185 nm radiation measurement of high output low pressure mercury lamps

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Abstract—For many years the low pressure mercury lamps are widely used in general lighting and ultraviolet radiation. Because of its strong 254 nm ultraviolet and 185 nm vacuum ultraviolet radiation, it has played a very active role in environment, agriculture and medical fields. In environmental treatments, 254 nm radiation has been used for disinfecting the air and water, while the 185 nm radiation is applied to the degradation of organic matter. In this paper, the 185 nm radiation of high output low pressure mercury lamp, with 80 cm in length, was measured in a customized vacuum chamber based on Keitz method. The radiant characteristics of the lamp was discussed, indicating that the 185 nm radiant efficiency reached the maximum of 11% at the cold spot temperature 70 ℃ while it is negatively related to the discharge current.

Keywords- Low pressure mercury lamp; 185 nm radiation; Keitz formula; cold spot temperature; radiant efficiency.

I. INTRODUCTION

Low pressure mercury lamps with quartz tubes as envelops are widely used in the field of ultraviolet (UV) disinfection, organic matter degradation, UV chemical reaction, ozone generator *et al* due to its very high output of 254 nm UV radiation and 185 nm vacuum ultraviolet (VUV) radiation. Amounts of papers on the applications of low pressure mercury lamps have been reported. For example, Dobrovic *et al* researched on photo degradation of natural organic matter in water with UV irradiation at 185, 254 nm [1]. Han *et al* has studied on photo catalysis of p-chlorobenzoic acid in aqueous solution under irradiation of 254, 185 nm [2]. Kim *et al* prepared flexible metal-oxide devices by room-temperature photochemical activation of sol-gel films with the assist of 254, 185 nm radiation from a low pressure mercury lamp [3].

Over the years, researches committed to accurate measurement and further improvement of the UV radiant efficiency of low pressure mercury lamps. Waymouth and his colleagues proposed a theoretical model for T12 fluorescent lamps, which referred to the ion density, the electron temperature and the radiant power changing with the cold spot temperature and the discharge current [4]. Koedam *et al* measured the radiance of spectral lines in the positive column of T12 Ar-Hg lamp, calculated the radiant power of each line by introducing the Koedam factor, and analysed the energy balance in the positive column [5]. Zhang *et al* studied the 254 nm radiant characteristics of T6 high output low pressure mercury lamp on radiant efficiency and the discharge parameters, obtained the optimum cold spot temperature at 45–48 ℃ when the highest 254 nm radiant efficiency reached more than 40% [6, 7]. Besides, the radiant efficiency decreases with the increases of the current and buffer gas pressure.

In 1971, Keitz proposed a formula to calculate the radiant power Prad by the irradiance Erad if the UV lamp is assumed to be a linear Lambertian light source [8, 9].

$$P_{\mathrm{rad}} = \frac{2\pi^2 DL}{2\alpha + \sin 2\alpha} E_{\mathrm{rad}} . \tag{1}$$

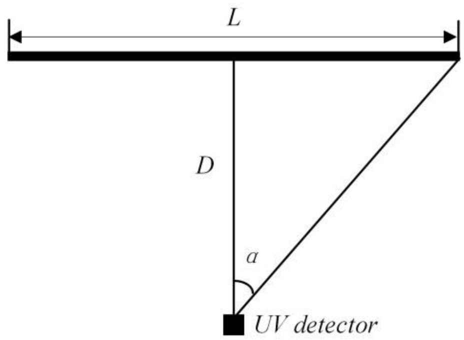

Figure 1. Geometrical illustration of measurement for linear light source with Keitz method.

Fig .1 shows the geometric relationship between the light source and the UV detector when using Keitz method. L shows the length of the linear light source while D represents the distance from the UV detector to the midpoint of the light source, which results in the semi-vertex angle α=arctan(L/2D).

Zhang *et al* compared Keitz method to traditional distributed radiometry method in measuring radiant power of approximate linear light source, confirming that if 2.5<D/L<4 the Keitz method only had a 1% deviation relative to the gonio-radiometry method. It was shown that Keitz method had a high accuracy in measuring radiant power of the linear light source [10].

It's very important to increase the radiant efficiency of 185 nm VUV radiation because of its high efficiency in direct photolysis of organic matter. Though the 185 nm output will increase with diameter of low pressure mercury lamps, the optimum parameters haven't been reported yet. This paper measured the radiant efficiency of 185, 254 nm as a function of pressure, cold spot temperature and discharge current for quartz low pressure Hg lamps filled with Ne-Ar buffer gases (Ne 55%) with the aid of Keitz method and a vacuum chamber.

