cdot s)$, for neon – 5.9 $cm^2/(V \cdot s)$, for argon – 1.85 $cm^2/(V \cdot s)$. Respectively, mobility of mercury ions in krypton and xenon is evens less. The lighter gas is, the mercury ion mobility is higher in it. Thus, temperature of electrons and consequently UV radiation output saturation level are maximum in helium and minimum in xenon.

From the practical point of view, xenon and krypton are inapplicable because of a low radiation output, and helium is extremely fluid and can be only considered here theoretically. Therefore in practice, argon, neon and their mixtures are used. Certainly, an important factor is gas purity.

LAMP ENVELOPE COATING

One of the most important characteristics of the lamps is UV radiations decrease at the lamp service end. To ensure a confident disinfection even after (12000–16000) h of operation, the UV machine design is calculated so that to take into consideration a possible weakening of the full bactericidal lamp flux. Certainly, the less is radiation decrease, the more profitable is the source from practical point of view and the higher is its efficiency by the end of the lifetime. It does not matter for a customer, what source efficiency was at the operation beginning but it is important what will be lamp efficiency at its end. So, all UV installations are calculated for their operation end.

Darkening mechanism of inner surface of a lamp quartz tube (Fig. 3) was studied and discussed in [9, 10]. It is connected with formation of mercury oxide on the quartz tube inner surface. This process is caused by the ambipolar diffusion, which is initiated by formation of electric field between plasma column and tube wall. Mercury ions are accelerated in this electric field, obtain kinetic energy and affect the quartz wall. This leads to formation of *Hg-O* links. Mercury oxide (*HgO*) intensely absorbs UV radiation.

Thus, a mercury oxide layer of only 10 nm thickness absorbs approximately 50 % of UVC radiation generated by the discharge.

For which purpose envelope inner surface is covered? The coating is needed to solve the problem of quartz glass surface effective protection against interaction with the discharge plasma. There are many methods and approaches to create a protect cover. The main approach is protection using a layer transparent for UVC radiation being more resistant to chemical exposure of mercury ions. As a rule, various metal oxides are used for this purpose. In total, the layer structure obtained using different coating methods can be divided into two groups: layers of nanoparticles and mesoporous layers as oxide films.

Each method has its advantages: use of nanopowders is an easy, technological and inexpensive way, whereas creation of thin and strong mesoporous coatings is much more complex technology, which means use of decomposition reactions at a high temperature, or of so-called sol-gel technology. The results of use of such technologies also differ. Decrease of UVC full flux of a lamp during the lifetime is connected with the protection cover type, filling of the lamp, current loading of the lamp, etc. After (12000–16000) hours of lamp operation, the decrease is from 5 % to 10 % for mesoporous coatings and from 15 % to 20 % for nanopowders (Fig. 4).

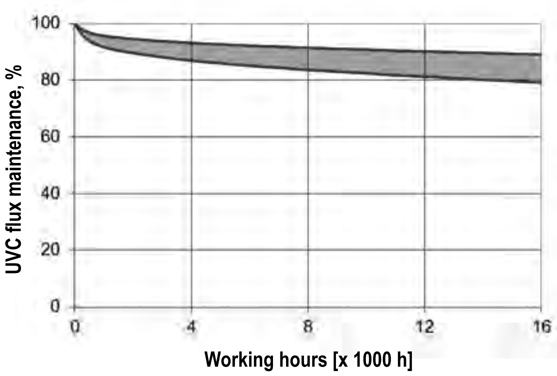

Fig. 4. Typical curves of UV radiation decrease for amalgam lamps of high power with mesoporous coating (above) and with coating of nanopowder (below)

CURRENT OF THE LAMP

With any filling of a lamp when current increasing, power of UV radiation grows first till r it achieves the saturation, or a speed of this increase is significantly reduce. In such a case, UV radiation efficiency due to discharge generation decreases. This is caused by increase of the electron concentration and by increase of contribution into gas heating of electron elastic collisions with atoms of inert gas and mercury, as well as by increase of suppressing excited states of mercury atoms by means of electrons during inelastic impacts of the second kind. The one more reason being the most important is a decrease of electric field strength and of electron energy owing to increase of concentration of metastable mercury atoms and to strengthening step process role.