II. EXPERIMENTS

A. Experimental setup

Fig .2 illustrates the geometry of the high output low pressure mercury lamps for experimental measurement. The lamp made of quartz is 80 cm in length with 17/19 mm inner/outer diameter, and two probes are encapsulated in the tube at a distance of 40 cm. Each lamp is filled with Ne-Ar mixed buffer gas (Ne 55% Ar 45%) at different pressure ranging from 1–5 Torr (133–667 Pa).

Figure 2. The geometry of the high output low pressure mercury lamp for 185 nm VUV radiation measurement.

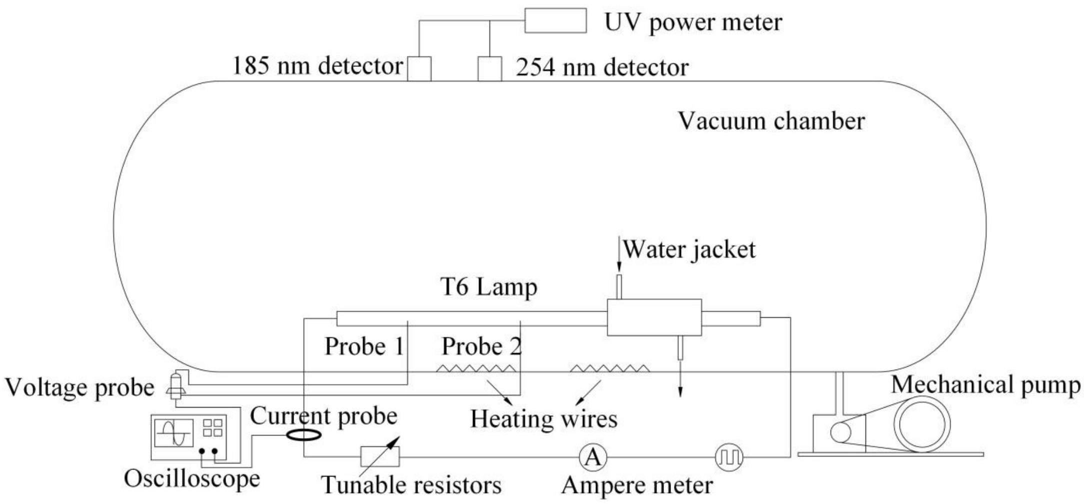

Figure 3. Experimental setup for 185 nm VUV radiation measurement.

Fig .3 shows the experimental setup for 185 nm UV radiation measurement of the high output low pressure mercury lamp. A water jacket connected with the circulating water bath (JEIO TECH RW-0525G), is set at one end of the tested lamp to determine the cold spot temperature and the resulting mercury vapor pressure. The discharge in lamp is driven by a commutated DC that is produced with a DC power supply in series with a square wave inverter, while the variable resistors are used as the ballast. The potential between the two probes is measured and recorded by an oscilloscope (Tektronix DPO3034). The 185 nm VUV detector (Hamamatsu H8025-185) is mounted at the top of the vacuum chamber, directed to the center of the lamp. The 254 nm UV detector (Hamamatsu H8025-254) is mounted near the 185 nm detector. These two detectors are connected with two control units of UV power meters (Hamamatsu C8026). The data are recorded by a laptop computer. The lamp is fixed at the bottom of the customized cylindrical vacuum chamber, whose inner diameter is 1.2 m, length 2 m, and volume about 2.5 m^3 including the volume of spherical crown at the two ends of the chamber. The chamber is exhausted by a mechanical pump (Trivac D60C, pumping speed 1.1 m^3/min), inflated with pure N_2 and exhausted three times, at last filled with 1 atm N_2 to expel the oxygen before the measurements.

B. Measurements

Before the experiment, the lamp was heated in a cylindrical asbestos tile for 3 hours, while the cold spot of the lamp was controlled at a temperature below 10 ℃ by the water bath, so as to remove the mercury deposition from main part of the lamp tube wall to the position of water bath, which is necessary to insure the accurate measurement of irradiance. Then the lamp was fixed at the bottom of the vacuum chamber. The sections of the lamp between the probes and the two ends were blocked by blackened metal sheets except for the length between the two probes which is referred to the emitting length *L*. The UV detectors were ensured to direct to the axis of the emitting tube with semiconductor lasers.

As the UV lines under 200 nm is absorbed by oxygen, the experiment of 185 nm radiation should be conducted in the condition of oxygen isolation. The vacuum chamber was pumped below 10 Pa by the mechanical pump, then inflated to 0.1 atm with pure N_2, and pumped to 10 Pa again. Repeated the operation of inflating and pumping three times, the chamber was filled with 1 atm N_2, reducing the content of oxygen and water vapor to less than 1 ppm. After then, the lamp can be ignited.

After aging for 8 h in the chamber to make the discharge stable, the lamp was tested in a stable operation.

The irradiance of 185, 254 nm as well as the potential between two probes, are measured in the range of cold spot temperature from 20 ℃ to 75 ℃, respectively at 20, 30, 40, 45, 50, 55, 60, 70, 75 ℃. For each cold spot temperature, the current is set at 0.8, 1.2, 1.6, 2.0 A. Each change in the parameters condition including temperature and current, demands for 10–15 min to make the discharge stable.

The electric field intensity *E* in the positive column can be derived from the floating potential between two probes *U* and the distance between two probes *d*, namely

$$E = U / d \,. \tag{2}$$

The input power per unit length in the positive column equals to the electric field intensity multiplied by the discharge current

$$P'_{\text{in}} = EI \,. \tag{3}$$

The 185 nm radiant power per unit length P'_{185} is calculated from the irradiance E_{185} measured by UV detector by using Keitz formula, namely

$$P'_{185} = \frac{2\pi^2 DL}{2\alpha + \sin 2\alpha} \frac{E_{185}}{d} \,. \tag{4}$$

The 254 nm radiant power per unit length P'_{254} is

$$P'_{254} = \frac{4\pi^2 DL}{2\alpha + 2\beta + \sin 2\alpha + \sin 2\beta} \frac{E_{254}}{d} \,, \tag{5}$$

where α and β are the two semi-vertex angles because the 254 nm detector doesn't aim at the center of the measured section of the lamp. Thus, the 185, 254 nm radiant efficiency can be obtained from

$$\eta_{\text{rad}} = P'_{\text{rad}} / P'_{\text{in}} \,, \tag{6}$$

where P'_{rad} represents P'_{185} or P'_{254}.

III. RESULTS AND DISCUSSIONS

Since low pressure mercury lamp is uniform linear light source, the following discussions are referred to the characteristics of positive column per unit length.

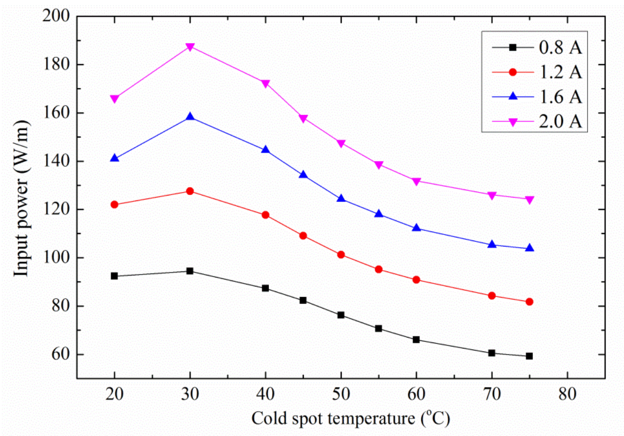

Figure 4. The dependence of input power on the cold spot temperature with various currents (Ne 55% Ar 45% 1.5 Torr).

Fig .4 shows the dependence of input power on the cold spot temperature with various currents. It is indicated that the input power reaches the maximum at the cold spot temperature about 30 ℃, and also shows a relative high value at 20 ℃, because low cold spot temperature results in low mercury vapor pressure which makes the buffer gas Ne and Ar to be excited and ionized. Due to the higher excitation energy of Ne and Ar than that of Hg, the lamp needs electric field, i.e. high input power to maintain the discharge. When the cold spot temperature increases to 40 ℃ or above, the lamp has a high mercury pressure and the mercury discharge accounts for the major part of the radiation. However, the main radiation of mercury in 185 nm (η185 ~ 10%) and 254 nm (η254 ~ 40%) begin to drop at the cold spot temperature about 70 ℃ and 45 ℃ respectively [6, 7], so the input power declines at a higher cold spot temperature. Although the low pressure mercury lamps have negative resistance characteristics which lead to a decrease of the electric field with increasing current, the increase of the current is more significant than the decrease of the electric field. So the input power per unit length, the product of the electric field and the current, increases with the increasing of current.

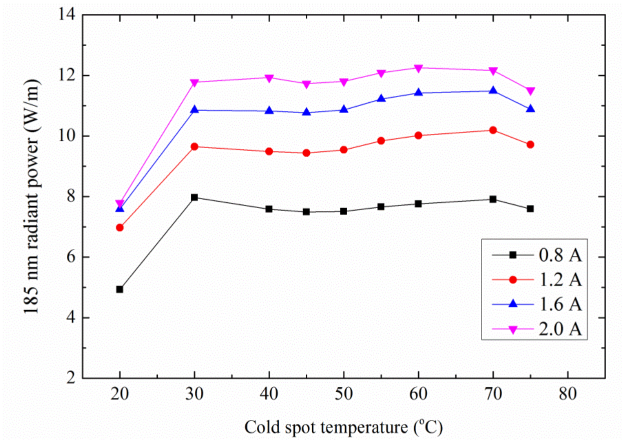

Figure 5. The dependence of 185 nm radiant power on the cold spot temperature with various currents (Ne 55% Ar 45% 1.5 Torr).