LAMP CURRENT FREQUENCY

Influence of the lamp current frequency was repeatedly studied [11, 12]. It is known that in the low pressure discharge, the main losses of charged particles occur due to ambipolar diffusion onto the envelope wall. Duration of ambipolar diffusion is milliseconds, and it is less than the mains voltage period in the event of the industrial frequency use of (50–60) Hz. Therefore, the discharge extinguishes at the end of each half-cycle and lights up at the beginning of each next half-cycle. With such mode, configurations of the discharge current and of the lamp voltage do not coincide. Use of an electromagnetic throttle as a current stabilizer is a traditional but outdated solution because of a small number of switches on, a relatively low lamp resource, a lesser energy contribution into plasma and a low power factor. In practice, for powerful amalgam lamps electronic ballasts are used, which operate with quasi-sinusoidal current of (20–70) kHz frequency. This allows eliminating the above listed defects of electromagnetic ballasts. However, a further frequency increase is not prospective. First, this does not lead to an essential increase of the 254 nm line output as the near-electrode losses reduction reserve is not infinitely big. Secondly, this leads to the wire noticeable capacitive losses. The practical limit is (60–70) kHz interval, and most often (30–40) kHz interval is used in view of an insignificant difference of the discharge efficiency in these frequency intervals, as well as proceeding from a necessary reserve for the systems of adjusting power, with which the lamp current frequency significantly increases.

Current configuration also influences discharge characteristics. For example, instead of sinusoid, one can apply rectangular pulses of meander type, which can theoretically lead to increase of discharge input efficiency into plasma. However, one can show that for the 254 nm line this efficiency additive is small (1–3)%, and wire losses due to use of such current configuration because of the higher harmonics may be very essential, so it can lead not to increase of the system general efficiency but to its decrease.

CHANGE OF DIAMETER

A change of the discharge diameter is influence the discharge in two ways. On the one hand, reduction of the diameter leads to increase in losses of charged particles, and on the other, it leads to increase in current density. Therefore, when increasing the discharge tube diameter, efficiency first is raise as charged particle losses decrease, and then is reduce as the electronic temperature falls.

THICKNESS OF THE LAMP ENVELOPE WALL

A lamp envelope wall thickness is determined by two major factors: mechanical strength and transmission factor of the quartz glass. From the view point of UV radiation output, minimum thicknesses are most advantageous, because depending on absorption factor (quality) of quartz glass, UV radiation output keeps in with the Beer–Bouger – Lambert law. However, traditionally proceeding from the reasons of mechanical strength, the wall thickness is selected though minimum but sufficient. Practically it is from 1mm to 2 mm. Transmission of a good quartz glass is (87–89)% relative to 1 mm of the thickness. A pure quartz glass allows obtaining transmission values even above 90 %, however alloying additives (100–200) *ppm* TiO_2 are specially added into quartz to block the 185 nm line, and in such case an insignificant decrease of the 254 nm line also takes place.

ISOTOPE COMPOSITION

Due to presence of seven isotopes in natural mercury: ^{196}Hg (0.146 %), ^{198}Hg (10.02 %), ^{199}Hg (16.84 %), ^{200}Hg (23.13 %), ^{201}Hg (13.22 %), ^{202}Hg (29.80 %) and ^{204}Hg (6.85 %), an effective capture of resonant radiation is less than if mercury would consisted of the one isotope. The studies of the mercury isotope composition influence on the resonant radiation output shows that its increase is possible, approximately by 10 %, using change of the isotopes ratio [13]. However, because of high prices of the photochemical method of isotope separation, this task is not topical.

We have considered characteristics, which to the maximum extent determine lamp operation efficiency. As it was already shown above, many factors limit UV radiation output. Theoretically, the efficiency of gas discharge in mercury vapour may be very high [14]. One can show that with very low pressure of some mixtures of buffer gases, as well as with low current density, it is possible to obtain the source efficiency close to (50–55)%. However, such sources do not have a practical sense in view of either short lifetime, or a low UV radiation flux.

CONCLUSION

Anyway, the data provided by lighting companies are very important for designers and manufacturers of UV equipment. On the basis of a wide practical experience, of theoretical studies, mutual lamp measurements in laboratories and of the reasons presented above, we declare that efficiency of modern powerful sources is within (30–40)% at the beginning of the lifetime. These data are generally accepted, multiply checked by mutual measurements and published in official catalogues of the fore-quoted companies.

Sometimes UV equipment manufacturers for the marketing purposes declare ultrahigh efficiency of their lamps, thereby consciously or unconsciously misleading the consumers, for example specifying efficiency of a lamp without regard to electron ballast losses and extending this efficiency to all UV system as a whole. Or they give the data obtaining with a special ballast, which can only provide such efficiency in some conditions (for example, being located near the lamp, which is often inconveniently and isn't applied), etc.

The consumers should remember that they should estimate the UV system energy efficiency proceeding from all consumed power carefully considering all its operation modes and should not believe the fore-quoted marketing statements.

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