Fig .5 shows the dependence of the 185 nm radiant power on the cold spot temperature with various currents. At a lower cold spot temperature there is a low mercury pressure in the lamp, which leads to a small amount of mercury atoms excited and consequently the radiant power in a low value. As the temperature increases, more and more mercury atoms are excited, so the 185 nm VUV radiant power begins to increase. But the increase of mercury pressure enhances the resonant trapping in mercury atoms [11, 12]. Therefore, the maximum of the 185 nm radiant power is determined by the balance between the parallel increase in density of radiate states and radiation trapping. As seen in Fig .5, the optimum cold spot temperature range for the 185 nm radiant power is 60–70 ℃ with a relative flat trend within 30–70 ℃.

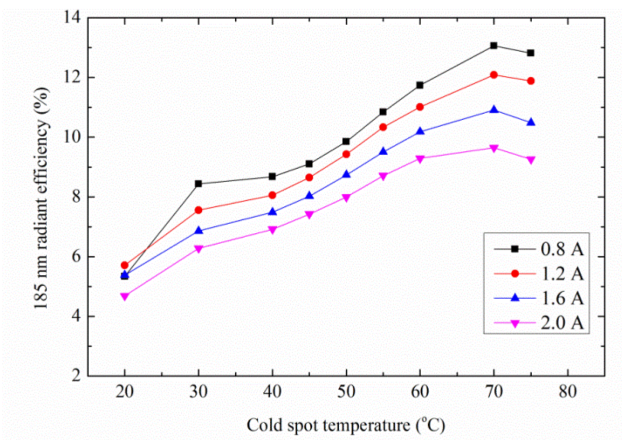

Figure 6. The dependence of 185nm radiant efficiency on the cold spot temperature with various currents (Ne 55% Ar 45% 1.5 Torr).

Fig .6 shows the dependence of the 185 nm radiant efficiency on the cold spot temperature with various currents. The optimum cold spot temperature has a relationship with the lamp diameter, because the narrowing of the lamp diameter leads to a decline in the resonant trapping. For example, the optimum cold spot temperature for 254 nm radiant efficiency is 40 ℃ for T12, 42 ℃ for T8, and 50 ℃ for T2 [13]. The 185 nm radiant efficiency, equals to the 185 nm radiant power divided by input power as seen in equation (6), has a maximum at the cold spot temperature about 70 ℃. The enhanced current results in higher electron density as well as more mercury atoms in excited state, leading to the radiant power increase. However, the electron temperature declines at the same time, increasing the probability of the second class inelastic collisions between low-energy electrons and the excited mercury atoms. For this reason, the increase of the radiant power in large current becomes slower than that in small current, but the input power increases linearly with the current. Therefore, the radiant efficiency is negatively related to the current as shown in Fig .6.

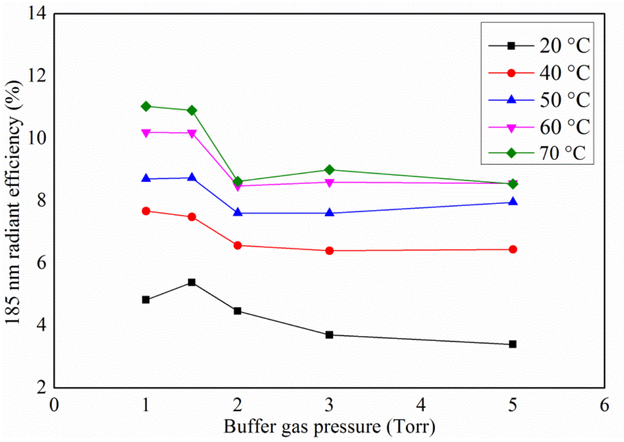

Figure 7. The dependence of 185 nm radiant efficiency on the buffer gas pressures with various cold spot temperatures

The dependence of 185 nm radiant efficiency on the buffer gas pressures with various cold spot temperatures is shown in Fig .7. It shows that the lamps reach the optimal 185 nm radiant efficiency at about 1–1.5 Torr, and has a lower radiant efficiency at a higher gas pressure. At a higher pressure the huge loss of energy, created by the elastic collision between electrons and atoms, is the main reason.

IV. Conclusion

It is indicated that 185 nm radiant efficiency reaches the highest of more than 11% at the cold spot temperature 70 ℃, and have a higher value in gas pressure 1–1.5 Torr, while it shows a negative relationship with the current. This conclusion is a significant reference to the industrial production. Comparing to 254 nm radiation about 40%, the 185 nm radiant efficiency in the lamp is still relative low, but it’s high enough for some VUV applications.

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